Technical Policy Briefing Note 7: Extreme Outcomes

Prospects for major tipping and socially contingent events and associated economic and social costs:

Summary of cross-sectoral results from the ClimateCost project, funded by the European Community's Seventh Framework Programme

Thomas E Downing and Ruth E Butterfield

With contributions from Sukhaina Bharwani, Mohamed Hamza, Chris Hope, Alistair Hunt, Vikrom Mathur, Neela Matin, Richard Taylor and Paul Watkiss

ClimateCost

SEVENTH FRAMEWORK PROGRAMME

Key Messages

- Extreme outcomes refer to near-catastrophic events and processes that would push the climate system into undesirable states. While highly uncertain, major discontinuities of this nature are poorly represented in most assessments of the economics of climate change.

- The understanding of extreme outcomes related to climate change is rapidly increasing. Earth systems and sustainability science have brought new insight into the nature of coupled socio-ecological systems, as well as the domains of resilience and surprises. ClimateCost has explored this new evidence and emerging science, considering two central policy questions: What impacts of climate change would make a significant difference to the global cost of climate change? What are the globally significant limits to adaptation?

- Biogeophysical tipping elements in the Earth system include a number of events that could have serious consequences within 50 to 100 years: melting of the Greenland and West Antarctic ice caps and the Hindu-Kush-Himalaya-Tibetan glaciers; changes in the Atlantic thermohaline circulation (THC) and El Niño/Southern Oscillation (ENSO); drought in the Amazon; and shifts in the Indian summer monsoon and rainfall in southwestern North America. ClimateCost has explored the consequences of some of these events.

- The study has first assessed major sea level rise. Over 600 million people currently live in the low elevation coastal zone (areas below 10 metres of elevation that are hydrologically connected to the sea). Economic activity in this zone is over $2 trillion GDP, slightly less than 3% of global GDP. Asia and the Asia-Pacific account for the majority of the exposed population and a third of the exposed economic activity.

- New scenarios of sea level rise (SLR) extend the IPCC AR4 assessment and highlight the possibility of more extreme changes. ClimateCost has used such projections to assess the potential impacts and economic costs of major sea level rise. A high-end scenario of over 1.5 m of SLR by the 2080s is estimated to result in nearly a 60% loss of global wetlands and to put over 30 million additional people / year at risk from coastal flooding. The economic costs of this high end SLR scenario could be in the region of $ 1 trillion per year (with no adaptation, current prices, undiscounted). However, such extreme scenarios are uncertain, with a low probability of occurrence.

Climate change over 4°C

significantly increases the likelihood of major tipping elements

Over 600 million people

currently live in the low elevation coastal zone, at less than 10m elevation

Over 100 million people

might seek to move due to climatic risks, possibly as soon as the 2050s

Potentially 25%

of the cost of climate change impacts is related to the discontinuities of major tipping elements

- New scenarios of sea level rise (SLR) highlight the possibility of more extreme changes than Intergovernmental Panel on Climate Change (IPCC) AR4 projections. ClimateCost has used such projections to assess the potential impacts and economic costs of major sea level rise. A high-end scenario of 1.65 m of SLR by the 2080s is estimated to result in nearly a 60% loss of global wetlands and to put over 30 million additional people / year at risk from coastal flooding when the effects of sea level rise and socio-economic change are considered. The economic costs of this high end SLR scenario could be in the region of $ 1 trillion per year (assuming no upgrades or adaptation, current prices, undiscounted, with 90% of this occurring due to climate induced sea level rise). However, such extreme scenarios are uncertain, with a low probability of occurrence.

- There are already over 30 million migrants that have been caused (at least partially) from environmental forcing (including weather-related disasters). While estimates of future migration from climate change vary considerably, a growing consensus estimate is that over 100 million people could seek to move due to climatic risks (acting with or on top of other factors), possibly as soon as the 2050s.

- A case study in South Asia has shown that security, conflict and the physical impacts of climate change could contribute to a socially contingent tipping point. South Asia is a major concern given the instability of the Indian monsoon and potential drought risk that might limit agricultural adaptation options.

- However, projecting these effects is challenging. Climate change, and in particular extreme outcomes, is an example of a 'wicked' environmental problem. The ability to predict the future is limited; the chains of causal factors cannot be easily disentangled; and a strong path-dependence means there are many plausible responses.

- Complex problems, such as tipping elements and extreme outcomes, can only be addressed through multiple lines of evidence. The ClimateCost project has explored a range of approaches, from qualitative narratives and case studies, to integrated assessment models and formal models of behavior based on actor-network approaches.

- The science base for understanding extreme outcomes and planning adaptive responses requires international cooperation and is an area where European policymakers have a leading role. This is obvious for international water resources, trans-boundary health threats, migration and security. Further science-policy dialogues are warranted, linking across thematic areas.

1. Introduction

The objective of the ClimateCost project is to advance the knowledge on the economics of climate change, focusing on three key areas: the economic costs of climate change (the costs of inaction), the costs and benefits of adaptation, and the costs and benefits of long-term targets and mitigation. This technical policy briefing note provides an overview of the global assessment of major extreme outcomes: those tipping elements and major impacts that have high economic and social costs.

The nature of extreme outcomes related to climate change has gathered considerable attention in the past five years or so (Lenton, 2008, Schellnhuber et al. 2006). Previously, those who proposed extreme outcomes were seen as catastrophists seeking attention to climate issues well beyond the evidence. Some were also fatalists in the sense that there seemed little reason to act in the face of such scenarios. More recently, a science community has emerged based on a range of approaches under a broad rubric of Earth Systems Science and sustainability science. The approaches focus on the nature of a coupled socio-ecological system, domains of resilience and surprises.

ClimateCost has recognized this emerging science and explored new evidence as it relates to the economics of climate change. By extreme outcomes, we refer to the panoply of near-catastrophic events and processes that would push the climate system into very undesirable states. For the most part these outcomes originate in views of the world as a collection of complex systems with more than one quasi-steady state that emerges from a wide range of interactions.

Two policy questions underlie the ClimateCost analysis:

- What impacts of climate change would make globally significant differences in the cost of climate change impacts? These are the consequences that have high costs or such a large scale that the range of estimates of the social cost of carbon would need to be dramatically increased.

- What are globally significant limits to adaptation? These are processes and conditions where responding to climate change would be severely limited, with high residual costs of impacts in the absence of effective adaptation.

This Technical Policy Briefing Note (TPBN) is organized to bring together a wide range of material. First, we provide an inventory of the major tipping elements and extreme outcomes as an orientation to the issues. Second, risk assessments in coastal zones provide initial estimates for causal pathways related to sea level rise. Third, a broader policy analysis of the nexus around climate, migration and security, is based on a wide range of work in the project including a global analysis of fragility, narratives, agent-based social simulation and an integrating case study of South Asia. Fourth, we draw together the multiple lines of evidence on the economic costs of extreme outcomes, using PAGE to illustrate the range of results. Finally, the TPBN summarizes the nature of the evidence for supporting further policy development and implications for policy.

2. Tipping elements and extreme outcomes in Earth systems

Biogeophysical tipping elements

Major changes in Earth systems that would represent a fundamentally new climate-state rather than an incremental change in existing climate conditions have been appraised for about a decade. For instance, one of the first proposed discontinuities was the collapse of the West Antarctic Ice Sheet (WAIS), with a resulting sea level rise of 5 to 6 meters. More recently, estimates have been made of the likelihood of such tipping elements. ClimateCost reviewed this literature as an introduction to the estimates of the economic and social consequences—extreme outcomes of climate change.

What is a tipping point? Messner and Rahmstorf (2010, see also Alley et al. 2003) note that tipping points are strong, non-linear responses by system components, likely to happen in the event of high global warming beyond 3-4°C of global average change relative to pre-industrial, though plausibly at lower levels. When a critical threshold has been crossed, the system may be triggered into runway changes that are difficult to control. And tipping points in the Earth system could trigger tipping points in the world economy and politics, including socially contingent responses. The sense of 'tipping' the Earth system into a qualitatively

Box 1. A note on terms

The language around climate extremes comes from diverse disciplines and traditions. While core concepts have been broadly agreed, some of the terms have different interpretations. This TPBN tends to use the dominant terms and definitions, but we recognize expert communities have different orientations and framings.

Extreme events usually refer to weather-related episodes that are infrequent—with a probability of say 1 in 25 years (4%) or 1 in 100 years (1%). We refer to **extreme outcomes** as the major consequences of climate-related processes—which may involve extreme events if they trigger accelerated and often global changes.

Flooding refers to a range of conditions from a seasonal wetland to a flood event (labelled an extreme event). Sea level rise changes the distribution and impacts of flood-extreme events. It also leads to loss of dry land due to permanent inundation (also called flooding too). Accelerated coastal erosion with sea level rise and more frequent extreme events have impacts even if the land is not flooded first.

Tipping elements: Extreme outcomes in Section 2 have been labelled tipping elements—those components of the Earth System that might combine to force qualitatively different states. Previously, these elements were called 'tipping points', which refers more specifically to time periods or events rather than global processes.

Climate-related migration has been at the centre of an intense debate. The term **refugee** is usually constrained to the political definition of the UN, although the notion of climate refugees is a popular image. Climate-driven or climate-related indicate the degree to which climate is a driver in a causal chain. Displaced person is not a perfect synonym for migration, as it implies an external forcing whereas most migration is voluntary to a considerable extent.

Population (or people) is often described as population-at-risk, although this implies that those people are themselves immediately exposed to some threat. This is less clear where the threat would evolve slowly over several generations, as for sea level rise. In the disasters language, population affected is often used as a less direct measure to include those people affected by second-order consequences.

In the results from the DIVA model(Section 3), the population at risk is defined as the number of people at risk from flooding due to submergence from extreme sea levels. This is defined as the expected number of people subject to annual flooding due to submergence and assuming those subject to a 1-in-1 flood move out of the coastal zone. The projected number of people residing in the coastal zone is based on the reference socio-economic scenario, and so is external to the projected rise in sea level. Obviously, governments, companies, urban planners and people themselves will make decisions on where to locate. If sea level rise is noticed, causing increased pressures in the coastal zone, people may choose to move away. This might be termed part of an autonomous adaptive process.

In order to avoid confusion with subsequent material on migration and humanitarian crises, we use the term **relocation from at-risk regions** in referring to the implications of the DIVA sea level rise results for a high-end scenario. This covers several categories:

Those who reside in the coastal zone and decide to relocate in response to a storm surge or extreme water levels or because they are subject to annual flooding due to submergence

Of course all such classifications are partial at best and the numbers generated by integrated assessment models, scenario-driven impacts models or 'not implausible' reasoning are impossible to validate and should not be considered predictions.

different state is important. Under certain circumstances, a small perturbation could change the global climate system.

These major effects have also been used as a wider catchall for processes that are not normally included in global climate models. For instance, the acidification of the oceans is often included, although the process is more like global temperature change than a discontinuity that triggers a new Earth systems state.

Tipping elements that are not readily captured in global climate models include:

- Impacts that are more extreme than expected from current probability distributions in global climate models, e.g., Amazon dieback and boreal forest disturbance

- Processes generated by instability in ocean-ice-atmospheric interactions: WAIS, ENSO, etc.

Table 1 Major tipping elements, potential impacts and time frame within next 50 years.

Tipping elements	Key concerns	Effects within 50 years?
Arctic sea-ice	Amplified regional and global warming: ice-albedo feedback in addition to thermal effects. Ecosystem change: effects on Arctic ecosystems and species, e.g., polar bear	Some
Greenland, West Antarctic and small ice caps	Aggregate sea level rise: about 0.5 m by 2050 is not implausible	Yes
Hindu-Kush-Himalaya-Tibetan glaciers	Reduction in river flow: melt-water from Himalayan glaciers and snow fields supplies up to 85% of dry season flow in India; models suggest this could be reduced to about 30% over the next 50 years	Yes
Permafrost (and carbon stores)	Amplified global warming: release of methane; 'runaway' scenarios are grossly exaggerated as effect is modest compared to other feedbacks	No
Boreal forest	Forest fire, spread of pests & diseases: covers large areas	Some expression
Atlantic thermohaline circulation	Weakening rather than collapse, leading to regional sea level change especially in North Atlantic; linked to other hydrological tipping elements	Yes
El Niño/ Southern Oscillation (ENSO	Complex effects, combined with other climate variables: higher amplification of ENSO events	Yes
Amazon rainforest	Drought: with effects on wildfire, hydroelectric generation, agriculture, river navigation, livelihoods and related services Die-back: biodiversity loss, decreased rainfall, livelihood impacts, destruction of carbon sinks	Yes (drought) Maybe (die-back)
West African monsoon and Sahel	Potential benefit: wetting and greening of the Sahel and parts of the Sahara toward conditions of some 6000 years ago	Perhaps
Indian summer monsoon	Interference with monsoon cycle and drought frequency: aerosol forcing could weaken the monsoon; but if removed local warming could trigger a stronger monsoon producing an oscillation affecting millions of people	Yes
South western North America	Prolonged drought impacts: increased wildfire and consequences for agriculture, water resources and water markets	Yes

Adapted from Lenton,T., Footitt, A. and Dlugolecki, A. (2009) Major Tipping Points in the Earth's Climate System and Consequences for the Insurance Sector. Published in November 2009 by WWF – World Wide Fund for Nature (formerly World Wildlife Fund), Gland,Switzerland and Allianz SE, Munich, Germany.

- Other biogeophysical effects that have weak or unknown links to climate impacts: e.g., methane

- Earth systems processes that intersect with climate impacts, e.g., ocean acidification

Socially contingent responses are large-scale, 'second-round' socio-economic responses to the impacts of climate change, such as conflict, migration and flight of capital (Stern 2006).

Based on ClimateCost and other reviews, eleven tipping elements were identified (Table 1).

Four are likely to have impacts within or beginning by the middle of the 21st century, but they are by no means the most important in terms of their impact and number of people affected:

- Global sea level rise (SLR) of up to 2m combined with a local anomaly on the eastern seaboard of North America – resulting in 0.65m rise by 2050 in Baltimore, Boston, New York, Philadelphia

- Hydrological system disturbance in Asia – summer monsoon changes due to ENSO, and disturbances to fluvial systems from Hindu-Kush- Himalayan-Tibetan glaciers, resulting in twice the drought frequency and reduced river flow

- Die back in the Amazon rainforest and increase in ENSO events – resulting in increase severity of drought

- Shift to a very arid climate in southwestern North America

Three scenarios of future climate change form the background for a subjective probability assessment of three tipping elements (Kriegler et al., 2009, reviewed by ClimateCost). The three scenarios are a low temperature corridor (climate is stabilized at less than 2°C), a medium corridor of 2 to 4°C, and a high temperature corridor of 4 to 8°C; all in 2200. Experts provided a range of probabilities for the tipping elements: thermohaline circulation (THC), Greenland Ice Sheet (GIS) and West Antarctic Ice Sheet (WAIS).

The results (Table 2) show the range of estimates from the 15 to 22 experts and the unweighted range for a core group of experts. Experts consider the risk of tipping of major climatic subsystems significant, although there is a wide range of views among the panel. The risks are judged to be quite high for all three elements with global warming over 4°C by 2200. Since the triggering of different elements might be correlated, e.g., the Greenland and West Antarctic ice sheets are likely to melt at the same time, tipping elements are an important boundary condition for acceptable levels of climate change.

Two integrated assessment models were used to evaluate the economic significance of these tipping elements (see sections below). Results for sea level rise using DIVA are presented in the next section. The PAGE IAM has the ability to play 'what if' scenarios of the costs of major outcomes. The implications for economic assessments are considerable. Long-term, low probability and nonlinear events are not readily reduced to a net present value. ClimateCost explored other metrics of costs of such socially contingent outcomes. Despite the uncertainty, assessments of tipping elements have significant policy relevance. They establish the need to make decisions in the context of uncertainty rather than limiting analysis to what we know and have been instrumental in reinforcing the case for a global target of 2°C.
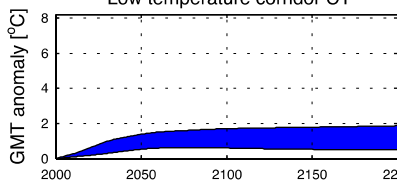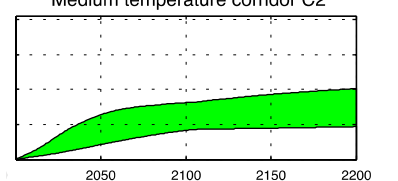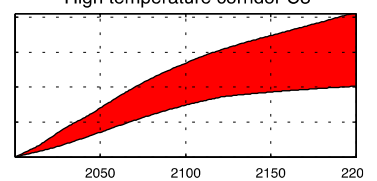
Other sources of extreme outcomes

The tipping elements catalogued above regularly appear in policy discussions and were the focus of ClimateCost. The project discussed several other sources of extreme outcomes that are rooted in social and economic systems rather than driven by impacts of large-scale climate-related processes.

A clear example of this conception of an extreme outcome is the link between climatic events that individually may not have extreme outcomes but that occur in conjunction with other processes. For example, the Arab Spring was due in part to high food prices caused by drought, floods and fires in major cereal producing regions, from Australia to Russia (Breisinger et al. 2011, Johnstone and Mazo 2011, see Figure 1). Other factors were also involved in the political upheaval—but the sensitivity of the middle class to global food prices was one factor. Curiously, Ahmed et al. (2009) had earlier noted the effect of climate volatility on poverty in 16 developing countries using a novel economic-climate analysis.

Many sources have noted barriers and limits to adaptation (e.g., Moser and Ekstrom, 2010). One category that recurs falls under the broad framing of governance—a lack of

Table 2. Subjective probability estimates for three tipping points and three scenarios of global warming.

Low corridor	Medium corridor	High corridor
THC		
• Experts: 0 to 3%	• Experts: 0 to 60%	• Experts: 5 to 100%
• Core: 0 to 2%	• Core: 5 to 40%	• Core: 20 to 65%
GIS		
• Experts: 0 to 90%	• Experts: 0 to 100%	• Experts: 1 to 100%
• Core: 5 to 40%	• Core: 35 to 75%	• Core: 65 to 95%
WAIS		
• Experts: 0 to 90%	• Experts: 0 to 100%	• Experts: 0 to 100%
• Core: 2 to 40%	• Core: 1 to 60%	• Core: 35 to 85%

Source: Kriegler et al. (2009)

Figure 1. Cereal prices spiked in 2008 and again in 2010-11 with global consequences. This volatility at a global level suggests that extreme outcomes of climate impacts are plausible in the future..

Monthly Cereals Price Index (2002-2004=100)
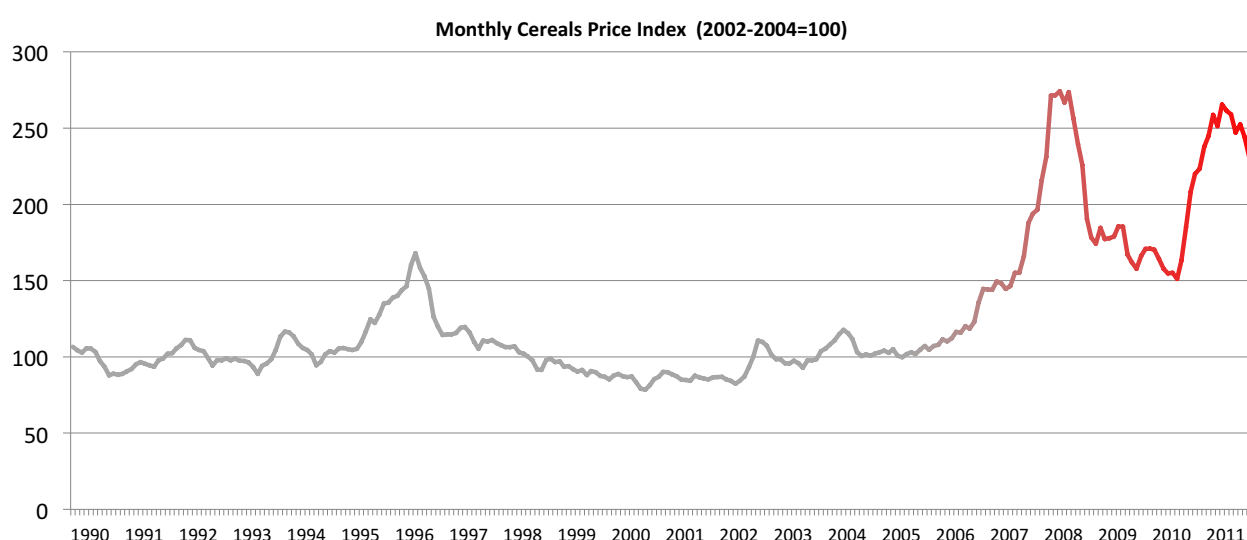
institutional capacity, political will and finance to tackle existing climate impacts (e.g. through disaster risk reduction). Preparedness for future climate change is constrained accordingly. For instance, it has taken some 20 years to put in place the beginnings of a systematic response to melting permafrost in Alaska—one of the wealthiest regions in the world (Marino and Schweitzer 2008). The idealized responses often predicted in global assessment models (such as DIVA, reported below) may be far from the reality of budgets and bureaucracies.

A more subtle linkage is the nature of future uncertainty and investment. The economic crisis that has captured headlines for the past five years is far from over. One implication has been a reduction in credit and further constraints on risk ratings. Where climate change might plausibly increase risks, investment from the private sector might be more cautious. This might then lead to a shift of investment to safer regions, sectors and projects. Such a shift need not be problematic and might be desirable if the risks are known, evaluated and compared. However, for many climate-related risks and regions, such as Africa, a lack of knowledge on risks might

cause (good) projects to fail due diligence and risk safeguards. There is little analytical work on this topic, although Bose (2011) highlights the need for a financial bridge to achieve sustainable, investment-grade climate projects.

Each of these social and economic processes have inherent instabilities. It is difficult to imagine what a solid base of evidence might be, given the limitations of predicting the future and modeling path-breaking transformations. Approaches based on surprise are a start (see Schneider 2004). The uncertainty is not a reason for inaction, however, as building a resilient capacity to manage future conditions and risks is not a short-term project.

3. Scenarios of impacts in coastal zones

This section presents new evidence developed by the ClimateCost project on the impacts of extreme scenarios of sea level rise. Scenarios of extreme SLR have been

[1] The EC Atlantis project evaluated the impacts and social, institutional and economic consequences of a 'not-implausible' scenario of 5 m SLR by 2100

discussed for two decades and remain contentious—seen as plausible but low probability events.[1]

The global consequences of a 10m rise in sea level

Exposure to extreme outcomes in sea level rise is principally driven by the prospect of collapse of the WAIS and advanced melting of Greenland. A benchmark indicator of future exposure is the Low Elevation Coastal Zone (LECZ).

This zone includes only the area below 10 m that is hydrologically connected to the sea.

ClimateCost has compiled a global data base with an initial estimate of the costs of an extreme scenario of sea level rise.[2] The baseline data is for 2000. High-resolution elevation data were combined with population data (GRUMP[3]) with a resolution of 30-arc seconds. Economic data were drawn from the Yale G-Econ[4] estimate of gross output at a 1-degree longitude by 1-degree latitude resolution at a global scale. Gridded values were calculated to add up to GDP at the national level.

Table 3. Global Population and GDP at risk for sea level rises up to 10m.

SLR, m	Population. Million	%	GDP, $Million	%
1	166	1.4	809,405	2.5
5	326	5.4	1,515,079	4.8
10	621	10.3	2,287,927	7.2

% is of global population and GDP. Note that the GDP coverage does not include China.

Table 4. Global population and GDP at risk from 10m sea level rise, split by region

	Population Million	%	GDP, $ Million	%
Africa	52.5	9.0	37,084	1.6
Asia	315	54.2	541,916	23.7
Asia-Pacific	120	20.6	203,555	8.9
Europe	46.7	8.0	720,964	31.5
Latin America	13.4	2.3	67,591	3.0
Middle East	4.6	0.8	19,154	0.8
North America	29.3	5.1	697,442	30.5
Global	582	100.0	2,287,705	100.0

% is of the at-risk population and GDP. Note that the GDP coverage does not include China.

(Lonsdale et al. 2008).
[2] The data base and analysis were led by Athanasios Vafeidis, University of Kiel in association with the University of Southampton.
[3] http://sedac.ciesin.columbia.edu/gpw/.
[4] Geographically based Economic data, http://gecon.sites.yale.edu/.

There are considerable limitations to this approach, as interpolating national population and economic activity to a fine grid cannot be wholly accurate. The data used is for current exposure: no attempt has been made to project exposure into the future, and no attempt has been made to factor in adaptation (in practice there would be an adaptation response that would reduce the population and assets at risk). Thus, the results are not a realistic projection of future exposure or costs of climate change impacts. Nevertheless, they are an indication of the order of magnitude of the risk based on current LEZ data.

Over 600 million people currently live in the LECZ, accounting for over $2 trillion in GDP. While these are large numbers, the exposed population is less than 10% of present global population. As world GDP in 2010 was over $60 trillion, the exposed economic activity is about 3% of the world total. The exposure of populations and economic activity is nearly linear from 1m to 10m, with no obvious break points.

Not surprisingly, Asia and the Asia-Pacific account for the majority of the population that might be affected and a third of the global GDP exposure. Europe and North America (including Mexico) stand out as having the highest economic exposure. In comparison, Africa is much less exposed to sea level rise as a whole. However, individual countries with high exposure are found in every region: from Egypt and the Maldives in Africa to Surinam in South America and Bangladesh in Asia (with many others).

A scenario of upper-end sea level rise

Extreme water levels caused by rising sea levels leading to inundation of coastal areas are a major concern as a tipping element. There are large uncertainties associated with the potential magnitude of SLR over the 21st century. In the Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4), Meehl et al (2007) projected sea-level rise by the end of the century between 0.18m and 0.59m, with a potential to increase up to 0.76m if the higher rate of recent melting from the large ice sheets continued (e.g. Solomon *et al.*, 2007, Rignot et al. 2008, van de Wal *et al.* 2008). Since the IPCC AR4, different methods (e.g. semi-empirical relationships, paleo-records) have been used to generate sea-level rise scenarios with much higher rises than reported in Meehl et al. (2007). These potentially extend up to 2.4m of rise per century e.g. Rohling et al, 2008. Recent scenarios based on Representative Concentration Pathways (RCP), suggest a rise between 0.36m and 1.65m by 2100 (Jevrejeva et al., 2012).

Some 600 million people (approximately 10% of the global population) live in Low Elevation Coastal Zones (McGranahan et al., 2007), and this figure is likely to grow faster than the rate of global population growth. People and the ecosystems and infrastructure they depend on are at risk. Some impacts will be inevitable (e.g. flooding due to subsidence causing a relative rise in land levels), and will be enhanced by sea level rise, whilst new impacts will occur.

ClimateCost projected the effects of higher estimates of SLR on coastal impacts. The scenarios are not the extreme outcomes suggested by collapse of the WAIS and Greenland Ice Sheet (e.g., exposure to 10m SLR reported above). The results provide a detailed analysis that extends a state-of-the-art integrated assessment model. This research assesses global wetland losses, number of people at risk and numbers who relocate throughout the 21st century.[5]

To determine the impacts of sea-level rise on the coastal zone, the Dynamic Interactive Vulnerability Assessment (DIVA) model (version 3.3.2) was used. DIVA is an integrated model of coastal systems that assesses biophysical and socio-economic impacts of sea-level rise and socio-economic development (Hinkel 2005; Vafeidis et al., 2008; Hinkel and Klein 2009). The climatic variables consist of the temperature change and sea level rise, whilst the socio-economic scenarios consist of population growth, gross domestic product (GDP) growth and land use. The impact assessment comprises a number of modules representing physical processes and economic costs, combined with a coastal adaptation strategy as shown in Figure 2 below. Since there is no empirical data on actual dike heights available at a global level, a demand for safety (based on population density in 1995) is computed and assumed to be provided by dikes (Tol, 2006; Tol and Yohe, 2007). In this study, it is assumed that defences have not been upgraded from this baseline level.

DIVA calculates impact metrics by disaggregating the world's

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[5] This analysis was led by Robert J Nicholls and Sally Brown at the University of Southampton.

coastline (excluding Antarctica) into 12,148 coastal segments (with an average global length of 85 km). The area at risk from flooding for each segment was based on the Shuttle Radar Topography Mission (SRTM) dataset, which has a horizontal resolution of 90 metres (Rabus et al 2003). For each segment, DIVA first downscales the sea-level scenarios and combines it with vertical land movement to create a record of relative sea level rise (RSLR). Vertical land movement occurs for example due to natural subsidence or tectonics. Rates of natural subsidence were based on the model of Peltier (2000a; 2000b). Additionally for 76 of the world's major deltas, actual subsidence rates (based on past records) were used, following the work of Ericson et al. (2006). Human-induced subsidence was not considered. Extreme sea-level events produced by a combination of storm surges and astronomical tides will be increased by rises in mean sea level: the return period of extreme sea levels is reduced by higher mean sea levels.

Further details about the DIVA modules are available in the ClimateCost Technical Policy Briefing Note 02 (Brown et al. 2011).[6]

To analyse the potential for an extreme outcome, a high-end scenario has been developed. A 1.9m rise by 2100 was used to represent the post AR4 scenarios. This high-end scenario is compared to A1B(I) Mid range scenario created from the HadGEM-A0 model, where atmospheric CO_2 concentrations reach 1050ppmv by 2100, resulting in a temperature rise of 3.8°C (with respect to 1980-1999) and global mean sea-level rise of 0.42m (van der Linden and Mitchell, 2009; Lowe et al., 2009).[7] For comparison, a scenario without sea level rise is included (see Figure 3 below). The three sea-level rise scenarios were combined with the A1B socio-economics scenario (Nakicenovic et al., 2000) of rapid economic growth, new and more efficient technologies and convergence between regions, with a balanced range of energy resources. Global population peaks around 9 billion in the 2050s, and declines to less than 8 billion by the end of the century. GDP grows from the base level of €2.8 x10^13 to €5.5 x10^14 in 2100. The results are presented for the baseline timeframe, and three further time frames based on a 30-year means.

Figure 2. Modules and structure of the DIVA model.
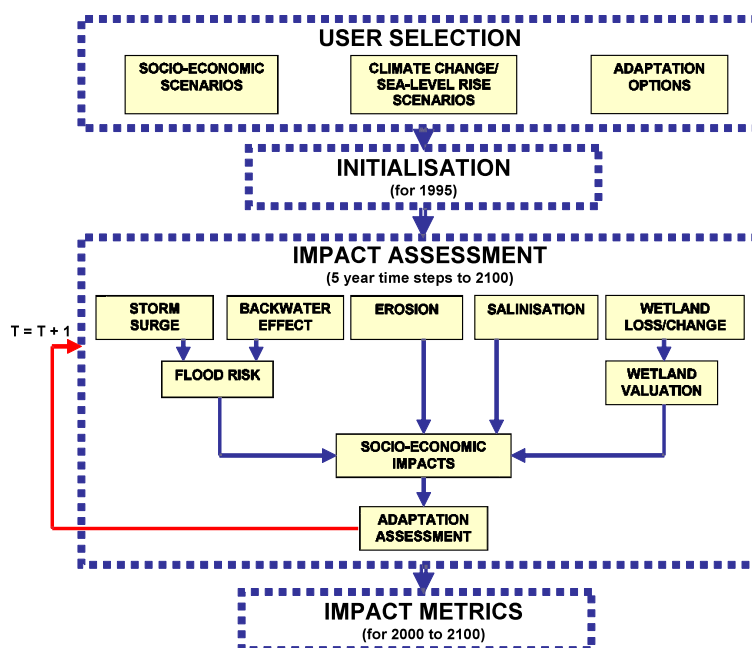
[6] http://www.climatecost.cc/images/Policy_brief_2_Coastal_10_lowres.pdf
[7] Further information about the AIB scenario is given in Pardaens et al. (2011) and Brown et al. (2011).

Table 5. Global mean SLR (m) for the high-end, A1B(1) Mid and no SLR scenarios, for the 2000s, 2020s, 2050s and 2080s.

	2000s	2020s	2050s	2080s
High-end	0.14	0.47	0.97	1.65
A1B(l) Mid	0.02	0.10	0.22	0.37
No SLR	0	0	0	0

The impacts of high-end sea level rise are presented as annual mean values (with no discounting) in the following figures.

Wetlands

Wetland loss includes coastal forest area, freshwater marsh area, high unvegetated areas, low unvegetated areas, mangroves and salt marshes. Wetlands are valuable coastal assets and have numerous benefits including primary habitat grounds for birds and fish, pollution cleansing/filtering, acting as a natural barrier to erosion and flooding, their ability to

absorb greenhouse gases, and heritage and recreational values. Small magnitudes of wetland losses are seen with the no sea-level rise scenario due to land subsidence – this particularly occurs around deltaic regions. By the 2080s, the high-end sea level rise could potentially lead to the loss of 59% of global wetlands, compared to a loss of 30% for the A1B(l) Mid scenario. Only 4% of this wetland loss would be expected if sea levels were not rising. The greatest rate of wetland loss per cm of sea-level rise occurs for very low rises in sea level. This is because wetlands are predominantly low and are periodically covered by tides.

Population at-risk

In the high-end scenario, 12 million people are at-risk per year in the baseline (2000s) (see Box 1 on the definition of terms). By the 2080s, the population occupying coastal zones subject to inundation (including storm surges) is over 35 m people per year. This is a 60% increase over the population at risk in the A1B(l) Mid scenario. By the 2080s, between 0.1% (no sea level rise scenario) and 0.4% (high-end) of the global population could be at risk from coastal flooding. The vast majority of the population at-risk is from low and middle-income countries.

Figure 3. Global relative sea level rise for a high-end scenario, compared to the A1B(l) Mid and no SLR scenarios. Results for the A1B scenario are reported in the ClimateCost TPBN on sea level rise (Brown et al. 2011).
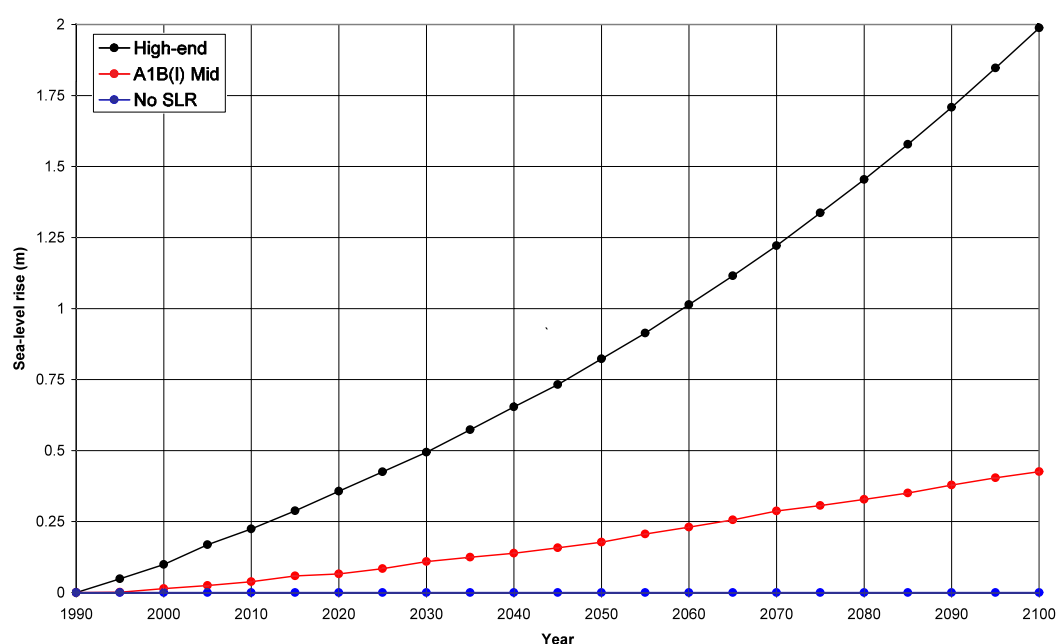
From the baseline (2000s) through to the 2050s, there is a linear increase in the number of people at risk in the high-end scenario. However, sea level rises at a non-linear rate—hence relative impacts are more severe in the early time periods and the marginal number of people at risk decreases especially beyond the 2050s. The increase in population at-risk is linear for the A1B(I) Mid scenario, and over the entire time period, but with a lower slope. Thus, many of the greatest impacts (number at risk, cost per cm of sea-level rise) would be expected to occur in the short to medium term with a high-end sea-level rise.

Relocation from at-risk regions

One reason for the change in the future population at-risk is that people migrate out of the coastal zone when subject to annual flooding. People will be at risk from flooding even without climate change due to changes in relative land levels. By the 2080s the number of people at risk increases by 50%, despite the global population increasing only by 30%.

When people are subject to regular flooding (defined as greater than a 1-in-1 year flood), there is an incentive to move away from the coastal zone. In this TPBN, this population is referred to as those who relocate from at-risk regions (see the definitions in Box 1).[8] The cumulative sum of people who relocate from the at-risk regions due to rising sea levels increases dramatically in the high-end scenario, compared with the A1B(I) scenario. Relocation is seen even for a no sea-level rise scenario as land subsidence forces a rise in relative sea levels. For higher levels of sea-level rise, there are a greater number of people flooded, despite a falling global population. Cumulatively, 286 million people could be forced to relocate throughout the century for the high-end scenario, reducing to 88 million for the A1B(I) Mid scenario (1.1% and 0.3% of the total global population). The DIVA results accord reasonably well with some of the scenarios of climate change migration (e.g., Myers and Kent, 1995).

For the high-end sea-level rise, the number of people who relocate increases linearly throughout the century, despite sea-level rise increasing exponentially. Hence for higher rises of sea level towards the end of the century, less people will

be affected per centimeter of sea level rise. The greatest sensitivity is seen for low rises in sea level.

Economic damage costs of seal level rise

The economic damage costs of the high-end scenario are in the region of Euro 1 trillion per year by the 2080s (current prices, undiscounted, combined effects of socio-economic and climate change), assuming defences are not upgraded. This does not include adaptation – or any costs of adaptation. These costs are four times greater than the A1B(I) Mid scenario, indicating the extreme outcomes that are possible in the future. In contrast to the population affected, damages costs are more evenly distributed across middle and upper income countries.

For wetlands, losses are particularly seen in the short time frame. Loss of wetlands will exacerbate reduced agriculture output due to salinisation. Wetlands are also under threat from non-climatic sources, such as conversion to agriculture or recreational areas (Coleman *et al*., 2008). Therefore wetlands need to be protected and preserved, and the Ramsar Convention – a global environmental treaty to converse and appropriately use wetlands at local, national and international scale in a co-operatively and sustainable manner (Ramsar Convention on Wetlands, 2008) helps to achieve this.

Sea level rise will result in more frequent flooding, damage to land and salinization. The high-end scenario brings these additional risks forward. Impacts on lives lost, income, livelihoods and quality of life are not quantied. If people are unable to adapt *in situ*, they may abandon land and move away from at-risk regions. Relocation due to sea level rise is most likely to be a long-term process: punctuated at times of crisis after a storm surge, forced by regulations and located in disperse social networks. Sea level rise on its own is unlikely to be the main 'push' factor. However, in the high-end scenario, sea level rise would start to dominate location decisions, certainly by the 2050s.

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[8] As an example of the confusion over these terms, some analysts refer to this population as 'people who are forced to migrate', while noting that this has no relationship to migrants that have to move for political reasons such as conflict or who are refugees. Subsequent sections of this TPBN refer to migration more explicitly in relationship to refugees and humanitarian crises. This highlights the need to clarify terms.

Figure 4. Global impacts of three scenarios of sea level rise.

Loss of wetlands

Population at-risk of flooding

Cumulative population relocated since 1990
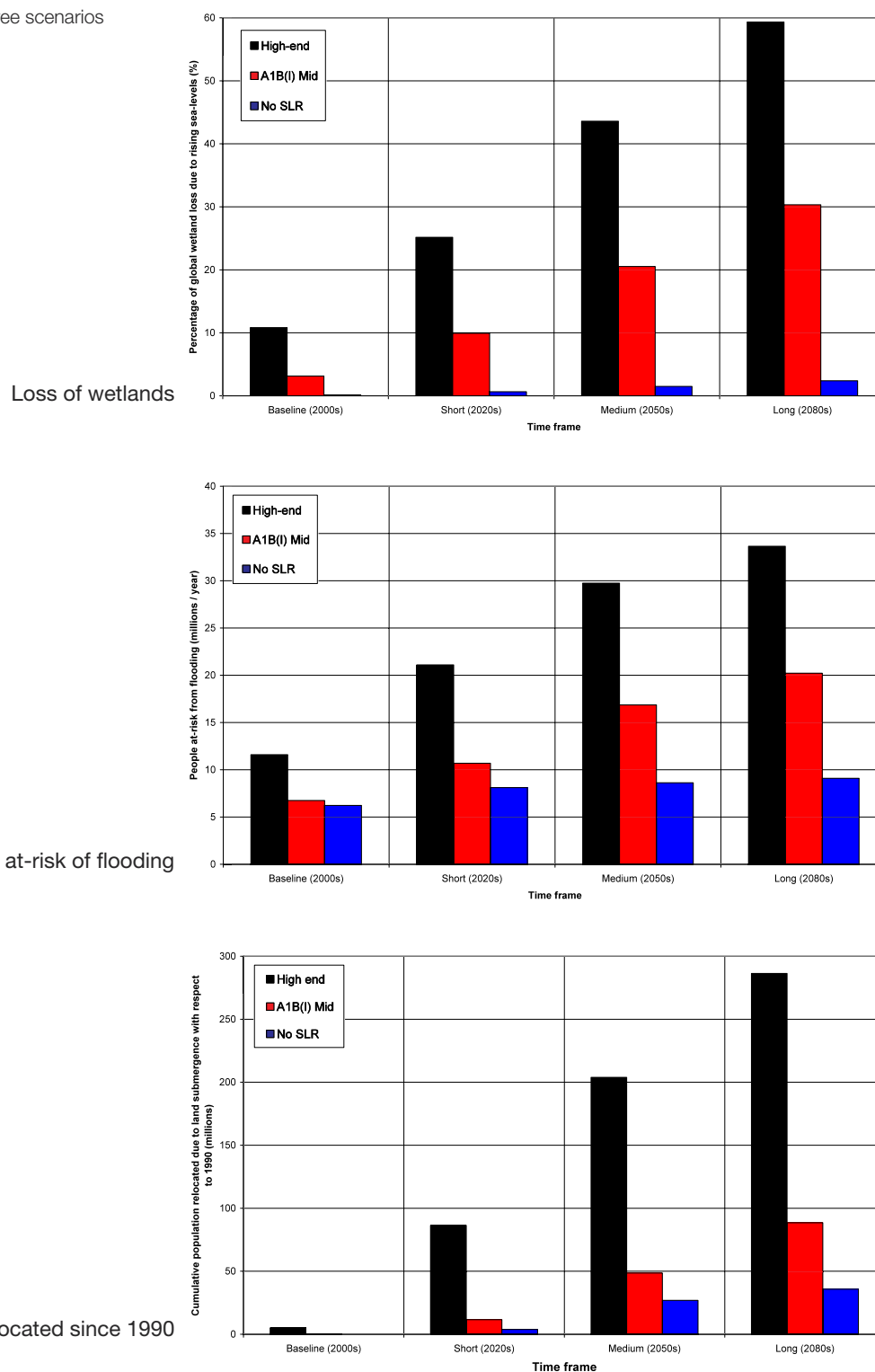
Notes: All scenarios assume a growing population in the coastal zone and no upgrade to adaptation measures, such as wetland nourishment. Numbers reported for the high-end and A1B(I) Mid scenarios include the combined effects of sea level rise and socio-economic change. The effects of future socio-economic change (without future climate change) can be seen with the no SLR scenario. Source: DIVA model.

4. Analysis of Socially Contingent Effects and Tipping Points

Security and state fragility

In part based on coupled socio-ecological systems approaches (including tipping elements, resilience and planetary boundaries) there is a rising concern for security issues related to climate change. This is seen as a legitimate policy area (e.g., Foresight Panel, 2011), but one in which there is a paucity of real evidence or even systematic approaches. This discourse is closely linked to migration (covered in next section).

ClimateCost contributed to several reviews (e.g., Shen et al., 2010) and an analysis of methodological approaches. The

project indirectly supported two major policy initiatives: the Climate Change, Environment and Migration Alliance (CCEMA), a multi-stakeholder forum for reviewing evidence and science-policy engagement, and the UK Foresight Panel's International Dimensions of Climate Change (IDCC) that reviewed how the impacts of climate change overseas would affect UK policy and governance (Foresight Panel, 2011).

The conventional analysis of 'hot spots' has tended to compile various indicators at the country level, induce some aggregate estimate of vulnerability and relate this to climate change.
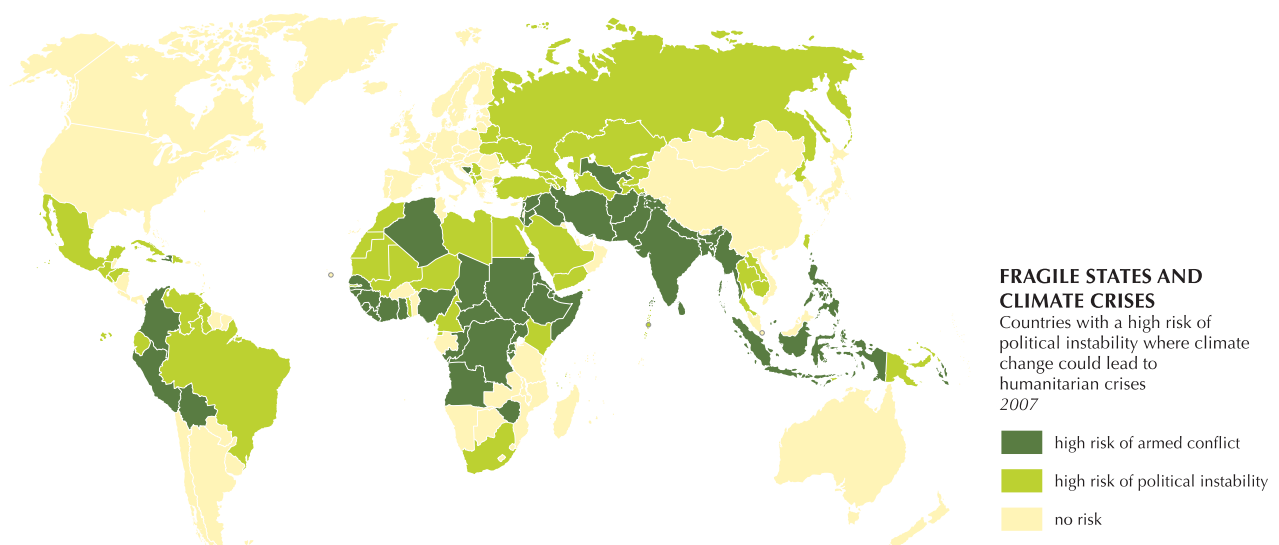
"Vulnerability is dynamic, as actors make decisions and interact with the environment, across space, iteratively at different times. It is impossible to represent such vulnerability as hot spots in Cartesian grids. Far better to approach issues such as extreme outcomes of climate change as hot systems."

Thomas E Downing,
keynote lecture as MunichRe Foundation
chair in social vulnerability.

More sophisticated approaches seek to build up a monitoring framework that tracks the factors affecting climate vulnerability (e.g. DARA, 2010). Four distinct sets of stress – health impact, human habitat loss, weather disasters, economic stress – are scaled from low up to acute for 2010 and 2030 for each country of the world. A far simpler approach is to group countries into similar categories. Alert International do this, based on the concept of state fragility (its own field) and an overlay of whether climate change would cause significant additional threats (see Figure 5). It identified some 102 countries that were at risk of significant negative knock-on socio-political effects. Of these countries, 46 faced a high risk of armed conflict. It seemed likey in 56 countries that their governmental institutions would not sustain the strain of climate change, leading to political instability (Smith and Vivekananda, 2007). This assessment of state fragility and risk of armed conflict was based on various indices already in use: UK DFID proxy list of Fragile States; Global Peace Index; International Crisis Group 'crisiswatch' list; and the World Bank list of Low Income Countries Under Stress. Other factors included the presence of an operational UN peacekeeping force and the prospect of economic or political transition (e.g., from

Figure 5. Areas at risk of political instability and high risk of armed conflict. Source: Smith and Vivekananda, 2007, after Dow and Downing, 2011.

FRAGILE STATES AND CLIMATE CRISES
Countries with a high risk of political instability where climate change could lead to humanitarian crises
2007

■ high risk of armed conflict

■ high risk of political instability

■ no risk

autocracy towards democracy or leadership succession).

Such maps do not make predictions but indicate risk against a backdrop of a changing climate. It should be borne in mind that armed conflicts vary widely in their levels of lethality and in whether they occur at a local, national or regional level.

Regardless of the approach, there are major challenges in validating such maps (Füssel 2009). Despite new maps (e.g., the Global Adaptation Index, www.GAIN.org which summarizes two measures – a country's vulnerability to climate change and also its readiness to improve resilience), the information content of such approaches is untested for making practical decisions. Mathur and Downing (2012) show that 'hot spots' methods are by and large untenable for policy analysis. Shen et al. (2010) propose a paradigm shift to 'hot systems' that captures the dynamic nature of multiple stresses and socio-institutional vulnerability. And such hot spots approaches do not extend to extreme outcomes.

The climate-security linkages follow several major narratives; each has particular challenges for economics of climate change. As illustrated above, state fragility is an inability to govern, and the state cannot guarantee achievement of economic growth and social development. In fact, the state may be a barrier to realizing globally agreed goals. Even a modest sized project could change the development status of a country, and discovery of oil or natural gas changes more than the financial flows. Terrorism and civil conflict have direct impacts on infrastructure that may constrain climate responses. Budgets increasingly devoted to peace-keeping and humanitarian crises may compete with investment in productive assets and disaster risk reduction. For example, the UK budget for peacekeeping and humanitarian affairs is about equivalent to what is promised on adaptation in the next five years (Foresight Panel, 2011). On the other hand, the Arab Spring offers hope that not all crises lead to adverse consequences.

These concerns have been raised in Europe (EC 2008). Socially contingent concerns included:

- Conflict over resources, economic damage and risk to coastal cities, loss of territory and border disputes, migration, fragility and radicalisation, tension over energy supply, international governance.

- In the Arctic, new trade routes because of melting may result in new territorial claims and access to trade routes. Hydrocarbon resources may change the geo-strategic

dynamics with implications for stability and European security interests.

Geographical regions of concern identified in the EC review were:

- Africa, Middle East, South Asia, Central Asia, Latin America and the Caribbean, the Arctic

- Special consideration to US, India, China and relations with Russia

And, climate impacts seen as driving security threats were:

- Nile Delta: SLR and salinisation;

- Food security and increased conflict across Africa leading to migration through Northern Africa to Europe;

- Health, vector borne diseases;

- Increasing stress on water systems leading to a drop in crop yields in the Middle East;

- SLR, agriculture impacts and change in monsoon rains in South Asia;

- Shortage of water for agriculture and energy generation in Central Asia;

- Salinisation and desertification in Latin America, also SLR, extreme events and hurricanes.

Narratives of forced migration

The concern for major outcomes has extended beyond biophysical elements to interactions with socio-economic conditions. ClimateCost conducted a global review of climate-migration issues and detailed case studies for Bangladesh and Kenya.

Bangladesh is one of the most climate-vulnerable countries in the world (MoEF 2008). The coastal areas of Bangladesh are about 710 km long and are home to more than 8 million people with a high population density of 930 people per square km. Most of the coastline and small islands are protected by embankments and polders that are built to save the land from tidal flooding and salinity and protect crops. Despite this, these areas remain vulnerable to frequent cyclone, storm-surge, and tidal intrusions.

Climate change induced rise in sea surface temperature,

Figure 6. Typical views of embankments in South Asia that are vulnerable to sea level rise and flooding from both rivers and storm surges. Photo credit: Krishnendu Bose, Earthcare Films.

change in the frequency and intensity of cyclones, and sea level rise may aggravate this situation. An analysis of tidal data collected from four coastal points in Bangladesh during 1975-2005 reveals that the mean sea level is rising and observed range of sea level variance can be taken as 5.05mm to 7.4mm per year (CEGIS 2009).

A major climate change impact will be changes in the frequency and magnitude of tropical and extra-tropical storms with potentially serious implications. The cyclone risk areas will move further inland affecting 14.6 million people in the 2020s and 20.3 million in the 2050s (Tanner et al. 2007) and riverine flooding is expected to increase as well (MoEF, 2005). Sea level rise will also result in drainage congestion requiring improvement and raising of embankments incurring considerable costs to the people and the economy (IWM and CEGIS 2007).

A large proportion of the local population who depend on natural resources will be affected by the projected sea level rise, expected to result in the inundation of cultivable land, saline water intrusion and loss of terrestrial and marine biodiversity. With projected sea level rise (SLR) of 32 cm and 88 cm, the coastal cultivable land will be reduced from the current level of 45%, to 40% and 15% respectively. Due to the rise in salinity, the major paddy crop will be reduced from current 88 to 60 percent and 12 percent with 32 cm and 88 cm SLR respectively. Once the world's largest stretch of mangrove ecosystem, the Sundarbans, a World Heritage site, is located in the southwest coastal area. This is particularly vulnerable to SLR as the area dominated by *Sundri* (*Heritiera fomes*, a major species in the Sundarbans)

area will be reduced from 20% of the area to 10% with 32 cm and to 2% with 88 cm SLR (MoEF 2008).

The climate change scenario is further complicated by high levels of environmental degradation. The coastal ecosystems, e.g. mangrove, marine, and forests provide habitats for a large number of plant species as well as fish and wildlife. Extensive resource extraction from coastal ecosystems, and unsustainable land use practices such as intensive shrimp cultivation, have created a situation where employment opportunities are being reduced steadily. Further, food security and access to safe drinking water are being threatened in many coastal areas. The situation is often aggravated by cyclones that result in human deaths, loss of valuable resources and damage to ecosystems.

The ClimateCost project supported a narrative approach to understanding the social and environmental interactions that prescribe vulnerability and adaptive pathways. The context for the narrative in Bangladesh is recurrent cyclones. On 25 May 2009, cyclone Aila hit south-west Bangladesh, causing massive damage, homelessness and raising worldwide humanitarian concerns. The coastal embankment, built in the 1960s, had burst in several places, and villages went under 3m of water, sweeping away everything they had. Crop and shrimp farms were also washed away. The Sundarbans was inundated under 6m of water with enormous damage to animals and plants. People were forced to take shelter on what was left of the embankment, and locals described the damage as the worst of its kind in living memory.

Aila followed cyclone Sidr which had hit the coast two years

earlier. Although the number of deaths directly resulting from Sidr was higher than that of Aila, the recovery period has been much longer. Six months after the cyclone, the area was still under saline water and open to the tidal flow of the Bay of Bengal. This has exposed the population for a longer period, increasing the risk of other stresses compounding the disaster, hence further delaying rebuilding and recovery.

People in these areas have adapted to environmental changes in various ways, migration being one way to secure a living in difficult times. Although people prefer to live in their forefathers' homes, more and more people are now migrating in search of jobs. The process often starts with temporary migration to nearby areas that might offer employment opportunities. The period of such migration varies from one week to six months or even more. In these cases a single person or a couple of members from a family leave while others stay at home. If the situation does not improve, or if a catastrophic event like a cyclone hits the area, seasonal migration may lead to permanent migration where entire families move out. Though it is difficult to establish a causal link between climate change and these migration episodes, climate change induced vulnerabilities play an increasingly important role in triggering permanent moves – when no other alternatives remain. The box (below) outlines a narrative composed of typical behavior in the region. It is based on household interviews, but is a constructed story rather than an individual life story.

Extrapolating from such context-rich local complexes to global estimates of the number of migrants who might be displaced by environmental or climatic factors is tenuous at best (Hamza et al., 2011). Studies of climate induced migration in the past have commonly calculated the numbers of environmental migrants by projecting physical climate changes, such as sea level rise, rain fall decline and drought, on exposed population. The fact of multi-causality of environment-induced migration and how extraordinarily difficult it is to develop and defend methodologies for calculating such numbers, has not stopped researchers and policy makers from trying. Some of the more prominent and often quoted estimates are as follows (see Boano et al. 2008):

- The International Federation of Red Cross and Red Crescent Societies (IFRC) estimated in 2001 that for the first time the number of environmental refugees exceeded those displaced by war.

- UNHCR (2002) estimated there were approximately 24 million people around the world who have fled because of floods, famine and other environmental factors.

- El-Hinnawi (1985) estimates there are already some 30 million, and 50 million environmental refugees by 2050 – equivalent to 1.5% of 2050's predicted global population of 10 billion (www.alternet.org/environment/19179).

- The Almeria Statement (1994) observed that 135 million people could be at risk of being displaced as a consequence of severe desertification.

- Myers, who made a 1993 prediction of 150 million environmental refugees, now believes the impact of global warming could potentially displace 200 million people (Myers and Kent 2005).

- The Stern Review, commissioned by the UK Treasury, agrees it is likely there could be 200 million displaced by 2050 (Stern 2006).

- Nicholls (2004) suggested that between 50 and 200 million people could be displaced by climate change by 2080.

- Friends of the Earth (2007) predict climate refugees at 200 million worldwide – and one million from small island states – by 2050.

- UNEP argues that by 2060 there could be 50 million environment refugees in Africa alone.

- Christian Aid have postulated that a billion people could be permanently displaced by 2050 – 250 million by climate change-related phenomena such as droughts, floods and hurricanes and 645 million by dams and other development projects (Christian Aid 2007).

Dow and Downing (2011) review the links between tipping points, complex emergencies and forced migration in a feature on climate and social crises in the *Atlas of Climate Change*. They suggest that climate-related migration might be 100 million people by 2050.

Modeling forced migration as a tipping point

ClimateCost supported development of an agent-based model of migration related to various disruption regimes,

A Narrative of Forced Migration in Bangladesh

Kabir started life as a fisherman, working in the numerous rivers and creeks in the Sundarbans. He would also collect forest products: forming a group of 4-6 people with approval from the Forest Department. They would go for about 2-4 weeks and were allowed to take certain non-timber forest products, e.g., fish, crab, reeds (Nipah Palm), honey etc.

However, decreasing resources of the Sundarbans and ever increasing number of people meant it was often hard to get enough from the 'approved' areas and people tended to venture deeper into the forests, knowing well that this was risky. The risks came not only from the forest guards but also from the Royal Bengal tigers (an endangered species found in the Sundarbans) that often killed people if they treaded too close to their habitat.

On 15 April 2009, Kabir went to the Sundarbans with his group. After a day's work, he anchored in one of the small creeks for the night. Suddenly, a tiger jumped into Kabir's boat and grabbed one of the fishermen, Kabir's uncle, named Gazi. Kabir and others joined a life and death struggle to free him from the tiger. Finally, the tiger left, but on the way back to the village, Gazi died of the injuries.

This was a life-changing shock for Kabir. He decided not to risk his life in this way. However, changing jobs was not easy. Employment opportunities have reduced in the area due to large-scale conversion of paddy fields to shrimp culture, which employ far less people. He also observed that the climate is changing, drastically. The monsoon is often late and when it comes, it is short and intensive, resulting in

Figure 7. Fishermen in the Sundarbans, Bangladesh.

water logged fields and crop losses. Tide levels are increasing, as is the salinity of water and land. The devastating ecological consequences of shrimp culture together with these environmental changes have created a situation where Kabir found that he could hardly make a living in his village.

The final blow came from cyclone Aila that struck the area in May 2009. Kabir lost all hopes of making a living in his area. He decided to leave the village and went to the city in search of employment. There he started life again – from scratch – working as a day laborer, sometimes pulling rickshaws, other times carrying loads in the factories or whatever is on offer.

informed by the case study of Gabura Union, Bangladesh (see the narrative above). The model, Transformations in Risk: Explaining Agent Diasporas (TREAD), explores the interaction between different hypothetical drivers of migration, comparing possible social processes and different outcomes. The general aim is to improve the formal analytical understanding of environmentally-induced migration.[9]

The TREAD model includes demographic, economic, and policy-related drivers of migration, as well as environmental disturbances. Processes and outcomes include temporary (i.e. seasonal) and permanent migration. 'Agents' in the model represent 'households' that rely upon natural resources and ecosystem services for livelihoods. TREAD concentrates on socio-economic changes that may be social tipping points.

[9] The model was developed by Richard Taylor; more complete results will be published in a forthcoming book (Taylor, 2013).

Households are represented as decision agents, with different levels of resources (wealth, skills, history of migration and employment, kinship and friendship networks). The sending area is an idealized spatial representation of the local economy, while the receiving area reflects variations in the availability of employment for migrants. Households need a certain level of wealth to migrate permanently.

Activity disruption, which includes major climate events as contributory factors, results in livelihood losses and the temporary reduction of economic activities available to households. The frequency of disruption—the average time interval between two successive disruptions—is an important trigger for migration.

Several archetypes, or model-derived scenarios, summarise the detailed simulation results:

- Stable: Local economy is stable with no significant trend usually with a steady stream of economic migration

- Collapse: A destitute population is unable to leave the area after a sudden change

- Economic migration: Can be gradual or sudden, with out-migration resulting in an unsustainable local economy

- Forced migration: A sudden change that results in significant migration, possibly cyclic in occurrence with a slow recovery period

Various model experiments were carried out to investigate differences between the archetypes, and to understand how the model's parametric drivers (e.g. environmental, demographic, political) influence the outcomes. In a stable regime (Figure 8, top) migration occurs but doesn't lead to large scale movements. Fluctuations in average income (left) correspond to variability in economic migration (right, heavy line) but only occasional peaks in forced migration (light line).

In contrast, a tipping point is reached in the Forced Migration archetype (bottom figure). A sudden loss in income (left) results in a collapse of economic migration and a peak in forced (right). This archetype was rare in the TREAD simulations—a possible outcome when drivers take extreme values, for example high population growth and a low number of migrant jobs or frequent disruptions.

Figure 8. Agent based simulation results from TREAD showing two archetypes: stable (top) and forced migration (bottom). Left panel is average income per householder; right panel permanent migration.
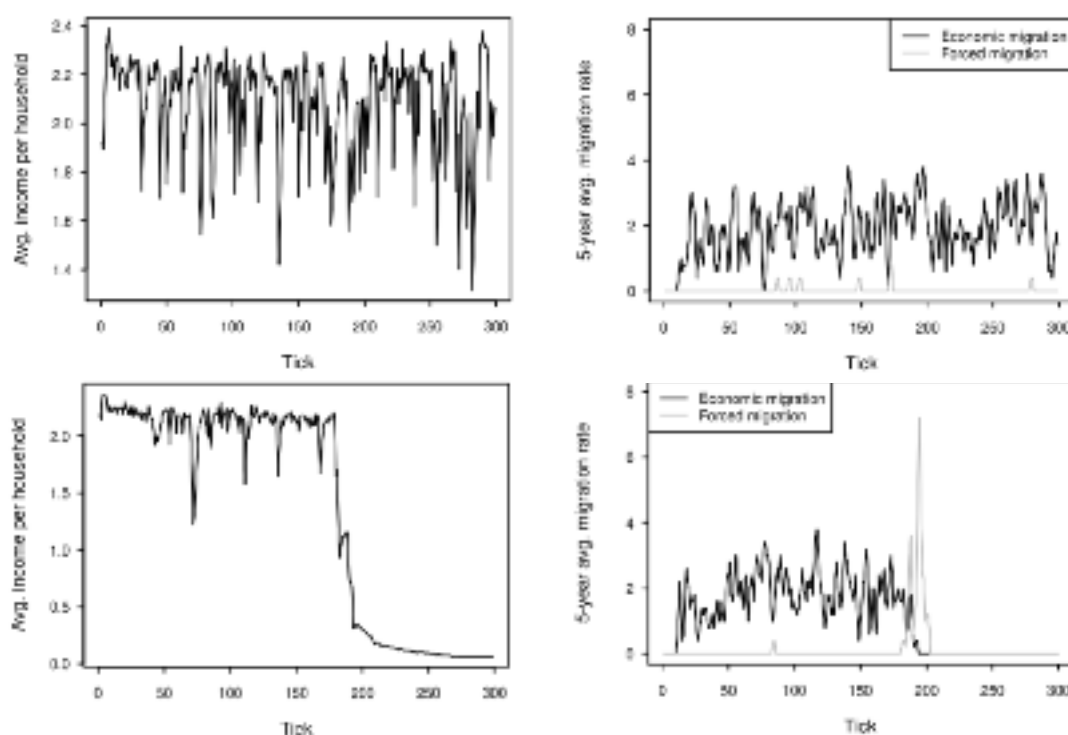
Agent based simulations highlight the social, economic and environmental drivers of migration and the potential for different combinations. They are helpful diagnostics to represent various formal propositions; however, they are not predictions of the future.

Challenges of multiple stresses in south Asia

South Asia is a focal point for many issues of climate change, from the economics of low carbon futures in one of the major developing economies, to the plight of millions below the poverty line living in vulnerable zones. Security, conflict and physical impacts of climate change could contribute to a socially contingent tipping point in South Asia (Figure 9). The assemblage of factors is not a prediction, but points to several ways in which multiple stresses might destabilize the economy of a region.

The Indian National Interest Policy brief listed ongoing conflicts that may be exacerbated by climate changes such as retreat of the glaciers, rising sea levels and extreme weather (Pai, 2008). For example the Jammu and Kashmir dispute may be affected by glacial retreat, resulting in an increased risk of war,

motivated in part by the need for water resources because of the link between the dispute and the distribution of the Indus river waters between India and Pakistan.

China could decide unilaterally to divert the waters of the Himalayan rivers, particularly the Brahmaputra flowing into India. This would severely affect the livelihoods of the population in Arunachal Pradesh and Assam. Or the head-waters of the Mekong, affecting millions in Southeast Asia.

In the summer of 2004 a landslide damned the Pareechu River in Tibet forming an artificial lake. The Indian authorities feared that the bursting of the 'dam' would result in flooding in populated areas in Himachal Pradesh (Jayaraman, 2004). The same month another artificial lake was found on the Tsangpo River in Tibet. While the two countries had agreed to share weather information after a similar incident in 2000 (Singh, H., 2008), Chinese authorities were blamed with being slow to alert their Indian counterparts. In the end, both countries improved their hydrological and satellite-based remote sensing capabilities but not before the Indian armed forces had mobilized for disaster management. These events have the capacity to exacerbate bilateral tensions, especially if India suffers a major natural disaster either due to lack of warning or by a Chinese act to protect its own interest (Pai, 2008).

Figure 9. Number of climate-related disasters by country, 2000-2010, with illustrative consequences for socially contingent tipping points.
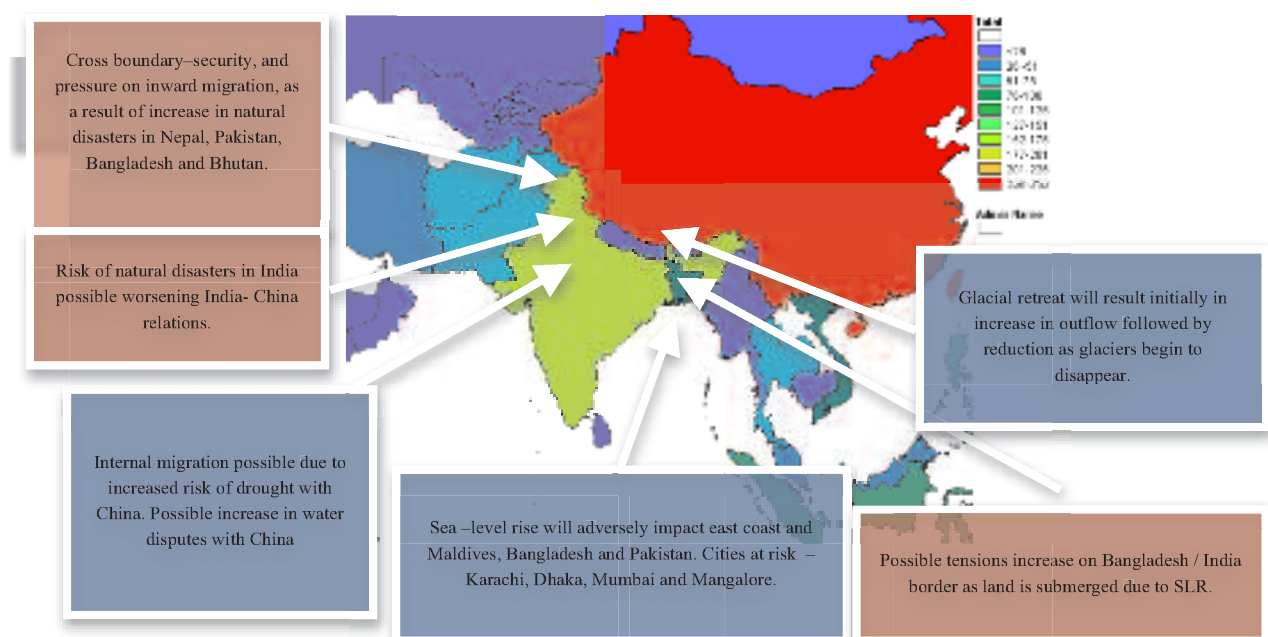
Source of map data: EM-DAT, www.emdat.net (Butterfield et al. 2011).

South Asia is a major concern given the instability of the Indian monsoon and potential drought risk that would limit initiatives to extend insurance to rural areas. Insurers would also be strongly impacted by the economic slow-down and deterioration in public finances caused by drought, through the liquidation of public savings and the impairment of investments in the public sector.

Assessment of climate-related migration

There is a consensus that the many studies of climate and migration often make simplistic assumptions, conflating exposure with vulnerability and ignoring people's ability to cope with variations in climate. Migration is assumed to be a failure to cope. In reality, migration is the response of much more complex behavioral decisions and risk trading. In some cases, it could represent planned adaptation, while in others it could be the last choice when all else fails. Those unable to migrate are often considered the most vulnerable of all.

Climate change is likely to change the magnitude of migration, as well as its characteristics. Migration in a world where there is a 2°C increase in temperature is likely to be different from a world where there will be a 4°C increase in temperature. Predictions are marred by the double uncertainty, first of the local impacts of climate change, and then of the way people will respond to these changes, as described by Gemenne (2011).

A partner in ClimateCost, The Energy and Resources Institute (TERI), with the India Institute of Tropical Meteorology (IITM), have produced key sheets on climate change and socio-economic scenarios for India that could be used as a basis for investigating cost and possibilities of reaching socially contingent tipping points (Mahajan et al., 2009).

A continuing high-level dialogue to develop, strengthen and harmonise international understanding of concepts, knowledge-bases, vocabulary and experience related to the multiple cause-effect links between environmental degradation, socio-economic impacts and environmentally-induced migration is not only needed but has to be sustained with commitment to research, policy and action.

"The global burden of migration related to climate change might be 100 million people by 2050".

Dow and Downing (2011)

5. Economic costs of extreme outcomes

Modeling the economic costs of major discontinuities

PAGE is an integrated assessment model that has been widely used to value the impacts of climate change, including the marginal cost of an additional tonne of CO_2 emissions (called the social cost of carbon, SCC). PAGE2002 (Hope 2006a) supported the Stern review (Stern, 2007) and the Asian Development Bank's review of climate change in Southeast Asia (ADB, 2009). The best-known result from PAGE2002 is the mean social cost of CO_2 in the year 2001 (in year 2000 dollars) is $85 per tonne of CO_2 cited in the Stern review. While this was towards the upper end of estimates at the time (Tol, 2002), its magnitude was explained by the low discount rate used in the review, and the inclusion of a full representation of uncertainty (Dietz et al, 2007).

The ClimateCost project has funded the development of the PAGE09 model. This updates the earlier PAGE2002 version. ClimateCost also contributed to the modeling of major tipping elements in PAGE. The PAGE model considers the tipping elements as a discontinuity—a break in an otherwise continuous function of climate impacts. In PAGE09, discontinuity losses build up gradually, with a mean characteristic lifetime of 90 years after the discontinuity is triggered, rather than all occurring immediately, as in PAGE2002.

The PAGE09 model includes a number of updates, which together significantly increase the social cost of carbon from previous estimates. As an example, previous mean

estimates, with central discount rates, led to SCC values of around $20 – 30/ tCO$_2$ from PAGE2002. The new PAGE09 has a mean value of $106 /t-CO$_2$ (for one extra tonne of CO$_2$ emitted in 2010), with a 5 – 95% range of $12 – $290 for the A1B scenario (assuming GDP, population and emissions follow the A1B scenario). The positive skewed distribution is pronounced, with a few values as high as about $10000 per tonne of CO$_2$. These high values arise when a small increase in emissions brings forward the date at which a discontinuity (such as collapse of the West Antarctic Ice Sheet) has been triggered.

An important issue to explore is the contribution of major tipping elements to the social cost of carbon. This analysis has been undertaken as part of ClimateCost. The default PAGE09 result is a mean value of $106 /tCO$_2$. If discontinuities are not included in the model, the mean value drops to $79 (a 25% decrease). These major events are therefore one of the top four PAGE model sensitivities, on a par with the inclusion of economic impacts. This shows that discontinuities are important in economic terms, even though they are very unlikely to be triggered for several decades.

The costs of historical extreme outcomes

Whilst the context for climate change-induced extreme events is in the future, in assessing the merits of economic attributes, and other metrics, it is helpful to review historical experience in relation to these types of events. Specifically, such events have provided the justification for multi-faceted measures to be used, particularly in the evaluation of adaptation. However, monetary measures typically conflate well-being with either utility (happiness, desire-fulfillment satisfaction) or resources (income, wealth, command over commodities) (Sen,1985, Nussbaum, 2000). Multi-dimensional metrics tend to be centered on the concept of human vulnerability (see e.g. Paton et. al., 2008), human welfare (Gough et al., 2004) and human security (Gough et al., 2004).

Two events – one climate-related, the other a natural disaster with climate-related dimensions – have been evaluated in these terms in the recent literature. The first, the Ethiopian famine of 1984-85, demonstrates the need for use of a metric that either combines climatic exposure with

coping capabilities in a less linear way than current vulnerability indices allow, or present these types of information separately on a spatially disaggregated basis.

The second, the Asian Tsunami of 2004, serves to show that social dimensions (in addition to economic dimensions) need to be included in metrics in order to ensure that vulnerability measures, and their corollary, adaptive capacity, effectively target resources for climate adaptation.

ClimateCost has reviewed existing adaptation decision methods, tools and metrics. The literature on the economics of adaptation is growing rapidly. However, many of the methods and metrics are not well suited to the longer run evolution of climate change impacts. An example of the multiple lines of evidence required is found in the review of adaptation economics in Africa (Watkiss et al. 2010).

6. Multiple lines of evidence to assess extreme outcomes

This section reviews the underpinnings of the analyses above. It begins with the perspective of climate change as fundamentally an issue of framing—what is allowed as evidence depends on the stakeholders involved in the decision space. Earlier work on uncertainty in the social cost of carbon, updated in ClimateCost, provides a view of the coverage of assessments of extreme outcomes.

Framing complex processes with extreme outcomes

The ability to predict future climate change impacts is limited – even more so for complex situations that drive extreme outcomes. The chains of causal factors cannot be easily disentangled and current integrated assessment models do not capture all the relevant factors, feedback loops and decision nodes. A strong path-dependence means there are many plausible impact-response pathways. For instance, the impact of a drought can be seen as the lack of rainfall reducing yields on a dry-land plot, the failure to deliver water to marginal farmers in a small irrigation scheme and adjustments to national food availability and prices mediated by the political economy. Differentiating climate change impacts and adaptation from this dynamic complexity over

the course of the next few decades is impossible in most situations.

Linkages between adaptation and mitigation further compound the issue. Adaptation and mitigation are policy complements and not substitutes (Klein et al. 2007). Yet, methods are not sufficient to make any real progress in trade-offs if the risks of extreme outcomes are included. The uncertainty reinforces the need for action but is too large to define an optimal policy without some further constraining assumptions.

Climate adaptation in general, and tipping elements leading to extreme outcomes in particular, is considered as a 'wicked' environmental problem (in the political science literature, Mathur and Downing 2012). Consequently, the value of climate and assessment models for finding solutions is limited by climate, development and environmental considerations.

Key features of wicked problems are:

- The definition of the problem depends on the framing— where to draw the boundaries of actors and processes. For extreme outcomes, the 'problem' might be seen as a global challenge to setting a target of above 2°C, or more narrowly as hypothetical worst case scenarios that should not drive policy until we have more information.

- Stakeholders bring to the problem different framings: there is no universal solution. For instance, some argue for mitigation, others that geo-engineering must be on the table.

- The future counts—low discount rates are implied—and time is running out. Climates are changing so there is only a limited window for action; and finding tractable solutions to the tipping points would take many decades.

Such complex problems as tipping elements and extreme outcomes can only be addressed through multiple lines of evidence. The ClimateCost project explored:

- Narratives: grounded but idealized accounts of impact-response experiences

- Reference socio-economic scenarios

- Multi-ensemble climate scenarios

- Formal models of behavior based on actor-network approaches

- Integrated assessment models

- Historical analogues

- Case studies and typologies

- Expert subjective judgment

- Mapping of multiple effects

The implications of framing tipping elements as a wicked problem are significant for the economic analysis of climate change—the definition of acceptable lines of evidence is contested by various stakeholders. In some cases, experts who don't 'trust' evidence on extreme impacts do not allow estimates of those potential costs in their assessments. In other cases, assessments that seek to establish a consensus on the range of extreme outcomes are branded as 'scaremongering' by environmentalists. Cost-benefit analysis and net present values are particularly contentious and many argue for cost-effective and multi-attribute analyses as a complement to traditional economic tools. Clearly, extreme outcomes are not marginal effects of climate change; and adaptive management will require significant departures from 'business as usual' scenarios.

Taking adaptation as a pathway, ClimateCost contributed to development of methods for understanding iterative decision making. The notion of adaptive pathways (labeled 'signatures' in Downing 2011) helps evaluate adaptation especially where outcomes cannot be predicted (and costed).

A simple pathway would be iterative learning in a sequence of nodes (say, 1 to 5 in the near term). Each node would take advantage of incremental improvements in knowledge and decision spaces. Progress would be considered steady with an expanding frontier of what is required and what works. This sort of pathway fits into the usual assumptions of marginal economics.

The worst case would be a pathway that seems to be satisfactory with incremental learning but then collapses in the face of an insurmountable threat (whether an event or an anticipated threat). The economics of collapse is poorly understood, although historical analogues are insightful.

In between these cases is what might be termed a transforming pathway. Early learning (say decision nodes 1 to 4) are designed to be able to take action (say in node 5) that cannot be taken at present and offers path-breaking options. Option values in economics start to address this

type of transformation, but the challenges of linking micro-decision making with systemic change and macro-economic features remain daunting.

More research, more uncertainty?

At the global level, estimates of the economic costs of climate change are produced by integrated assessment models (IAMs) that combine scientific and economic aspects of climate change within a single analytical framework. Sectoral modules link emissions, climate modeling, climate change impacts and the economy (e.g., FUND: Tol, 2002a, 2002b, Anthoff and Tol, 2010; PAGE: Hope, 2006a, 2006b, 2009a, 2009b; and DICE: Nordhaus and Boyer, 2000, Nordhaus, 2008, 2009). The incremental damage that can be attributed to a marginal increase in emissions is known as the social cost of carbon.

IAMs produce a wide range of results (Watkiss, 2011), notably due to the use and choice of damage functions, discount rates, equity weights, uncertainty and risk. However, another important reason for the difference is the coverage of the studies, i.e. which impacts they actually include, and in particular whether they include major catastrophic events

(tipping extremes) or socially contingent effects.

Downing and Watkiss (2003) introduced a risk matrix to assess the coverage of the social cost of carbon in IAMs (Figure 10). On the horizontal axis, the matrix includes three categories of effect: market, non-market and socially contingent effects, the latter associated with large scale dynamics related to human values and equity that are poorly represented in cost values, e.g. conflict, famine and poverty. On the vertical axis are three categories of climate change. First, effects that could be relatively well projected (at least in sign) such as average temperature and sea level rise; second, more uncertain parameters with more complex bounded ranges such as precipitation and extreme events; and finally, major catastrophic events, discontinuities or tipping points/elements (Schellnhuber et al, 2006; Lenton et al, 2008), such as the instability of the West Antarctic ice sheet, which could exhibit threshold-type behavior at a critical point but where thresholds and subsequent effects are highly uncertain.

Watkiss et al. (2005) mapped the coverage of the main four IAMs and SCC estimates (based on Nordhaus and Boyer, 2000; Mendelsohn et al, 1998; Tol, 2002a, 2002b; Hope, 2005) against this matrix. An updated version of the coverage is presented in Figure 10.

Figure 10. Coverage of the social cost of carbon from three of the main economic IAMs: PAGE, FUND and DICE. Note that IAMs continue to evolve and cover more aspects of the SCC. Source: based on Watkiss (2011).
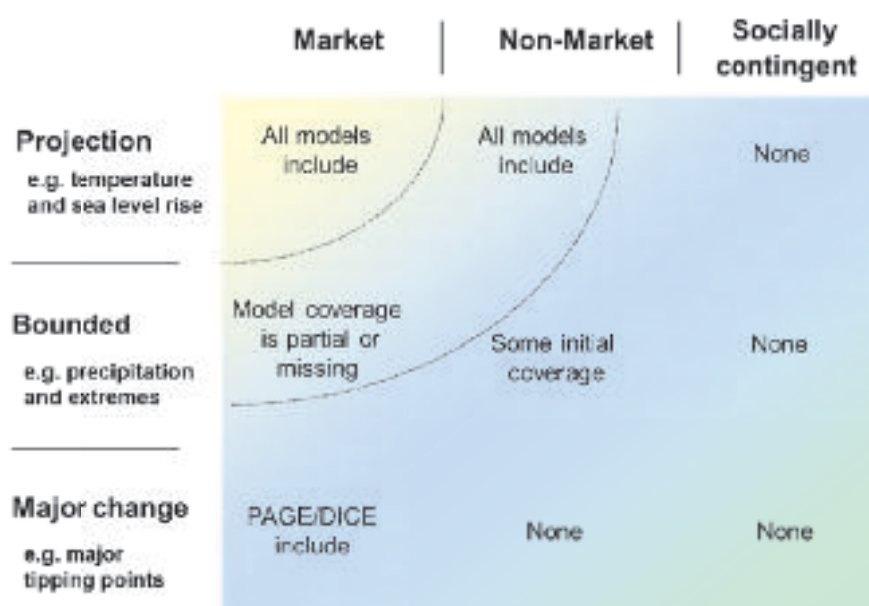
Most IAMs have good coverage in the top left hand area of the matrix, reflecting market damages from relatively predictable changes such as temperature and sea level. All models now include some coverage of non-market damages (Nordhaus and Boyer, 2000; Hope, 2005; Tol, 2002a, 2002b), notably in relation to health, but also some limited consideration of biodiversity and natural environments. More recently, there is greater recognition of non-market costs through ecosystem services (MEA, 2005), ocean acidification, nutrition and tropospheric ozone (among other areas); these are not yet included in most IAMS.

The rest of the matrix continues to be poorly covered. The original mapping found a low coverage against major discontinuities and no coverage of socially contingent effects, reflecting the state of knowledge in the supporting literature. The updated matrix shows that the models have advanced considerably, though there remain differences in coverage between the models (which explains much of the differences between model results).

Coverage remains partial and incomplete, a key point in translating aggregated model estimates through to policy. The lack of coverage – particularly of the very major events – has led to concerns over the partial coverage of impacts and that how this leads to a systematic under reporting of costs (Watkiss et al, 2005; Warren et al. 2006). Watkiss and Downing (2008) highlighted that some of the missing categories were likely to include both positive as well as negative effects, but considered the missing effects were likely to have potentially large net damages.

The omission or incomplete consideration of major catastrophic events and abrupt climate change is a particular concern in aggregated estimates in cost-benefit analysis (CBA) and optimization. Undertaking a CBA for climate change relies critically on the assumption that marginal costs and benefits, as well as absolute costs and benefits, are finite. This is not necessarily the case as outlined by Tol (2003). This has been examined more recently in relation to the plausible, if unknown, probability of catastrophic climate change (Weitzman, 2009) and 'fat tails', where uncertainty is so large that the tails of the distribution are likely to dominate any conclusions, as the expected welfare loss is potentially unbounded. The consideration of these outcomes leads to radically different conclusions for policy from the conventional advice from standard economic analysis and formalized CBA, as the latter ignores the potential for disasters.

The implications of potential extreme outcomes are noted in the negotiations leading to the global consensus target of 2°C (as expressed in the Cancun agreements), and to some extent the push by some of the most vulnerable countries for a 1.5°C target.

The ClimateCost project investigated the gaps in this risk matrix. This risk based approach, complementing standard economic frameworks, has started to derive values for a broader range of impacts in the matrix above, including the catastrophic and socially contingent events. The key aim has been to investigate how potentially important these omissions are, and to consider the implications of the current gaps for policy.

7. Implications for European Policy

The implications of this emerging science of extreme outcomes for European policy is collated in three questions.

Do we know enough to act?

The lines of evidence developed in the ClimateCost indicate the breadth of science on extreme outcomes that has been developed in the past 5 to 10 years. The economic exposure to major tipping elements is significant, likely to be well over $ 1 trillion per year by the 2080s (current prices, undiscounted). Inclusion of tipping elements (as discontinuities) in PAGE point to a significant increase in the social costs of carbon.

Over the past decade or so, there has been increased awareness of the linked nature of vulnerability (e.g., the global linkages in finance) and therefore projected climate impacts and adaptation strategies (e.g., Foresight Panel, 2011).

The implications for state security could be profound. Warner *et al* (2010) suggest that global migration due to sea-level rise could start to take place in the next 30-50 years. Although the effects of sea-level rise only involves a small fraction of the land surface, the coastal zone contains some of the most densely populated place in the world and would affect large numbers of people.

Downing et al., (2005) concluded that conditions of multiple stresses related to the 1970s-1990s drought and dryness in the Sahel leading to food insecurity, migration, changes in livelihoods and land use conflicts might be both intensified and more widespread with climate change. Regional effects on economic growth and wellbeing could be significant and lead to quite high (non-marginal) estimates of the social cost of carbon.

Already, this science has spurred action at the policy level and in raising awareness. The uncertainty is a reason for action, not an excuse for inaction.

What European actions are urgent?

The evidence clearly supports the policy position of limiting global climate change at 2°C. The negotiations are far from promising and a mandatory regime that ensures this target is realistic is unlikely in the next year or two. Further impetus, from every region, should be drawn from the ClimateCost review.

Sectoral adaptation strategies are urgent, in Europe and among Europe's development partners. For example, with appropriate monitoring of sea level and planning, many adverse impacts of sea level rise could be avoided. Defenses can be planned many years ahead, envisaging how much sea levels will rise, and accommodation strategies developed with local populations. Similar lists of strategies and actions are available for all sectors.

Given the large uncertainties about future tipping elements and the upper end of potential climate change impacts, sectoral strategies should move from a predict-and-provide paradigm to building capacity and resilience. Monitoring of risk will help constrain the range of outcomes expected, but this is unlikely to be a sound strategy for another decade or longer until the signal of climate impacts outweighs the background of current variability.

The science base for understanding extreme outcomes requires international cooperation. Europe's interdisciplinary 'research area' must continue to be a strong supporter of climate-adaptation science.

Planning adaptive responses will require international cooperation as well and is an area where European policy

making would have leading roles. This is obvious for international water resources, trans-boundary health threats, migration and security. Further science-policy dialogues are warranted, linking across thematic areas (e.g., linking disaster risk reduction to climate adaptation, Hamza et al. 2011).

Developing such policy processes is urgent. It takes decades to develop sound, multi-stakeholder regimes to handle any wicked problem.

How might we improve the evidence?

Bringing multiple lines of evidence to bear is essential. It does not seem likely that well-validated assessments of global and regional extreme outcomes (and quantification of their economic costs) are likely to be forthcoming soon. The uncertainties in regional climate predictions and underlying vulnerability leave open a wide range of plausible scenarios of future costs at this scale.

Methodologies for exploring the climate-migration-tipping element nexus are still lacking (Piguet, 2009). The historic fascination for mapping 'hot spots' is not justified either. Overlays of climate-scenario driven impacts do not address socially contingent and extreme outcomes.

Methods based on dynamic, multi-agent models can provide insight into the processes that might lead to undesirable outcomes. However, such models are difficult to construct and few have attempted to address socially contingent impacts at a regional to global scale. Bounding exercises to provide end-points to the range of economic valuations would help identify the significance of these risks to global estimates of the social costs of climate change.

Metrics of extreme outcomes are required, such as proportion of people at risk of flooding whose flood risk increases or decreases. These metrics can be drawn directly from model data. Many of the changes are reported as the proportion of receptors (people or cropland) exposed to an increased or reduced risk of an event, such as a flood or altered suitability for crops. Parry et al. (2001) use a similar set of metrics to tell a story about the 'millions at risk' from four types of impact.

Simple migration scenarios have been developed, which

address the multi- stresses of environmental change, human security and conflict (e.g., International Organisation for Migration, 2007). However, these sit uncomfortably with the traditional approach of climate-related scenarios (such as the IPCCs Reference Concentration Pathways). Archetypes of complex behavior are an important conceptual tool that could allow researchers to build universal, albeit simplified, stories linking stresses, processes and outcomes process.

The ClimateCost review showcases several lines of evidence. All are worth further development, and ultimately integration into a more robust body of evidence to support policy.

8. Acknowledgements

DIVA in bold?

9. Abbreviations

AR4	Fourth Assessment Report
CBA	cost-benefit analysis
CCEMA	Climate Change, Environment and Migration Alliance
DIVA	Dynamic Interactive Vulnerability Assessment
ENSO	El Niño/Southern Oscillation
GDP	Gross Domestic Product
GIS	Greenland Ice Sheet (or) Geographic Information System
IAM	integrated assessment model
IDCC	International Dimensions of Climate Change
IPCC	Intergovernmental Panel on Climate Change
LECZ	Low Elevation Coastal Zone
RCP	Representative Concentration Pathway
RSLR	relative sea level rise
SLR	sea level rise
SRTM	Shuttle Radar Topography Mission
THC	thermohaline circulation
TPBN	Technical Policy Briefing Note
TREAD	Transformations in Risk: Explaining Agent Diasporas
WAIS	West Antarctic Ice Sheet

10. References

Ahmed, SA, Diffenbaugh, NS and Hertel, T. (2009). Climate volatility deepens poverty vulnerability in developing countries. *Environ. Res. Lett* 4: 034004 (8pp). doi:10.1088/1748-9326/4/3/034004; http://ibcperu.org/doc/isis/11182.pdf (accessed 12 March 2012).

Alley, RB, Marotzke, J, Nordhaus, WD, Overpeck, JT, Peteet, DM, Pielke Jr., RA, Pierrehumbert, RT, Rhines, PB, Stocker, TF, Talley, LD and Wallace, JM (2003). Abrupt climate change. *Science* 299 (5615): 2005-2010, DOI: 10.1126/science.1081056.

Anthoff, D and Tol, RSJ (2010). On international equity weights and national decision making on climate change. *Journal of Environmental Economics and Management* 60(1): 14-20.

Asian Development Bank (ADB) (2009). The Economics of Climate Change in Southeast Asia: A Regional Review. Manila: Asian Development Bank.

Boano, C, Zetter, R and Morris, T (2008). Environmentally displaced people: Understanding the linkages between environmental change, livelihoods and forced migration. Forced Migration Policy Briefing 1. Oxford: Refugee Studies Centre, University of Oxford.

Bose, A (2011) Financial Gradients: A financial mechanism for climate or sustainable development action. Delhi: TERI.

Breisinger, C, Ecker, O and Al-Riffai, P (2011). Economics of the Arab awakening: From revolution to transformation and food security. IFPRI Policy Brief 18. Washington, D.C.: International Food Policy Research Institute (IFPRI); http://www.ifpri.org/sites/default/files/publications/bp018.pdf.

Brown, S, Nicholls, RJ, Vafeidis, AT and Hinkel, J (2012). Costs and benefits of climate change/adaptation. Results and analysis of WP2A: Coasts prepared as part of the European Commission funded research ClimateCost: The Full Costs of Climate Change.

Brown S, Nicholls, RJ, Vafeidis A, Hinkel J and Watkiss P (2011). The impacts and economic costs of seas-level rise in Europe and the costs and benefits of adaptation. Summary of results from the EC RTD ClimateCost project. In Watkiss, P (editor), 2011. The ClimateCost project. Final Report. Volume 1: Europe. Oxford: Stockholm Environment Institute. ISBN 978-91-86125-35-6.

Butterfield, RE, Lambat, S, Downing, T, Hamza, M, Taylor, R, and Matin, N (2011). Major catastrophic events: Socially-contingent implications of climate change. Final deliverable for ClimateCost Workpackage 3. Oxford: Stockholm Environment Institute.

Centre for Environmental and Geographic Information Services (CEGIS) (2009). Economic modeling of climate change adaptation needs for physical infrastructures in Bangladesh (Phase-II). Dhaka: CESIS; http://www.cegisbd.com/climate_div.htm.

Christian Aid (2007). Human tide: The real migration crisis. A Christian Aid report. London: Christian Aid.

Coleman, JM, Huh, OK and DeWitt, B Jr, (2008). Wetland loss in world deltas. *Journal of Coastal Research*, 24, (1A), 1-14.

DARA. (2010). Climate Vulnerability Monitor 2010: The state of the climate crisis. Madrid: DARA. Retrieved from http://www.ukcds.org.uk/_assets/file/publications/CVM1.pdf.

Dietz, S, Hope, C, Stern, N and Zenghelis, D (2007). Reflections on the Stern Review (1), A robust case for strong action to reduce the risks of climate change. *World Economics*, 8,1, 121-168.

Dow, K and Downing, TE (2011). The atlas of climate change. London: Earthscan.

Downing, TE (2012). Views of the frontiers in climate change

adaptation economics. *WIREs Clim Change* doi: 10.1002/wcc.157.

Downing, TE, Aerts, J, Soussan, J, Barthelemy, O, Bharwani, S, Hinkel, J, Ionescu, C, et al. (2005). Integrating social vulnerability into water management. Oxford: SEI. Retrieved from http://www.sei-international.org/mediamanager/documents/Publications/Risk-livelihoods/integrating-social-vulnerability-water-management.pdf.

Downing, T, and Watkiss, P (2003). The marginal social costs of carbon in policy making: Applications, uncertainty and a possible risk based approach. Paper presented at the DEFRA International Seminar on the Social Costs of Carbon. Oxford: SEI.

El-Hinnawi, E (1985). Environmental refugees. Nairobi: UNEP.

Ericson, JP, Vorosmarty, CJ, Dingman, SL, Ward LG and Meybeck, M (2006). Effective sea-level rise and deltas: causes of change and human dimension implications. *Global Planet Change*, 50, 63-82.

European Commission (2008). Climate change and international security. Paper from the High Representative and the European Commission to the European Council, 14 March 2008. S113/08. Brussels: EC.

Foresight Panel (2011). Foresight international dimensions of climate change: Final project report. London: The Government Office for Science, London. http://www.bis.gov.uk/assets/bispartners/foresight/docs/international-dimensions/11-1042-international-dimensions-of-climate-change.pdf.

Friends of the Earth (2007). A citizen's guide to climate refugees, Fact sheet rour: Predictions of climate refugees to 2050. London: FoE.

Füssell, HM (2009). Review and quantitative analysis of climate change exposure, adaptive capacity, sensitivity and impacts. Background note to the World Development Report 2010. Washington: World Bank.

Gemenne, F (2011). Climate-induced population displacements in a 4°C+ world. *Philosophical Transactions of the Royal Society A*, 10: 182-195,1098/rsta.2010.0287.

Gough, I, Wood, G, Barrientos, A, Bevan, P, Davis, P and Room, G, eds. (2004). Insecurity and welfare regimes in

Asia, Africa and Latin America: Social policy in development contexts. Cambridge: Cambridge University Press.

Hamza, M, Moriniere, L, Taylor, R, Matin, N and Ali, B (2011). Emerging issues: Forced migration by climate change, in *Climate Change Adaptation and Development Cooperation*, eds. Fujikura, R and Kawanishi, M. Tokyo: Hosei University and JICA.

Hinkel, J (2005). DIVA: An iterative method for building modular integrated models. *Advances in Geosciences*, 4, 45-50.

Hinkel, J and Klein, RJT (2009). The DINAS-COAST project: developing a tool for the dynamic and interactive assessment of coastal vulnerability. *Global Environmental Change*, 19, (3), 384–395.

Hope, C. (2005). Memorandum by Dr Chris Hope, Judge Institute of Management, University of Cambridge. The economics of climate change, HL12-II,Oral evidence: 18 January 2005, House of Lords Select Committee on Economic Affairs, London: The Stationery Office, London.

Hope, C. (2006a). The marginal impact of CO2 from PAGE2002: An integrated assessment model incorporating the IPCC's five reasons for concern. *Integrated Assessment* 6 (1), 19–56.

Hope, C. (2006b). The social cost of carbon: What does it actually depend on? *Climate Policy* 6 (5), pp. 565-572.

Hope, C. (2009a). PAGE optimization: The social cost of CO2 and the optimal timing of emissions reductions under uncertainty. Prepared for the Pew Center Workshop on Assessing the Benefits of Avoided Climate Change 16-17 March 2009 by Dr Chris Hope Judge Business School University of Cambridge. Available at http://www.pewclimate.org/docUploads/Hope_0.pdf.

Hope, C. (2009b). The costs and benefits of adaptation. In, Assessing the Costs of Adaptation to Climate Change: A Review of the UNFCCC and Other Recent Estimates, eds. Parry, ML, et al. London: International Institute for Environment and Development and Grantham Institute for Climate Change.

International Organisation for Migration (IOM) (2007). Expert seminar: Migration and the environment. *International Dialogue on Migration*, No. 10. Geneva: IOM.

IWM and CEGIS (2007). Investigating the impact of relative sea level rise on coastal communities and their livelihoods in Bangladesh. Delhi: CEGIS.

Jayaraman, KS (2004). Crisis forments as unstable lake builds in Himalayas. *Nature*, 420 , 18. (19 August, 2004).

Jevrejeva, S, Moore, JC, and Grinsted, A. (2012). Sea level projections to AD2500 with a new generation of climate change scenarios. *Global and Planetary Change*, 80-81, 14-20. DOI 10.1016/j.gloplacha.2011.09.006.

Johnstone, S and Mazo, J. (2011). Global warming and the Arab Spring. *Survival* 53:11-17.

Klein, RJT, Huq, S, Denton, F, Downing, TE, Richels, RG, Robinson, JB, Toth, FL, Biagini, B, Burch, S, Studd, K, Taylor, A, Warren, R, Watkiss, P and Wolf, J (2007). Interrelationships between adaptation and mitigation. In Parry, ML, Canziana, OF, Palutikof, JP, Hanson, CE and van der Linden, PJ, eds. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Geneva: IPCC (on-line), Cambridge: Cambridge University Press.

Kriegler, E, Hall, JW, Held, H, Dawson, R and Schellnhuber, HJ (2009). Imprecise probability assessment of tipping points in the climate system. *PNAS* March 16, 2009, doi:10.1073/pnas.0809117106PNAS March 16.

Lenton, T.M., Held, H. Kriegler. E.. Hall, J.W., Lucht, W., Rahmstorf S. and Schellnhuber H.J. (2008). Tipping elements in the Earth's climate system, *Proceedings of the National Academy of Sciences* USA 105(6), 1786–1793.

Lenton,T, Footitt, A and Dlugolecki, A (2009).
Major tipping points in the Earth's climate system and consequences for the insurance sector. Gland: World Wide Fund for Nature and Munich: Allianz SE.

Lonsdale, KG, Downing, TE, Nicholls, RJ, Parker, D, Vafeidis, AT, Dawson, R and Hall, J. (2008). Plausible responses to the threat of rapid sea-level rise in the Thames estuary. *Climatic Change* 91: 145-169.

Lowe, JA, Hewitt, CD, van Vuuren, DP, Johns, TC, Stehfest, E, Royer, JF and van der Linden, PJ (2009). New study for climate modeling, analyses, and scenarios. *Eos, Trans Am Geophys Union*, 90, (21) 181-182.

Mahajan, D, Sharma, D, Jayashree, V, Talwar, S and Ganeshan, S (2009). Climate change induced migration and

its security implications for India's neighborhood. Discussion paper prepared by TERI for the 15th Conference of Parties to the UN Framework Convention on Climate Change, December 2009, Copenhagen. Dehli: TERI.

Marino E and Schweitzer P (2008). Talking and not talking about climate change. In: Anthropology and climate change. Crate S and Nuttall M, eds. Walnut Creek, CA: Left Coast Press, pp. 209-217.

Mathur V and Downing TE (2012). Framing adaptation to climate change: From prediction to a wicked problem and implications for vulnerability assessment. Oxford: Global Climate Adaptation Partnership, Oxford.

McGranahan, G, Balk, D and Anderson, B (2007). The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, 19(1), 17-37.

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ, and Zhao Z-C (2007). Global climate projections. In: Solomon S, Qin D, and Manning M et al. (eds) *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, pp 433-497.

Mendelsohn, RO, Morrison, WN, Schlesinger, ME, and Andronova, NG (1998). Country-specific market impacts of climate change. *Climatic Change* 45(3-4): 553-569.

Messner, D and Rahmstorf, S (2010). Tipping points in the Earth system and their implications for world politics and economy. In *Global Trends 2010*, T. Debiel, ed. Frankfurt: S. Fischer Verlag, p. 63-80.

Millennium Ecosystem Assessment (MEA) (2005). Ecosystems and human well-being: Synthesis. Island Press, Washington, DC. http://www.maweb.org/en/index.aspx

Ministry of Environment and Forests (2005). Government of the People's Republic of Bangladesh National Adaptation Programme of Action (NAPA), Final Report. Dhaka: MoEF.

Ministry of Environment and Forests (2008). Bangladesh climate change strategy and action plan 2008. Dhaka: Ministry of Environment and Forests, Government of the People's Republic of Bangladesh, 68 pp.

Moser, SC and Ekstrom, JA (2010). A framework to diagnose barriers to climate change adaptation. *PNAS* 107 (51) 22026-22031.

Myers, N and Kent, J (1995). Environmental exodus: An emergent crisis in the global arena. Washington: Climate Institute.

Myers, N and Kent, J (2005). Environmental refugees: An emergent security issue. Organisation for Security and Cooperation in Europe, www.osce.org/documents/eea/2005/05/14488_en.pdf.

Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, et al. (2000). Special report on emissions scenarios, Working Group III, Intergovernmental Panel on Climate Change (IPCC). Cambridge: Cambridge University Press, pp. 595. http://www.grida.no/climate/ipcc/emission/index.htm.

Nicholls, RJ (2004). Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. *Global Environmental Change* 14: 69–86.

Nicholls, RJ, Marinova, M, Lowe, JA, Brown, S, Vellinga, P, de Gusmão, D, Hinkel, J and Tol, RSJ (2011). Sea level rise and its possible impacts given a 'beyond 4°C world' in the twenty-first century. *Philosophical Transactions of the Royal Society A*. 369, 161-181. DOI 10.1098/rsta/2010.0291.

Nordhaus, WD (2008). The challenge of global warming: Economic models and environmental policy. New Haven, Connecticut: Yale University.

Nordhaus, WD (2009). DICE 2009. New Haven, Connecticut: Yale University. http://nordhaus.econ.yale.edu/DICE2007.htm.

Nordhaus, WD and Boyer, JG (2000). Warming the World: Economic models of global warming, Cambridge: The MIT Press.

Nussbaum, MC (2000). Women and human development – The capabilities approach, Cambridge: Cambridge University Press.

Pai, N (2008). Climate change and national security: Preparing India for new conflict scenarios. *Indian National Interest Policy Brief*, April 2008, http://nationalinterest.in/wp-content/uploads/2008/04/inipolicybrief-no1-climatechangeandnationalsecurity-nitinpai-april2008.pdf.

Pardaens, AK, Lowe, JA, Brown, S, Nicholls, RJ, and de Gusmão, D (2011). Sea-level rise and impacts projections under a future scenario with large greenhouse has emission reductions. *Geophysical Research Letters* 38, L12604. DOI 10.1029/2011GL047678.

Parry, ML, Canziani, OF, Palutikof, J, van der Linden, PJ and Hanson, CE, eds. (2007). Climate change 2007: Impacts, adaptation and vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 976 pp.

Paton, D., Gregg, C.E., Houghton, B.F., Lachman, R., Lachman, J., Johnston, D.M. and Wongbusarakum, S (2008). The impact of the 2004 tsunami on coastal Thai communities: assessing adaptive capacity. *Disasters* 32, (1) pp. 106-119.

Peltier, WR (2000a). Global glacial isostatic adjustment and modern instrumental records of relative sea level history. In, BC Douglas, MS Kearny and SP Leatherman, eds, Sea level rise: History and consequences. San Diego: Academic Press, pp 65–95.

Peltier, WR (2000b). ICE4G (VM2) Glacial isostatic adjustment corrections, In, BC Douglas, MS Kearny and SP Leatherman, eds, Sea level rise: History and consequences. San Diego: Academic Press.

Piguet, E (2008). Climate change and forced migration. Research Paper No 153, New Issues in Refugee Research Series. Geneva: UNHCR.

Ramsar Convention on Wetlands (2011). A framework for assessing the vulnerability of wetlands to climate change (published jointly as CBD Technical Series No. 57). Gland: Ramsar Convention Secretariat.

Rignot E, Bamber JL, van den Broeke MR, Davis C, Li Y, van de Berg WJ and van Meijgaard, E (2008). Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. *Nature Geosci* 1, 106–110 (DOI:10.1038/ngeo102).

Rohling, E, Grant, K, Hemleben, C, Siddall, M, Hoogakker, B, Bolshaw, M and Kucera, M (2008). High rates of sea-level rise during the last interglacial period. *Nature Geoscience* 1, 38-42, DOI 10.1038/ngeo.2007.28.

Schellnhuber, HJ, Cramer, W, Nakicenovic, N, Wigley, T and Yohe, GW, eds. (2006). Avoiding dangerous climate change. Cambridge: Cambridge University Press, ISBN 9780521864718 DOI: 10.2277/0521864712.

Schneider, SH (2004). Abrupt non-linear climate change, irreversibility and surprise. *Global Environmental Change* 14 (3): 245–258.

Sen, AK (985). Commodities and capabilities. Amsterdam: North-Holland.

Shen, X, Downing, TE and Hamza, M (2010). Tipping points in humanitarian crisis: From hot spots to hot systems. Outcomes of the 4th UNU-EHS. Summer Academy of the Munich Re Foundation Chair on Social Vulnerability 26 July – 1 August 2009 in Hohenkammer, Germany. Bonn: United Nations University.

Singh, H (2008). Dealing with China - India needs pragmatic policies, *The Tribune*, 29 February 2008, available at http://www.tribuneindia.com/2008/20080229/edit.htm#4.

Smith, D and Vivekananda, J (International Alert) (2007). A climate of conflict: The links between climate change, peace and war. London: International Alert.

Solomon, S, Qin, D, Manning, M, Chen, Z, Marquis, M, Averyt, KB, Tignor, M, and Miller, HL (eds) (2007). Climate Change 2007: The physical science basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

Stern, N (2006). Stern review on the economics of climate change. Cambridge : Cambridge University Press and UK Treasury.

Tanner, TM, Hassan, A, Islam, KMN, Conway, D, Mechler, R, Ahmed, AU and Alam, M (2007). ORCHID: Piloting climate risk screening in DFID Bangladesh: Summary research report. *IDS Research Summary.* Brighton: IDS.

Taylor, R, ed. (2013). Transformations in risk: The humanitarian consequences of environmental migration. New York : Elsevier (forthcoming).

TERI and MoEF (n.d.). Keysheet 3: Socioeconomic scenarios for climate change impacts in India. Delhi: TERI.

Tol, RSJ (2002a). New estimates of the damage costs of climate change, Part I: Benchmark estimates. *Environmental and Resource Economics* 21 (1): 47-73.

Tol, RSJ (2002b). New estimates of the damage costs of

climate change, Part II: Dynamic estimates. *Environmental and Resource Economics* 21 (1): 135-160.

Tol, RSJ (2003). Is the uncertainty about climate change too large for expected cost-benefit analysis? *Climatic Change* 56, 265-289.

Tol, RSJ (2005). The marginal damage costs of carbon dioxide emissions: An assessment of the uncertainties. *Energy Policy* 33: 2064–2074.

Tol, RSJ (2006). The DIVA model: Socio-economic scenarios, impacts and adaptation and world heritage. In, DINAS-COAST Consortium 2006. DIVA 1.5.5. Potsdam: Potsdam Institute for Climate Impact Research, CD-ROM. Available at http://www.pik-potsdam.de/DIVA.

Tol, RSJ and Yohe, GW (2007). The weakest link hypothesis for adaptive capacity: An empirical test. *Global Environmental Change*, 17, 218-227.

UNHCR (2002). A critical time for the environment. *Refugees*. No.127. Geneva: UNHCR.

Vafeidis, AT, Nicholls, RJ, McFadden, L, Tol, RSJ, Hinkel, J, Spencer, T, Grashoff, PS, Boot, G and Klein, RJT (2008). A new global coastal database for impact and vulnerability analysis to sea-level rise. *Journal of Coastal Research*, 24, 917-924.

van de Wal, RSW, Boot, W, van den Broeke, MR, Smeets, CJPP, Reijmer, CH, Donker, JJA, and Oerlemans, J (2008). Large and rapid melt-induced velocity changes in the ablation zone of the Greenland ice sheet. *Science* 321, 111–113 (DOI:10.1126/science.1158540).

van der Linden P and Mitchell, JFB (eds.) (2009). ENSEMBLES: Climate change and its impacts: Summary of research and results from the ENSEMBLES project. Exeter: UK, Met Office Hadley Centre. http://ensembles-eu.metoffice.com/docs/Ensembles_final_report_Nov09.pdf.

Warner, K, Hamza, M, Oliver-Smith, A. Renaud, F, and Julca, A (2010). Climate change, environmental degradation and migration. *Natural Hazards*, 55, 689-715. DOI 10.1007/s11069-009-9419-7.

Warren, R, Arnell, N, et al. (2010). Review of literature subsequent to IPCC AR4. The AVOID programme, Report AV/WS1/R01/D2, DECC/Defra GA0215. London: DEFRA.

Watkiss, P (2011). Aggregate economic measures of climate change damages: Explaining the differences and implications. *Wiley Interdisciplinary Reviews - Climate Change*. 2 (3): 356ff. Published online. 2 May 2011. DOI: 10.1002/wcc.111.

Watkiss, P, Anthoff, D, Downing, TE, Hepburn, C, Hope, C, Hunt, A and Tol, RSJ (2005). The social costs of carbon (SCC) review: methodological approaches for using SCC estimates in policy assessment. Final Report. London: Defra, UK, 124 pp.

Watkiss, P and Downing, TE (2008). The social cost of carbon: Valuation estimates and their use in UK policy. *The Integrated Assessment Journal* 8 (1), Available from http://journals.sfu.ca/int_assess/index.php/iaj/article/view/272.

Watkiss, P, Downing, TE and Dyszynski, J (2010). AdaptCost project: Analysis of the economic costs of climate change adaptation in Africa. Nairobi: UNEP.

Weitzman, ML (2009). On modeling and interpreting the economics of catastrophic climate change. *The Review of Economics and Statistics* 91(1): 1-19.

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Further information

The ClimateCost project involved 22 partners, the lead organization was the Stockholm Environment Institute (Oxford).

ISBN 978-91-86125-35-6

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