Loss & Damage

Science update -

Loss and Damage - Climate Change Today and under Future Scenarios

Dim Coumou & Michiel Schaeffer

A report prepared by Climate Analytics

November 2012

CDKN

ICCCAD International Centre for Climate Change and Development

GERMANWATCH

MCII

UNITED NATIONS UNIVERSITY UNU-EHS

Contents

Update of climate science relevant for Loss and Damage debate	1
Contents	2
1. Introduction	3-4
2. Implication for international climate policy	4-5
3. Risk of Loss and Damage	5-7
4. Impacts: From present day levels of warming to 4°C warming	7-11
Impacts at Present levels (0.8°C)	7-8
Impacts at 1.5°C	8-9
Impacts at 2°C	9
Impacts at 4°C	9-11
'Residual' Impacts at different warming levels	11
5. Recent progress in attribution	11-15
Heat waves	13
Precipitation and drought extremes	13-14
Sea level rise	14-15
Ocean acidification	15
6. Conclusion	15-16
7. References	17-23

Editor/Layout: Claudia Kaiser

This paper has been prepared in the context of the 'Loss and Damage in Vulnerable Countries Initiative', which is part of the Climate and Development Knowledge Network. Responsibility for the content solely lies with the authors.

1. Introduction

IPCC's Fourth Assessment Report noted that climate has changed since pre-industrial times. The changes since the mid-20th century are 'very likely' due to human activities, in particular those that lead to greenhouse-gas emissions. Many regions and countries have characteristics that make them vulnerable to the effects of climate change, which include increasing land and ocean temperatures, sea level rise, and the increase in frequency and severity of several extreme weather events. Climate change inflicts loss and damage on these countries' economies, livelihoods, coastal infrastructure, ecosystems and food and water supplies. Increased loss and damage is projected with further increasing GHG emissions.

> *...the context of this report is that UNFCCC has decided to explore a range of approaches including an international mechanism to address loss and damage.*

Ultimately, the scale of climate-change impacts will depend upon the timing and scale of efforts to reduce emissions over the next decades and to adapt to climate change, as well as a range of other and local factors. This makes the quantification of loss and damage from future climate change challenging. Nevertheless, much is known about the types and scale of impacts experienced today and those that can be expected in different regions in the future under different scenarios. Our understanding today already shows the need for an international response to address loss and damage and the context of this report is that UNFCCC has decided[1] to explore a range of approaches including an international mechanism to address loss and damage.

To systemize the response of the international community within the climate change negotiations, proposals have been made including the establishment of an international mechanism to address loss and damage. One question informing the loss and damage discussion is to what extent can loss and damage from climate change be quantified, and to what extent can these losses and damages be linked to anthropogenic forcing?

This paper considers:

- Expected impacts at different warming thresholds of 1.5, 2 and 4°C above pre-industrial.
- Risks of loss and damage from these impacts
- The state of attribution science and the degree to which it is now possible to link impacts directly to human forcing of the climate.

In this paper, we conclude that several slow-onset events, notably heat waves and also precipitation extremes, can be attributed to human-induced climate change. As warming intensifies in the coming decades, attribution of the impacts of these events will become statistically more significant. Attribution science is rapidly developing and thus over the same period methods and models will improve drastically.

Given the uneven distribution of GHG emissions and projected climate change impacts, even an imperfect quantification of loss and damage from extreme weather events and slow-onset events can inform an assessment of the extent to which nations most responsible for global warming should assist other nations in coping with climate change impacts, with the associated adaptation costs, and with approaches to manage impacts that go beyond adaptation capacity and hence lead to loss and damage[1,2].

In Sections 2 and 3 we will briefly reflect on the policy discussions and explain concepts related to loss and damage, for framing our assessment of recent scientific information required to inform the discussion on loss and damage, presented in Sections 4 and 5.

[1] http://unfccc.int/resource/docs/2011/cop17/eng/09a02.pdf

...even an imperfect quantification of loss and damage from extreme weather events and slow-onset events can inform an assessment of the extent to which nations most responsible for global warming should assist other nations in coping with climate change impacts...

2. Implication for international climate policy

Extreme weather events, such as droughts, heat waves, floods, cyclones and hurricanes, can cause great physical, economic or social havoc on societies. The number of several types of weather extremes is increasing due to climatic change[3], yet the associated costs is hardly accounted for in cost-benefit analysis for global climate policy[1,4]. Similarly, sea level rise and ocean acidification from increasing GHG concentrations, are also impacting vulnerable countries and ecosystems. Quantifying projected loss and damage from these phenomena over time, or at various temperature thresholds, gives an indication of the economic, social and cultural burden imposed by increasing GHG emissions.

Conceptually, loss and damage result when impacts exceed adaptive capacity, or outpace local adaptive development, even when strengthened by (guaranteed) international funding. The greater the investment in adaptation and the mitigation of emissions, the less loss and damage that will be suffered. For some regions, adaptation efforts will only be able to address a small portion of the loss and damage that will be suffered from the impacts of climate change, as illustrated further on in this paper.

Quantification of future loss and damage from projected climate change impacts will assist countries in making decisions related to adaptation investments. The international community needs such information as well, when considering how to minimize loss and damage through adaptation and mitigation, and how to address the needs of vulnerable countries where the avoidance of loss and damage is not possible.

Parties to the UN Framework Convention on Climate Change have agreed to consider at COP18 in Doha recommendations for the role of the Convention in addressing loss and damage.

In the international climate change negotiations, Parties to the UN Framework Convention on Climate Change have agreed to consider at COP18 in Doha recommendations for the role of the Convention in addressing loss and damage (Decision 1/CP.16)[2]. This will include, according to the decision taken at COP17 in Durban (Decision 7/CP.17)[3], the exploration of "a range of possible approaches and potential mechanisms, including an international mechanism, to address loss and damage". Country groups particularly at risk from loss and damage, notably the Alliance of Small Island States (AOSIS) and the Least Developed Countries (LDCs)[4], have suggested in their submissions certain features and functions which an international mechanism might address. Three elements mentioned in both these submissions are relevant to recall here, as each of these relates somewhat differently to the scientific assessment of different sectors and climate phenomena presented in the rest of this paper:

[2] http://unfccc.int/resource/docs/2011/cop17/eng/09a02.pdf
[3] Ibid.
[4] the submissions can be found here: http://unfccc.int/documentation/submissions_from_parties/items/5902.php.

- A risk management component to support and promote risk assessment and risk management tools and inform the other two components
- An insurance component to help SIDS and other particularly vulnerable developing countries manage financial risk from increasingly frequent and severe extreme weather events through the design and operationalization of risk management products
- A rehabilitation/compensatory component to address the progressive negative impacts of climate change, such as sea-level rise, increasing land and ocean temperatures, and ocean acidification.

While the exact form of the international response is not the focus of this paper, the latest climate science shows that at least for some type of phenomena enough is known to provide critical information for any discussions on such approaches and mechanisms - in particular heat waves, droughts and sea-level rise.

While the exact form of the international response (e.g. through an international mechanism or other approaches) are not the focus of this paper, the latest climate science shows that at least for some type of phenomena enough is known to provide critical information for any discussions on such approaches and mechanisms -- in particular heat waves, droughts and sea-level rise. We consider risk of loss and damage from these impacts, and the state of attribution science -the degree to which a climate or weather event or its impact can be linked to a specific cause, i.e. either natural or anthropogenic. We discuss two types of phenomena: extreme events (heat waves, droughts, floods, storms, etc.) and slow-onset events (slower trends that increase the risk of crop failures, for example, or increase sea-level and ocean acidification). Slow-onset events also include the gradually accumulating impacts of repeated extreme events, in which each extreme event weakens the resilience against the next event. Extreme events and slow onset events are thus closely inter-related and their impacts cannot always be segregated.

3. Risk of Loss and Damage

Impacts of both slow-onset and extreme events are typically expressed in terms of either death toll, or financial costs. As a result, published cost estimates are 'conservative' estimates, as many impacts, like losses in the informal economy, of cultural heritage, or of ecosystem services, are difficult to monetize and therefore have been poorly reflected in the literature[5]. The impact is a function of both the vulnerability and the exposure of societies to them. The latter refers to the presence of people and assets in areas subject to hazards[5]. Future estimates of exposure and vulnerability are derived from socio-economic scenarios and strongly depend on assumptions of socioeconomic development, demography, urbanization, wealth and expenditures on protection against hazards[6].

Risk is defined as the product of the probability of an event and the severity of its impact. A quantification of loss and damage depends on data and assumptions concerning a baseline, so that shifts in relevant parameters over time can be assessed (e.g., temperature, sea level, return rates of extreme events).

For extreme events, part of the baseline is a stationary climate probability, or frequency of occurrence, and *event-probability* can be quantified by applying statistical methods to either historical data or climate model scenarios. The latter hinges on the climate model adequately representing extreme-event statistics, which may well be true for large-scale, continent-wide heat extremes, but is more questionable for storm, or precipitation events[7]. Comparable methods have been applied to attribute observed events to either natural, or human causes[8-12].

Climate modeling studies have provided much more confidence in attribution of past extremes and in the expected patterns of future change.

Sea level will rise and oceans will acidify on a global scale with increasing GHG emissions. In forecasting, the distinguishing risk factor for slow-onset events like these is the probability that a certain level is exceeded at a certain point in time, while for hind casting, like attributing changes observed so far, the key factor is the probability that a certain part of the signal, like local sea-level rise, is due to global climate change, rather than local subsidence, or episodic local rises (e.g. natural variability).

Indeed, for any global indicator, local severity and timing of associated impacts, and hence local risk, will be different. For sea level rise, for example, this would require consideration of topography, asset distribution, exposure, vulnerability etc), and the value of exposed assets[13]. Monetization of these future impacts is difficult, as they may include the cost of the relocation of assets, permanent or long-term land loss, loss of agricultural land, loss of ecosystem services (e.g., coral reefs), loss of water access or availability, and even a loss of sovereignty.

Below we review the literature on impacts that drive loss and damage. First, the text box provides a summary of the key findings of the IPCC Special Report on Extremes (SREX)[5]. Although the SREX literature cut-off date (31 May 2011) is only one-and-a-half year ago, a large amount of literature has appeared since then. Climate modeling studies have provided much more confidence in attribution of past extremes and in the expected patterns of future change. The rest of the paper provides a review of the more recent scientific literature on both extreme and slow-onset events.

BOX: Key conclusions of the Summary for Policy Makers of IPCC's Special Report on Extremes

Past climate trends and disaster losses

- It is very likely that the number of warm days increased and cold nights decreased globally, which is likely attributable to anthropogenic influences
- With medium confidence, the length or the number of heat waves increased in many regions
- There have been statistically significant trends in the number of heavy precipitation events in some regions, while other regions have experienced more intense and longer droughts
- With medium confidence, human influences have contributed to this intensification of extreme precipitation at the global scale.
- Confidence levels in any observed increases in tropical cyclone activity are low due to short or inhomogeneous data series and large variability in the number and intensity of storms.
- It is likely that extreme coastal high water increased due to sea level rise, which is likely attributable to anthropogenic influence.
- Total economic losses from weather and climate-related disasters increased over recent decades
- Economic losses in terms of proportion of GDP are substantially higher in developing countries. Also impact in terms of death toll from natural disasters is much higher in developing countries

- Economic losses from weather- and climate-related disasters have been heavily influenced by increasing exposure over recent decades of both people and economic assets
- There is limited to medium evidence available to assess climate-driven observed changes in the magnitude of floods at regional scales

21st century projections in climate extremes and disaster losses

- It is virtually certain that the frequency of warm days will increase and cold nights decrease on a global scale. Very likely the length, frequency or intensity of heat waves will increase.
- The frequency of heavy precipitation likely increases over many areas, especially over tropical regions and high latitudes. Over some catchments, the projected increase in heavy precipitation will likely contribute to increases in local flooding.
- With medium confidence droughts will intensify in some regions.
- Maximum wind speed of tropical cyclones is likely to increase though the number of cyclones might decrease or remain essentially unchanged.
- Very likely mean sea level rise will contribute to upward trends in extreme coastal high water levels in the future. Locations currently under threat, due to adverse impacts such as coastal erosion and inundation, will continue to do so in the future.
- Tropical small island states are especially at risk due to the combination of increased coastal high waters due to sea level rise and the likely increase in tropical cyclone maximum wind speed.
- Changes in extreme events have the largest impact on sectors that are closely linked to climate, such as water resources and agriculture, but they are not the only drivers of future change.

4. Impacts: from present-day levels of warming to 4°C warming

Climate change has already led to drought, water stress and decreased production of staple crops, including maize and wheat, with consequent impacts on vulnerable economies around the world.

The rise in sea level and increase in the frequency and intensity of heat, drought and precipitation extremes due to climate change have already impacted societies and ecosystems and will have increasingly severe impacts on societies and ecosystems in the 21st century.

Impacts at present levels (0.8°C)

Climate change has already led to drought, water stress and decreased production of staple crops, including maize and wheat, with consequent impacts on vulnerable economies around the world.

Though end-to-end attribution science is in its infancy, qualitatively the causality between some meteorological extremes and their impact is clear.

As listed in Table 1, recent meteorological *events* that have caused major damage to and disruption of societies have been attributed to anthropogenic climate change with medium to high confidence. To attribute the *impacts* of these events to either natural or anthropogenic forcings however remains challenging and requires accurate knowledge of the vulnerability of societies or ecosystems to the meteorological event in question. Such information is often poorly quantified[1]. To date, only few end-to-end attribution studies, i.e. attribution from greenhouse gas forcing to impacts, have been published. One study linked climate models with precipitation run-off models, and showed that greenhouse gas forcing substantially increased the risk of floods occurring in England and Wales in autumn 2000[14]. Though end-to-end attribution science is in its infancy, qualitatively the causality between some meteorological extremes and their impact is clear.

Drought and water stress: Globally, warming-induced drying has likely increased the area under drought by 8%[15], increasing water-stress in vulnerable regions. Since the 1960s, sown areas for all major crops were increasingly affected by drought, with drought-affected areas for maize more than doubling from 8.51% to 18.63%[16]. Anthropogenic greenhouse gas and aerosol forcing are key attributable factors for the increased drying in the Eastern Mediterranean[8], accumulating in several extremely dry-years in Syria recently. The region is highly vulnerable to meteorological drought, as the vast majority of crops in the region are non-irrigated and therefore dependent on winter-time precipitation[17]. In combination with water mismanagement, the meteorological drought in 2008 thus rapidly led to water-stress with more than 40% of the cultivated land affected, strongly reducing wheat and barley production[17].

Crop yields: Warmer seasonal temperatures reduce yields from annual crops like wheat and maize, since the crop duration shortens. Since the 1980s, global crop production has been negatively affected by climate trends, with maize and wheat production declining respectively 3.8% and 5.5% compared to a case without climate trends[18]. More frequent and intense extreme weather events, like drought and heat waves, can severely damage crop yields and thereby contribute to food price volatility[19]. Recent extreme heat waves, of which some can be attributed to global warming with medium to high confidence (see Table 1), caused severe damage to agricultural production in Russia (2010)[20], Texas (2011)[21] and U.S. (2012)[22]. Wheat production in Russia and Ukraine in 2010 was down by ~25% and ~20% respectively[20]. Disruptions in supply, even when relatively small, can still generate large price swings on the international market especially when stocks are limited, and hence have strong effects on vulnerable countries far removed from the location of the heat waves[23]. The production drop in 2010 caused grain prices to increase on the international market and the effect was magnified when the Russian government banned grain export to protect local consumers[23] [24]. This can lead to a panic-driven price spike due to a highly nonlinear process: Other major exporting countries limit exports in response to uncertainty in the global market, which in turn is exacerbated by these bans[23].

Ecosystem impacts: Climate change has already clearly played a role in observed ecosystem changes. Coral reefs are very sensitive to elevated sea temperatures, which cause coral bleaching[25]. The sensitivity is amplified by local pollution and other human influences. Mass coral bleaching and mortality events have been observed worldwide since the early 1980s and have affected reefs at regional scales[26]. Recent modeling studies indicate that a 1°C warming above pre-industrial levels, likely to be surpassed already in the next decade, puts about 16% of reef locations at risk[27]. Tree die-back related to heat and drought has already been observed in boreal forest over substantial areas of North America[28]. Also recent unprecedented dry years in the western Amazon (2005 and 2010, see Table 1) caused massive tree mortality[29].

Impacts at 1.5°C

A 1.5°C rise by 2100 would pose serious challenges worldwide, especially in the LDCs, SIDS and Africa.

Drought and water stress: An estimated 75 to 250 million people would be at risk of increased water stress in just the next few decades[30]. A robust response in 21st century climate simulations is a decline in subtropical precipitation and increase in high latitude precipitation[7,31]. Thus, in general, precipitation changes will increase water stress in regions that are already drought-affected today. In Tanzania, reduced power generation from hydro-electric plants (due to water stress) alone is estimated to produce a climate-induced loss in national GDP of up to 1.7% by 2030[32].

A 1.5°C rise by 2100 would pose serious challenges worldwide, especially in the LDCs, SIDS and Africa.

Ecosystem impacts: Recent science shows that coral reef ecosystems are likely to be extremely adversely affected by the combined effects of ocean acidification and warming, already at levels as low as 1.5°C[27].

Sea-level rise: Sea level is projected to rise to 75 cm above 2000 by 2100[33], With temperatures dropping well below a 1.5°C increase, the rise might be stabilized below levels 1.5 m in the longer term[33]. Sea-level rise of only 45 cm would already result in a loss of 10% of land area in Bangladesh, with flood risk increasing most rapidly between 0 and 2°C warming[34]. Without adaptation such moderate sea level rise will increase the number of people flooded by storm surges more than five fold, with South and South-east Asia being especially at risk due to vulnerable low-lying and populated deltas[35].

Impacts at 2°C

Drought and water stress: For global warming up to roughly 2.5°C[36], the hydrological response is approximately linear with regions experiencing drier conditions under 1.5°C warming becoming even drier under warmer conditions[37]. Severe and widespread droughts would occur in the next 30–90 years over many densely populated areas[38], including regions like southern Europe, Australia and large parts of Africa and North and South America. The population at risk of increased water stress would reach 350-600 million people by 2050[30]. Climate change is projected to exacerbate water stress in countries that already need to cope with water scarcity, in particular in Northern Africa and the Middle East. In addition, in a 2°C world additional countries would newly have to cope with water-scarce mostly due to population changes rather than climate change[37].

Crop yields: Water- and heat-stress will negatively affect crop yields in regions that are already drought prone today, putting pressure on food security. Even under low-emission scenarios, drought disaster frequency in major crop sowing areas is expected to double[16]. Sub-Sahelian crop damages might exceed 7%, with a small chance of 27% damages[39]. In general, models tend to underestimate the damaging effects of temperature and drought extremes on crop yields[19,40], giving quantitative impact projections limited validity. Field experiments have shown that crops are highly sensitive to temperatures above thresholds of 30-36°C, something which is not accounted for in most crop models[19,40]. Therefore, crop models probably underestimate yield losses for a +2°C by as much as 50% for some sowing dates[19], an effect which is likely to be significantly stronger for higher levels of warming.

Ecosystem impacts: 10-15% of Sub-Saharan ecosystem species would be at risk of extinction[30] and a projected decrease in precipitation over the Amazonian forests may result in substantial forest retreat here[41]. At 2°C of warming roughly 25% of the original land extent of the humid tropical forest is at threat[41].

Sea level rise: Sea level would rise to 80 cm above 2000 by 2100, only 5cm above 1.5°C projections, thus resulting in comparable impacts by that time. However, in contrast to warming that drops below 1.5°C, a long-term stabilization at 2°C warming implies a commitment to continuous sea-level rise for centuries, with levels to approach 3 m by 2300[33]. The threshold for the Greenland ice sheet to irreversibly melt down is now estimated to be 1.6°C above preindustrial, compared to the IPCC AR4 estimate of 3.1°C[42].

Impacts at 4°C

4°C warming, as may be regarded as the currently most likely scenario given the global community´s insufficient pledges to limit and reduce greenhouse gas emissions, results in the most severe impacts, which might largely be beyond the potential capacities of adaptation. The conditions of some of the most extraordinary heat waves experienced today will become the new norm and a completely new class of heat waves, with magnitudes never experienced before, will occur regularly[43,44]. This will have severe but as yet un-quantified impacts on agricultural production and human health.

4°C warming might largely be beyond the potential capacities of adaptation.

Drought and water stress: Climate impacts become large enough to dominate changes in water stress, and the changes in water run-off projected for 4°C warming are roughly double those of a 2°C world[45]. Timing of warming is critical as the world population is expected to grow until the second half of the 21st century. Under high-emission scenarios, the adverse impacts on water availability may thus coincide with maximum demand as the world population peaks[37]. At 4°C, the proportion of arid and semi-arid lands in Africa is likely to increase by 5% to 8%[46]. When accounting for the amount of water needed to produce a certain amount of food in a given location, it is estimated that the global population living in water-scarce countries will double compared to today[47].

Crop yields: Globally, drought disaster-affected areas in major crop sowing areas are predicted to increase three-fold (from 15.4% to 44.0%) in 2100[16]. Crop yields for maize are expected to decrease between -13% and -23% and for beans between -47% and -87%, implying that "[…] the kind of changes that would occur in a 4°C world would be way beyond anything experienced in recent times"[48]. Wheat production is likely to disappear from Africa by 2080[46], while millet yield in Sahelian Africa is projected to decrease by 40%[49].

Ecosystem impacts: In a 4°C world, climate change may become the dominant driver of ecosystem shifts, surpassing habitat destruction as the greatest threat to biodiversity[50,51]. Due to ocean acidification, corals around the world are likely to start dissolving above 550 ppm CO_2[52]. The Amazonian forest area is expected to contract to 25% of its original size[53] and up to 30% of other tropical rainforests, in central Sumatra, Sulawesi, India and the Philippines, is threatened by forest retreat[41]. In Africa, 25%–42% of plant species could lose all suitable range by 2085[54]. The interactions between impacts of climatic change, human actions (like deforestation), and forest responses (like fire) represent potential positive feedbacks that could lead to widespread Amazon forest degradation or loss[55]. Substantial loss of tropical forest would release large amounts of carbon dioxide into the atmosphere, which would accelerate climate change further. Between 2°C and 3°C of global-mean warming the global terrestrial plants carbon sink is expected to strengthen, due to the CO_2 fertilization effect, but it is estimated to saturate above 3°C[56].

Climate change has the potential to catalyze rapid shifts in dynamic, out-of-equilibrium ecosystems, such as sudden forest loss or regional loss of agricultural productivity due to desertification[57]. The ramifications of these shifts would be far-reaching, ranging from extensive loss of biodiversity and diminished land cover, through to loss of ecosystems services[58]. Ecosystem degradation diminishes biodiversity which decreases the overall stability of the ecosystem again. Recent work on competition and habitat suggests models generally underestimate the impact of climate change on biodiversity[59]. 4°C warming by 2100 would likely result in global temperatures stabilizing at 6°C above pre-industrial over the next few centuries[60]. The most recent geological analogue for a 6°C world, the Palaeocene-Eocene thermal maximum 55 million years ago, saw a period of rapid global change, though still at a slower pace than projected for a future 4-6°C world[61]. No paleo-analogue exists for the rapid warming projected under unmitigated climate change and it is fair to say that this will lead at least to widespread extinctions in ecosystems that are shown to have happened 55 million years ago[62].

Sea-level rise: Sea-level rise would exceed 1 m by 2100[33], while post-2100 sea-level is hard to project, due to large knowledge gaps in understanding of the response of the ice caps to such strong warming. The potential impact of 1m sea-level rise or more would be severe, with the real risk of the forced displacement of up to 187 million people over the century (up to 2.4% of global population)[63]. East Asia, South-east Asia and South Asia would be expected to be most affected with an expected 53-125 million people displaced. The small islands states, Africa and parts of Asia are the most likely to see coastal abandonment as the likelihood of successful protection measures is lowest here. Coastal cities in developing regions are especially vulnerable to SLR, due to high population densities and the often-inadequate urban planning and coastal protection. Including demographic information, Brecht et al.[64] estimate the future impact of climate change on storm surges that will strike coastal populations, economies, and ecosystems.

They identify 10 Asian cities that account for 50% of the future exposure of SLR with over 40% falling on Manila, Karachi, and Jakarta alone. In Africa, countries with the highest total impacts under a 126 cm SLR scenario are Egypt, Mozambique and Nigeria with respectively 8, 5 and 3 million people displaced annually[65]. The impacts on 15 Caribbean countries of 1 and 2 m of sea-level rise were estimated at an annual capital costs between US $26 to US $60.7 billion (equivalent to between 6.2 and 12% of projected GDP in 2050) in the absence of adaptation, either through structural protection or planned retreat and replacement of vulnerable infrastructure assets[13].

The frequency of the most damaging (category 4 and 5) Atlantic tropical cyclones is projected to nearly double by the end of the 21st century[66]. New research shows mortality risk depends on tropical cyclone intensity, exposure, levels of poverty and governance[67].

'Residual' Impacts at different warming levels

Some impacts can be avoided or minimized through anticipatory adaptation (e.g., use of drought-resilient crops, retrofitting buildings to withstand more frequent or severe tropical storms, strengthening coastal zones, etc.), but some impacts will be unavoidable (e.g., permanent land loss due to sea level rise). A recent attempt[68] to illustrate the relationship between adaptation and loss and damage shows that an increase in global temperatures from 2°C to 3°C for several regions of particular relevance to LDCs will greatly increase loss and damage relative to GDP (see Figure 1) and outpace what can be achieved through adaptation. Even at 2°C adaptation only avoid a minor part of projected loss and damage.

The assessment summarized in Figure 1 is based on monetized impacts and derives so-called 'residual damage' from these impacts, as a proxy for loss and damage. 'Residual damage' refers to damage that results when adaptation is implemented only to the level beyond which further adaptation efforts would become more expensive than the monetary value of damages they would prevent. However, the monetization of impacts and residual damages is both problematic and often highly controversial for many types of loss, for example loss of lives, health, ecosystems and cultural values. Efforts to extend adaptation beyond what is 'optimal' based on monetized cost-benefit analysis might therefore needed to reduce loss and damage.

Efforts to extend adaptation beyond what is 'optimal' based on monetized cost-benefit analysis might be needed to reduce loss and damage.

5. Recent progress in attribution

Recent studies provide strong additional evidence that heat waves and precipitation extremes will greatly increase in a warming climate and have in fact already done so.

Improvements in climate models, i.e. Ref. [69], and the application of novel statistical analysis[70-72] have given much higher confidence in that some observed

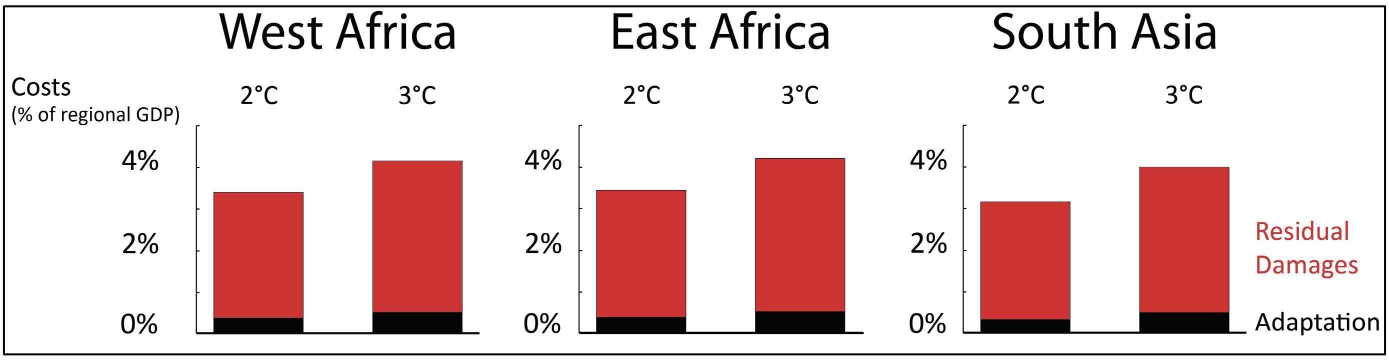

Figure 1: Illustration of regional monetized costs of adaptation and 'residual damage' (see text) for 2 and 3°C warming above pre-industrial. Adapted from Hof et al.[68]

extremes, notably heat waves, can be attributed to climatic warming. Recent studies provide strong additional evidence that heat waves and precipitation extremes will greatly increase in a warming climate and have in fact already done so[3,15,73,74]. For other extremes, like storms, the evidence is still less conclusive.
Table 1 provides a list of record-breaking meteorological extremes that occurred since the start of the 21st century, their estimated impact on societies and the (qualitative) confidence level that these events can be attributed to 20th century climatic warming.

Table 1: Selection of record-breaking meteorological events since 2000, their societal impacts and confidence level[5] that it can be attributed to climate change. Adapted from Ref. 3.

Region (Year)	Meteorological Record-breaking Event	Confidence in attribution to climate change	Impact, costs
England and Wales (2000)	Wettest autumn on record since 1766. Several short-term rainfall records[75]	Medium based on[14,76,77]	~£1.3 billion[14]
Europe (2003)	hottest summer in at least 500 years[78]	High based on [12,73,74,79]	Death toll exceeding 70,000[80]
England and Wales (2007	May to July wettest since records began in 1766[81]	Medium based on [14,76]	Major flooding causing ~£3 billion damage
Southern Europe (2007)	hottest summer on record in Greece since 1891[82]	Medium based on [11,73,74,83,84]	Devastating wildfires
Eastern Mediter-ranean, Middle-East (2008)	Driest winter since 1902 [44]	High based on [8,85]	Substantial damage to cereal production [86]
Victoria (Aus) (2009)	Heat wave breaking many station temperature records (32-154 years of data)[87]	Medium based on [11,73,74]	Worst bushfires on record, 173 deaths, 3500 houses destroyed[87]
Western Russia (2010)	Hottest summer since 1500[20]	Medium based on [10,11,70,73,74,84,88]	500 wildfires around Moscow, crop failure of ~25%, death toll ~55,000, ~US$15B economic losses[20]
Pakistan (2010)	Rainfall records[89]	Low to Medium based on [90,91]	Worst flooding in its history, nearly 3000 deaths, affected 20M people[92].
Eastern Australia (2010)	Highest December rainfall ever recorded since 1900[93]	Low to Medium based on [90]	Brisbane flooding in Jan 2011, costing 23 lives and estimated $2.55 billion[94]
Colombia (2010)	Heaviest rains since records started in 1969[95]	Low to Medium based on [90]	47 deaths, 80 missing[95]
Western Amazon (2010)	Drought, record low water level in Rio Negro[29]	Low [29]	Area with significantly increased tree mortality spanning3.2 million km[29]
Western Europe (2011)	Hottest and driest spring on record in France since 1880[96]	Medium based on [11,73,74,97]	French grain harvest down by 12%
Texas, Oklahoma, New Mexico and Louisiana (US) (2011)	Record-breaking summer heat and drought since 1880[98,99]	High based on [11,84,99,100]	Wildfires burning 3 million acres (preliminary impact of $6 to $8 billion)[21]
Continental U.S. (2012)	July warmest month on record since 1895[101] associated with severe drought conditions	Medium based on [11,84,100]	Abrupt global food price increase due to crop losses[22]

[5] High confidence levels have been assigned to those events for which the long-term trend of the relevant meteorological variable and the event itself have been attributed to anthropogenic forcing. These criteria have been fulfilled for several heat waves, including the Russian heat wave of 2010[10,11,70,84]. For the latter, however, one study[88] did not detect any anthropogenic signal and thus confidence level for this event has been set to medium. Other type of extremes have lower confidence levels based on the available literature.

The confidence levels assigned here refers to the attribution of the meteorological event itself, but not necessarily of its societal impact. Nevertheless, the impacts of many of the events listed clearly have been devastating to societies in terms of human toll, or infrastructural or agricultural damage. The majority of literature studies in Table 1 focused on impacts in developed countries. However, IPCC SREX found that over 95% of deaths from natural disasters occurred in developing countries between 1970 and 2008.

Heat waves

The second half of the 20th century has seen an approximate global-mean warming of 0.5°C. Over this same time frame, monthly[70,74] and seasonal[73] temperature extremes have increased strongly. Extremely hot summer months and seasons (as listed in Table 1) would almost certainly not have occurred in the absence of global warming[73,74]. Moreover, climate modeling studies have shown that the increased *frequency* in very warm monthly and seasonal temperatures can be directly attributed to human influence[11,97,100,102]. Also individual heat waves, like the ones in Europe in 2003[12], Russia in 2010[10] and Texas in 2011[99], have been attributed to greenhouse gas forcing and are now many times more likely than in the 1960s. The impacts of these events have been devastating for many countries (see Table 1 - right column). Thus the limited global-mean warming over the past half century has already strongly increased the occurrence probability of regional heat extremes.

Over the next century, climate models project up to 6°C warming compared to pre-industrial[103], and thus monthly[43,44] and seasonal[7,104,105] heat extremes are projected to increase strongly. Diffenbaugh and Scherer[104] demonstrated that many areas of the globe are likely to permanently move into a new climatic regime, whereby the coolest warm-season of the 21st century is hotter than the hottest warm-season of the late 20th century. The tropics are especially vulnerable to unprecedented heat extremes[44,104], exhibiting a 50% likelihood of permanently moving into a novel seasonal heat regime already in the next two decades[104].
Even if the global-mean temperature increase remains below the 2°C target, large regions could experience seasonal extremes with high regularity[105]. Under 4°C warming, the conditions experienced during some recent extraordinary heat waves (in Europe, Greece, U.S. and Russia, see Table 1) will effectively become the norm and a completely new class of heat waves, with magnitudes never experienced before in the 20th century, is projected to occur regularly[43,44]. Also heat extremes on shorter (e.g. daily) time scales will increase in accord with the seasonal amplification, underlining the importance of the latter [7].

Precipitation and drought extremes

Based on physical principles, warming of the lower atmosphere is expected to strengthen the water cycle, as warmer air can hold more moisture[3,106]. Such strengthening causes dry regions to become drier and wet regions to become wetter, something which is also predicted by climate models[106]. Recently, this global water cycle intensification has indeed been detected in changing precipitation patterns over oceans over the last 50 years, revealing that it occurs at a rate twice that predicted by the models[107].

> *Under 4°C warming a completely new class of heat waves, with magnitudes never experienced before in the 20th century, is projected to occur regularly.*

Apart from this thermodynamic mechanism, changes in atmospheric circulation patterns can also strongly affect the frequency of precipitation extremes. Latest observational and modeling studies indicate that anthropogenic aerosol forcing played a key role in changing precipitation patterns[8,108,109].

These mechanisms contributed to the observed increase in global aridity since the 1970s, which has been about 1.74% per decade, though natural cycles have played a role as well[85,110]. Warming-induced drying, i.e. more evaporation, likely increased the areas under drought by about 8% by the first decade of this century[15]. Focusing on the Mediterranean region, Hoerling et al[8] show that the long-term wintertime drying here can be attributed to anthropogenic aerosol and greenhouse gas forcing. Also, individual drought events, like the ones in Texas and East Africa in 2011 have become much more likely due to climate change since the 1960s[99,111]. For the African event, Funk[111] concludes that anomalously high sea surface temperatures (SSTs) in nearby oceans were important and those can largely be attributed themselves to anthropogenic green house gas forcing[112]. Record high tropical SSTs in 2010 also provided a source of unusually abundant atmospheric moisture contributing to flooding in Pakistan, Colombia and Queensland[90], causing widespread havoc in these countries (see Table 1). Also, the intensification of heavy precipitation over large swathes of land in the Northern Hemisphere during the latter half of the 20th century has been linked to increases in greenhouse gasses directly[76,113]. Over some regions, this has substantially increased the risk of damage from the associated flooding[14]. Confidence levels for attribution of heavy rainfall extremes is generally lower than those for heat extremes as they are less-well represented in climate models[3]. This is true for future precipitation changes as well[7]. Still, some robust features appear: Increasing dryness over sub-tropical regions[7,31] and more intense and frequent heavy precipitation over tropics[114] and Northern high-latitudes[7]. Over regions where temperature and precipitation head in opposite directions, severe drought conditions are expected by the late half of this century. These areas include densely populated regions like Europe, the U.S., Brazil, southern Africa and southeast Asia[15].

Increasing dryness over sub-tropical regions and more intense and frequent heavy precipitation over tropics.

Sea level rise

Global mean sea level rise (SLR) has accelerated from about 1.7 mm/yr during the 20th century to about 3 mm/yr since the beginning of the 1990s[115]. Regionally SLR can be substantially larger, as seen for instance in the tropical Western Pacific with a rate three times larger than the global mean[116]. The largest contributions to SLR come from the thermal expansion of the upper ocean layers and melting of mountain glaciers followed by melting of the large ice sheets[115].

Recent dynamic mass losses of the Greenland ice sheet (GIS) have raised concerns about its long-term contribution to SLR. Latest observations confirm an overall acceleration of marine-terminating glaciers, showing that their present rate of retreat is more widespread than during earlier periods of the 20th century[117,118].

Even an abrupt switch to zero-emissions would practically have limited effect on sea level over the coming 100 years, due to the slow response of large ice sheets and the deep ocean...

Physics-based models have underestimated SLR, compared to observed levels[119]. Projecting specific levels of SLR into the future is still associated with large uncertainties, in the first place due to uncertainties in the response of the large ice sheets[115,120]. Since physics-based models cannot accurately reproduce observed SLR, scientists have relied on semi-empirical models to project future SLR[119,121]. For high emission scenarios (reaching about 4°C warming by 2100), these models predict SLR in the range of 80 to 115 cm above 1990 by 2100, with values that are regionally up to 20% higher possible[122,123]. Limiting global-mean warming to 2°C will reduce this predicted SLR range by only about 20 cm. Even an abrupt switch to zero-emissions would practically have limited effect on sea level over the coming 100 years, due to the slow response of large ice sheets and the deep ocean[120], avoiding about half of the sea-level rise of a high-emission scenario.

However, the scale of mitigation over the coming years will have a strong effect on the *rate* of rise by 2100 and are crucial for SLR in the centuries thereafter, which could diverge by meters if the effects of the most ambitious 21st century mitigation scenarios are compared to unmitigated warming[120].

Also, high-emission scenarios increase the risk of crossing a potential tipping point threshold, which could result in ice sheet collapse[123,124].

Ocean acidification

Increasing CO_2 concentrations in the atmosphere lead directly to ocean acidification. The ocean has already increased in acidity by approximately 30% since pre-industrial times[125], as a result of increasing CO_2 concentrations in the atmosphere, with negative impacts on coral reefs and related ecosystems. A further deterioration of coral reefs will have negative impacts on dependent species, fisheries, coastal protection and tourism in many regions.

The atmospheric CO_2 concentration has surpassed 390 ppm recently, which has led to increased absorption of CO_2 by the oceans and an increase of the ocean's acidity, estimated at a reduction of 0.1 units of pH since pre-industrial[125]. A lower pH value indicates higher acidity and since pH is a logarithmic scale, a reduction of 0.1 represents approximately a 30% increase in acidity. Higher acidity of ocean waters leads to reduced availability of calcium carbonate (aragonite), the resource vital for coral species and ecosystems to build skeletons and shells. Reduced reef calcification due to acidification has been observed in the last decades[126-128]. Especially vulnerable are warm-water coral reefs, cold-water corals and ecosystems in the Southern Ocean. Identified impacts of reduced pH on these systems are a reduction in coral calcification (reduced growth), coral skeleton weakening and reduced resilience to high-temperature events, i.e. increased risk of bleaching due to rising temperature of surface waters[129].

IPCC AR4 projections for SRES scenarios indicate a further increase of the ocean's acidity of 0.14 to 0.35 units of pH over the 21st Century[125] (equivalent to an increase in acidity of 80-180% since pre-industrial). A recent review shows that the anthropogenic rate of carbon input into the oceans appears to be greater than during any of the ocean acidification events identified so far over the geological past, dating back millions of years and including mass-extinction events[130].

If atmospheric CO_2 reaches 450 ppm, coral reef growth around the world is expected to slow down considerably and at 550 ppm reefs will start to dissolve[52,131]. The effects of acidification have already been observed and will gradually worsen as acidification increases. Hence, reduced growth, coral skeleton weakening and increased temperature dependence will start to affect coral reefs below 450 ppm. A deterioration of coral reefs will have negative impacts on dependent species, fisheries, coastal protection and tourism in many regions.

...a CO_2 level of below 350 ppm is required for the long-term survival of coral reefs...

A recent assessment concludes that a CO_2 level of below 350 ppm is required for the long-term survival of coral reefs, if multiple stressors are included, like high ocean surface-water temperature events, sea-level rise and deterioration in water quality[132]. A scenario that is consistent with a 1.5°C warming limit may start to approach a CO_2 concentration of 350 ppm by the end of this century[133].

6. Conclusions

Climate change impacts related to, for example, ecosystems, food and water security, extreme events, ocean acidification, sea-level rise and rate of sea-level rise, are all projected to worsen considerably if warming is allowed to increase beyond 1.5 and 2°C. Hence, loss and damage is strongly reduced by successful and deep mitigation, but even at 2°C warming loss and damages will be high for several regions relevant for LDCs, and loss and damage will outstrip the impacts possibly avoided by successful adaptation.

...loss and damage is strongly reduced by successful and deep mitigation...

...but even at 2°C warming loss and damages will be high for several regions relevant for LDCs, and loss and damage will outstrip the impacts possibly avoided by successful adaptation.

Recent progress in impacts science shows that for several categories of impacts, like heat waves, droughts and sea-level rise, attribution to human-induced climate change has become possible. As warming intensifies in the coming decades, the signal from these and other climate impacts will become stronger and thus detection and attribution will become statistically more significant. Attribution science currently is in its infancy, but rapidly developing and near real-time attribution of extreme events shortly after their occurrence is becoming possible[69]. In the next decade, methods and models will improve further which should enable us to accurately quantify other impacts, like heavy precipitation events and ocean acidification as well. In the mean time, our scientific understanding today already allows for the design of a mechanism to manage loss and damage and start its operation.

...our scientific understanding today already allows for the design of a mechanism to manage loss and damage and start its operation.

Our assessment shows that since IPCC's Special Report on Extremes, improved data and methodologies have strongly increased our confidence in attribution of observed upward trends in heat waves, as well as of individual heat waves to anthropogenic climate change. The situation is similar for drought extremes. Clearly, observed heat and drought extremes have had severe impacts on agricultural production and will continue to do so in the future. This means that for these events increased frequency due to climate change can be derived, and hence increased loss and damage attributed to climate change. A helpful approach would be to estimate increased probabilities for each climatic zone, such as the 26 regions defined by SREX, as on this sub-continental scale both models and observations tend to provide statistically robust results.

Although other non-climate factors may amplify vulnerability and exposure, it should be possible for each case to disentangle loss and damage due to global climate-change from local trends that increase vulnerability. In the Pacific, a study has succeeded in identifying the anthropogenic contribution to sea level rise, as distinct from natural variability, and vertical ground motion[134]. However, it is an ethical, not scientific, question to what extent a country can be demanded to not make full social and economic use of areas vulnerable to climate change. In other words, should activities that increase exposure in vulnerable regions be a reason to forfeit a country's right to, for example, rehabilitation or compensation under an international loss and damage mechanism?

References

1 Brouwer, L. M. Have Disaster Losses Increased due to Anthropogenic Climate Change. *BAMS*, 39-46 (2011).
2 Brouwer, L. M. & Aerts, J. Financing climate change adaptation. *Disasters* **30**, 49-63 (2006).
3 Coumou, D. & Rahmstorf, S. A decade of weather extremes. *Nature Climate Change* **2**, 491-496 (2012).
4 Van den Berg, J. Safe climate policy is affordable - 12 reasons. *Clim. Change* **101**, 339-385 (2010).
5 IPCC. in *Special Report on Extremes of the Intergovernmental Panel on Climate Change* (eds C.B. Field & etal) (Cambridge Univ. Press, Cambridge UK, 2012).
6 Brouwer, L. M. Projections of Future Extreme Weather Losses. *Risk Analysis*, 1-16 (2012).
7 Orlowski, B. & Seneviratne, S. I. Global changes in extreme events: regional and seasonal dimension. *Climatic Change* **110**, 669-696 (2012).
8 Hoerling, M., Eischeid, J., Perlwitz, J., Quan, X., Zhang, T. & Pegion, P. On the Increased Frequency of Mediterranean Drought. *Journal of Climate* **25**, 2146-2162 (2012).
9 Karoly, D. J., Braganza, K., Stott, P. A., Arblaster, J. M., Meehl, G. A., Broccoli, A. J. & Dixon, K. W. Detection of a Human Influence on North American Climate. *Science* **302**, 1200-1203 (2003).
10 Otto, F. E. L., Massey, N., Oldenborgh, G. J. v., Jones, R. & Allen, M. R. Reconciling two approaches to attribution of the 2010 Russian heatwave. *Geooph. Res. Lett.* **39**, 1-5 (2012).
11 Stott, P. A., Jones, G. S., Christidis, N., Zwiers, F., Hegerl, G. & Shiogama, H. Single-step attribution of increasing frequencies of very warm regional temperatures to human influence. *Atmospheric Science Letters* **12**, 220-227 (2011).
12 Stott, P. A., Stone, D. A. & Allen, M. R. Human contribution to the European heatwave of 2003. *Nature* **432**, 610-614 (2004).
13 Simpson, M. C., Scott, D., Harrison, M., Silver, N., O'Keefe, E., Harrison, S., Taylor, M., Sim, R., Lizcano, G., Wilson, M., Rutty, M., Stager, H., Oldham, J., New, M., Clarke, J., Day, O. J., Fields, N., Georges, J., Waither, R. & McSharry, P. Quantification and Magnitude of Losses and Damages Resulting from the Impacts of Climate Change: Modelling the Transformational Impacts and Costs of Sa Level Rise in the Caribbean. (United Nations Development Programme (UNDP), Barbados, West Indies, 2010).
14 Pall, P., Aina, T., Stone, D. A., Stott, P. A., Nozawa, T., Hilberts, A. G. J., Lohmann, D. & Allen, M. R. Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature* **470**, 382-386 (2011).
15 Dai, A. Increasing drought under global warming in observations and models. *Nature Climate Change*, Published online 05 August (2012).
16 Li, Y., Ye, W., Wang, W. & Yan, X. Climate change and drought: a risk assessment of crop-yield impacts. *Clim. Res.* **39**, 31-46 (2009).
17 Trigo, R. M., Gouveia, C. M. & Barriopedro, D. The intense 2007–2009 drought in the Fertile Crescent: Impacts and associated atmospheric circulation. *Agricultural and Forest Meteorology* **150**, 1245-1257 (2010).
18 Lobell, D. B., Schlenker, W. & Costa-Roberts, J. Climate trends and global crop production since 1980. *Science* **333**, 616-620 (2011).
19 Lobell, D. B., Sibley, A. S. & Ortiz-Monasterio, J. I. Extreme heat effects on wheat senescence in India. *Nature Climate Change* **2**, 186-189 (2012).
20 Barriopedro, D., Fischer, E. M., Luterbacher, J., Trigo, R. M. & García-Herrera, R. The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe. *Science* **332**, 220-224 (2011).
21 NOAA. National Climatic Data Center (NCDC), State of the Climate: Global Hazards for August 2011. http://www.ncdc.noaa.gov/sotc/hazards/2011/8 (2011c).
22 World-Bank. Severe Droughts Drive Food Prices Higher, Threatening the Poor. *World Bank - Press release* (2012).
23 Wright, B. International Grain Reserves And Other Instruments to Address Volatility in Grain Markets. (World Bank, New York, USA, 2009).
24 Mundi. http://www.indexmundi.com/agriculture/?commodity=wheat&graph=exports.

25 Hoegh-Guldberg, O. & Smith, G. J. The effect of sudden changes in temperature, light and salinity on the population density and export of zooxanthellae from the reef corals Stylophora pistillata Esper and Seriatopora hystrix Dana. *J. Exp. Mar. Biol. Ecol.* **129**, 279-303 (1989).

26 Eakin, C. M. & etal. Caribbean Corals in Crisis: Record Thermal Stress, Bleaching, and Mortality in 2005. *Plos ONE* **5**, 1-9 (2010).

27 Frieler, K., Meinshausen, M., Golly, A., Mengel, M., Lebek, K., Donner, S. D. & Hoegh-Guldberg, O. Limiting global warming to 2°C is unlikely to save most coral reefs. *Nature Climate Change* advance online publication 16 September 2012, doi:http://www.nature.com/nclimate/journal/vaop/ncurrent/abs/nclimate1674.html - supplementary-information (2012).

28 Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D., Hogg, E. H., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S. W., Semerci, A. & Cobb, N. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* **259**, 660-684 (2010).

29 Lewis, S. L., Brando, P. M., Phillips, O. L., Heijden, G. M. F. v. d. & Nepstad, D. The 2010 Amazon Drought. *Science* **331**, 554 (2011).

30 Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J. & Hanson, C. E. *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, 2007).

31 Scheff, J. & Frierson, D. Twenty-first-century multimodel Subtropical precipitation declines are mostly Midlatitude shifts. *Journal of Climate* **25**, 4330-4347 (2012).

32 Climate Adaptation working group. Shaping climate-resilient development. A framework for decision-making 164 (2009).

33 Schaeffer, M., Hare, W., Rahmstorf, S. & Vermeer, M. Long-term sea-level rise implied by 1.5°C and 2°C warming levels. *Nature Climate Change* Published online 24 June 2012 (2012).

34 Mirza, M. Climate change, flooding in South Asia and implications. *Regional Environmental Change* **11**, 95-107, doi:10.1007/s10113-010-0184-7 (2011).

35 Nicholls, R. J., Hoozemans, F. M. J. & Marchand, M. Increasing flood risk and wetland losses due to global sea-level rise : regional and global analyses. *Global Environmental Change* **9**, S69–S87 (1999).

36 Diffenbaugh, N. & Giorgi, F. Climate change hotspots in the CMIP5 global climate model ensemble. *Clim. Change* **114**, 813-822 (2012).

37 Fung, F., Lopez, A. & New, M. Water availability in +2°C and +4°C worlds. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences* **369**, 99-116 (2011).

38 Dai, A. Increasing drought under global warming in observations and models. *Nature Clim. Change* Published online 05 August 2012, doi:http://www.nature.com/nclimate/journal/vaop/ncurrent/abs/nclimate1633.html - supplementary-information" (2012).

39 Schlenker, W. & Lobell, D. B. Robust negative impacts of climate change on African agriculture. *Environmental Research Letters* **5**, 014010 (2010).

40 Rötter, R. P., Carter, T. R., Olesen, J. E. & Porter, J. R. Crop–climate models need an overhaul. *Nature Climate Change* **1**, 175-177 (2011).

41 Zelazowski, P., Malhi, Y., Huntingford, C., Sitch, S. & Fisher, J. B. Changes in the potential distribution of humid tropical forests on a warmer planet. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences* **369**, 137-160 (2011).

42 Robinson, A., Calov, R. & Ganopolski, A. Multistability and critical thresholds of the Greenland ice sheet. *Nature Climate Change* **2**, 429-432, doi:http://www.nature.com/nclimate/journal/v2/n6/abs/nclimate1449.html - supplementary-information" (2012).

43 Coumou, D. & Robinson, A. Increase of extreme heat waves in a two- to four-degrees warmer world. (in prep.).

44 Schellnhuber, H. J., Coumou, D., Martin, M. A., Perrette, M. & Robinson, A. Preparing for a 4°C World – Analysis of Regional Sea-Level Rise and Extreme Heat Waves. (World Bank New York, 2012).

45 Arnell, N. W., van Vuuren, D. P. & Isaac, M. The implications of climate policy for the impacts of climate change on global water resources. *Global Environmental Change* **21**, 592-603 (2011).

46 Boko, M., Niang, I., Nyong, A., Vogel, C., Githeko, A., Medany, M., Osman-Elasha, B., Tabo, R. & Yanda, P. in *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, & C.E. Hanson) 433-467 (Cambridge, UK, 2007).

47 Gerten, D., Heinke, J., Hoff, H., Biemans, H., Fader, M. & Waha, K. Global Water Availability and Requirements for Future Food Production. *Journal of Hydrometeorology* **12**, 885-899 (2011).

48 Thornton, P. K., Jones, P. G., Ericksen, P. J. & Challinor, A. J. Agriculture and food systems in sub-Saharan Africa in a 4C+ world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **369**, 117-136 (2011).

49 Ben Mohamed, A. Climate change risks in Sahelian Africa. *Regional Environmental Change* **11**, 109-117, doi:10.1007/s10113-010-0172-y (2011).

50 Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W. & Courchamp, F. Impacts of climate change on the future of biodiversity. *Ecology letters*, 365-377 (2012).

51 New, M., Liverman, D., Schroeder, H., Schroder, H. & Anderson, K. Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **369**, 6-19 (2011).

52 Silverman, J., Lazar, B., Cao, L., Caldeira, K. & Erez, J. Coral reefs may start dissolving when atmospheric CO_2 doubles. *Geophysical Research Letters* **36**, L05606, doi:10.1029/2008GL036282 (2009).

53 Zelazowski, P., Malhi, Y., Huntingford, C., Sitch, S. & Fisher, J. B. Changes in the potential distribution of humid tropical forests on a warmer planet. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **369**, 137-160, doi:10.1098/rsta.2010.0238 (2011).

54 Midgley, G. & Thuiller, W. Potential responses of terrestrial biodiversity in Southern Africa to anthropogenic climate change. *Regional Environmental Change* **11**, 127-135, doi:10.1007/s10113-010-0191-8 (2011).

55 Lewis, S. Tropical forests and the changing earth system. *Philos Trans R Soc Lond B Biol Sci.* **361**, 195-210 (2006).

56 Scholze, M., Knorr, W., Arnell, N. W. & Prentice, I. C. A climate-change risk analysis for world ecosystems. *Proc. Nat. Ac. Sc.* **103**, 13116-13120 (2006).

57 Barnosky, A. D. & al.:, e. Approaching a state shift in Earth's biosphere. *Nature* **486**, 52-58 (2012).

58 Reich, P. B., Tilman, D., Isbell, F., Mueller, K., Hobbie, S., Flynn, D. F. B. & Eisenhauer, N. Impacts of Biodiversity Loss Escalate Through Time as Redundancy Fades. *Science* **336**, 589-592 (2012).

59 Urban, M. C., Tewksbury, J. J. & Sheldon, K. S. On a collision course: competition and dispersal differences create no-analogue communities and cause extinctions during climate change. *Proc. R. Soc. B*, 1471-2954 (2012).

60 Schaeffer, M. & van Vuuren, D. Evaluation of IEA ETP 2012 emission scenarios. (Climate Analytics, Berlin, Germany, 2012).

61 Ridgwell, A. & Schmidt, D. N. Past constraints on the vulnerability of marine calcifiers to massive carbon dioxide release. *Nature Geoscience* **3**, 196\-200, doi: http://www.nature.com/ngeo/journal/v3/n3/suppinfo/ngeo755_S1.html (2010).

62 Thomas, E. in *Large Scale Ecosystem Perturbation: Causes and Consequences: Geological Society of America Special Paper 424* (eds S. Monechi, R. Coccioni, & M.R. Rampino) 1-23 (Geological Society of America, 2007).

63 Nicholls, R., Marinova, N., Lowe, J., Brown, S., Vellinga, P., de Gusmão, D., Hinkel, J. & Tol, R. Sea-level rise and its possible impacts given a 'beyond 4°C world' in the twenty-first century. *Philos Transact A Math Phys Eng Sci.* **369**, 161-181 (2011).

64 Brecht, H., Dasgupta, S., Laplante, B., Murray, S. & Wheeler, D. The Journal of Environment & Development. *Sea-Level Rise and Storm Surges : High Stakes for a Small Number of Developing Countries* **21**, 120-138 (2012).

65 Hinkel, J., Brown, S., Exner, L., Nicholls, R., Vafeidis, A. & Kebede, A. Sea-level rise impacts on Africa and the effects of mitigation and adaptation: an application of DIVA. *Regional Environmental Change* **12**, 207-224 (2011).

66 Bender, M. A., Knutson, T. R., Tuleya, R. E., Sirutis, J. J., Vecchi, G. A., Garner, S. T. & Held, I. M. Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes. *Science* **327**, 454-458, doi:10.1126/science.1180568 (2010).

67 Peduzzi, P., Chatenoux, B., Dao, H., De Bono, A., Herold, C., Kossin, J., Mouton, F. & Nordbeck, O. Global trends in tropical cyclone risk. *Nature Clim. Change* **2**, 289-294, doi:http://www.nature.com/nclimate/journal/v2/n4/abs/nclimate1410.html - supplementary-information" (2012).

68 Hof, A., den Elzen, M. & van Vuuren, D. Including adaptation costs and climate change damages in evaluating post-2012 burden-sharing regimes. *Mitigation and Adaptation Strategies for Global Change* **15**, 19-40, doi:10.1007/s11027-009-9201-x (2010).

69 Peterson, T. C., Stott, P. A. & Herring, S. Explaining Extreme Events of 2011 from a Climate Perspective. *BAMS*, 1041-1067 (2012).

70 Rahmstorf, S. & Coumou, D. Increase of extreme events in a warming world. *Proceedings of the National Academy of Science of the USA* **108**, 17905-17909 (2011).

71 Benestad, R. E. Record-values, nonstationarity tests and extreme value distributions. *Global and Planetary Change* **44**, 11-26, doi:10.1016/j.gloplacha.2004.06.002 (2004).

72 Benestad, R., Nychka, D. & Mearns, L. O. Spatially and temporally consistent prediction of heavy precipitation from mean values. *Nature Climate Change*, 544-547 (2012).

73 Hansen, J., Sato, M. & Ruedy, R. Perception of climate change. *Proc. Nat. Ac. Sc.* (2012).

74 Coumou, D., Robinson, A. & Rahmstorf, S. Global increase in record-breaking monthly-mean temperatures. (in review).

75 Alexander, L. V. & Jones, P. D. Updated Precipitation Series for the U.K. and Discussion of Recent Extremes. *Atmospheric Science Letters* **1** (2001).

76 Min, S. K., Zhang, X., Zwiers, F. W. & Hegerl, G. C. Human contribution to more-intense precipitation extremes. *Nature* **470**, 378-381 (2011).

77 Kay, A. L., Crooks, S. M., Pall, P. & Stone, D. A. Attribution of Autumn/Winter 2000 flood risk in England to anthropogenic climate change: A catchment-based study. *Journal of Hydrology* **406**, 97-112 (2011).

78 Luterbacher, J. & et al. European seasonal and annual temperature variability, trends and extremes since 1500. *Science* **303**, 1499-1503 (2004).

79 Della-Marta, P. M., Haylock, M. R., Luterbacher, J. & Wanner, H. Doubled length of western European summer heat waves since 1880. *Journal of Geophysical Research* **112**, 1-11 (2007).

80 Robine, J. M., Cheung, S. L. K., Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J. P. & Herrmann, F. R. Death toll exceeded 70,000 in Europe during the summer of 2003. *Comptes Rendus Biologies* **331**, 171-U175, doi:10.1016/j.crvi.2007.12.001 (2008).

81 World Meteorological Organisation. State of the Climate in 2007. Report No. WMO-No 1036, 193 (WMO, Geneva, 2009).

82 Founda, D. & Giannakopoulos, C. The exceptionally hot summer of 2007 in Athens, Greece — A typical summer in the future climate? *Global and Planetary Change* **67**, 227-236 (2009).

83 Kuglitsch, F. G., Toreti, A., Xoplaki, E., Della-Marta, P. M., Zerefos, C. S., Turkes, M. & Luterbacher, J. Heat wave changes in the eastern Mediterranean since 1960. *Geophysical Research Letters* **37**, doi:L04802 10.1029/2009gl041841 (2010).

84 Jones, G. S., Stott, P. A. & Christidis, N. Human contribution to rapidly increasing frequency of very warm Northern Hemisphere summers. *Journal of Geophysical Research* **113**, 1-17 (2008).

85 Dai, A. Characteristics and trends in various forms of the Palmer Drought Severity Index during 1900–2008. *J. Geoph. Res.* **116**, doi:10.1029/2010JD015541 (2011).

86 Trigoa, R. M., Gouveiaa, C. M. & Barriopedroa, D. The intense 2007–2009 drought in the Fertile Crescent: Impacts and associated atmospheric circulation. *Agricultural and Forest Meteorology* **150**, 1245-1257 (2010).

87 Karoly, D. The recent bushfires and extreme heat wave in southeast Australia. *Bulletin of the Australian Meteorological and Oceanographic Society* **22**, 10-13 (2009).
88 Dole, R., Hoerling, M., Perlwitz, J., Eischeid, J., Pegion, P., Zhang, T., Quan, X., Xu, T. & Murray, D. Was there a basis for anticipating the 2010 Russian heat wave? *Geophys. Res. Lett.* **38**, L06702, doi:doi:10.1029/2010GL046582 (2011).
89 Webster, P. J., Toma, V. E. & Kim, H. M. Were the 2010 Pakistan floods predictable? *Geophys. Res. Lett.* **38** (2011).
90 Trenberth, K. & Fassullo, J. Climate extremes and climate change: The Russian Heat Wave and other Climate Extremes of 2010. *J. Geoph. Res.*, doi: 2012JD018020 (2012).
91 Lau, W. & Kim, K. M. The 2010 Pakistan Flood and Russian Heat Wave: Teleconnection of Hydrometeorological Extremes. *J. Hydrometeorology* **13**, 392-403 (2012).
92 Hong, C., Hsu, H., Lin, N. & Chiu, H. Roles of European blocking and tropical-extratropical interaction in the 2010 Pakistan flooding. *Geophys. Res. Let.* **38**, 6 (2011).
93 Australian Bureau of Meteorology. *Australian climate variability & change - Time series graphs*, <http://www.bom.gov.au/cgi-bin/climate/change/timeseries.cgi> (2011).
94 Honert, R. C. v. d. & McAneney, J. The 2011 Brisbane Floods: Causes, Impacts and Implications. *Water* **3**, 1149-1173 (2011).
95 NOAA. National Climatic Data Center (NCDC), State of the Climate: Global Hazards for December 2010. http://www.ncdc.noaa.gov/sotc/hazards/2010/12. (2011).
96 WMO. Provisional Statement on the Status of the Global Climate. http://www.wmo.int/pages/mediacentre/press_releases/gcs_2011_en.html (2011).
97 Cattiaux, J. Contribution of atmospheric circulation to remarkable European temperatures of 2011. *BAMS*, 1054-1057 (2012).
98 NOAA. National Climatic Data Center (NCDC), State of the Climate: National Overview for August 2011. http://www.ncdc.noaa.gov/sotc/national/2011/8 (2011b).
99 Rupp, D. E., Mote, P. W., Massey, N., Rye, C. J. & Allen, M. Did Human influence on climate make the 2011 Texas drought more probable? *BAMS*, 1053-1057 (2012).
100 Duffy, P. B. & Tebaldi, C. Increasing prevalence of extreme summer temperatures in the U.S. *Climatic Change* (2012).
101 NOAA. National Climatic Data Center (NCDC), State of the Climate: Global Hazards for July 2012. http://www.ncdc.noaa.gov/sotc/national/2012/7 (2012).
102 Hegerl, G., Luterbacher, J., Gonzalez-Rouco, F., Tett, S. F. B., Crowley, T. & Xoplaki, E. Influence of human and natural forcing on European seasonal temperatures. *Nature Geoscience*, published online, 16 January (2011).
103 Betts, R. A., Collins, M., Hemming, D. L., Chris D. Jones, Lowe, J. A. & Sanderson, M. G. When could global warming reach 4°C? *Phil. Trans. R. Soc. A.* **369**, 67-84 (2011).
104 Diffenbaugh, N. S. & Scherer, M. Observational and model evidence of global emergence of permanent, unprecedented heat in the 20th and 21st centuries. *Climatic Change*, DOI 10.1007/s10584-10011-10112-y (2011).
105 Anderson, B. T. Near-term increase in frequency of seasonal temperature extremes prior to the 2 degree global warming target. *Climatic Change* **108**, 581-589 (2011).
106 Trenberth, K. E. Changes in precipitation with climate change. *Climate Research* **47**, 123-138 (2010).
107 Durack, P. J., Wijffels, S. E. & Matear, R. J. Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. *Science* **336**, 455-458 (2012).
108 Booth, B. B. B., Dunstone, N. J., Halloran, P. R., Andrews, T. & Bellouin, N. Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature* **484**, 228\-232\, doi:http://www.nature.com/nature/journal/v484/n7393/abs/nature10946.html - supplementary-information" (2012).
109 Sun, F., Roderick, M. L. & Farquhar, G. D. Changes in the variability of global land precipitation. *Geophys. Res. Lett.* **39**, L19402, doi:10.1029/2012gl053369 (2012).
110 Dai, A. Drought under global warming: A review. *WIRE* **2**, 45-65 (2010).

111 Funk, C. Exceptional warming in the western Pacific-Indian ocean warm pool has contributed to more frequent droughts in Eastern Africa. *BAMS*, 1049-1051 (2012).

112 Glecker, P. J., Santer, B. D., Domigues, C. M., Pierce, D. W., Barnett, T. P., Chruch, J. A., Taylor, K. E., AchutaRao, K. M., Boyer, T. P., Ishii, M. & Caldwell, P. M. Human-induced global ocean warming on multidecadal timescales. *Nature Climate Change* (2012).

113 Allan, R. P. Human influence on rainfall. *Nature* **470**, 344-345 (2011).

114 Chou, C., Chen, C.-A., Tan, P.-H. & Chen, K. T. Mechanisms for Global warming impacts on precipitation frequency and intensity. *Journal of Climate* **25**, 3291-3306 (2012).

115 IPCC. in *The Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & H. L. Miller) (Cambridge Univ. Press, Cambridge UK, 2007).

116 Becker, M., Meyssignac, B., Letetrel, C., Llovel, W., Cazenave, A. & Delcroix, T. Sea level variations at tropical Pacific islands since 1950. *Global and Planetary Change*, 85-95 (2012).

117 Bjørk, A., Kjær, K. H., Korsgaard, N. J., Khan, S., Kjeldsen, K. K., Andresen, C. S., Box, J. E., Larsen, N. K. & Funder, S. An aerial view of 80 years of climate-related glacier fluctuations in southeast Greenland. *Nature Geoscience* **5**, 427-432 (2012).

118 Howat, I. M. & Eddy, A. Multi-decadal retreat of Greenland ' s marine-terminating glaciers. *Journal of Glaciology* **57**, 389-396 (2012).

119 Rahmstorf, S. A semi-empirical approach to projecting future sea-level rise. *Science* **315**, 368-370 (2007).

120 Schaeffer, M., Hare, W., Rahmstorf, S. & Vermeer4, M. Long-term sea-level rise implied by 1:5C and 2C warming levels. *Nature Climate Change* (2012).

121 Rahmstorf, S. A new view on sea level rise. *Nature Reports Climate Change* **4**, 44-45 (2010).

122 Perrette, M., Landerer, F., Riva, R., Frieler, K. & Meinshausen, M. Probabilistic projection of sea-level change along the world's coastlines. *Earth System Dynamics Discussions* **3**, 357-389 (2012).

123 Hare, W., Serdeczny, O. & Schellnhuber, H. J. Preparing for a 4 degree World - Sectoral Impact. (Worldbank, New York, 2012).

124 Robinson, A., Calov, R. & Ganopolski, A. Multistability and critical thresholds of the Greenland ice sheet. *Nature Climate Change* **2**, 1-4 (2012).

125 Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M., Noda, A., Raper, S. C. B., Watterson, I. G., Weaver, A. J. & Zhao, Z.-C. in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller) (Cambridge University Press, 2007).

126 Tanzil, J., Brown, B., Tudhope, A. & Dunne, R. Decline in skeletal growth of the coral Porites lutea from the Andaman Sea, South Thailand between 1984 and 2005. *Coral Reefs* **28**, 519-528 (2009).

127 De'ath, G., Lough, J. M. & Fabricius, K. E. Declining Coral Calcification on the Great Barrier Reef. *Science* **323**, 116-119, doi:10.1126/science.1165283 (2009).

128 Cooper, T. F., De'Ath, G., Fabricius, K. E. & Lough, J. M. Declining coral calcification in massive Porites in two nearshore regions of the northern Great Barrier Reef. *Global Change Biology* **14**, 529-538, doi:10.1111/j.1365-2486.2007.01520.x (2008).

129 Fischlin, A., Midgley, G. F., Price, J. T., Leemans, R., Gopal, B., Turley, C., Rounsevell, M. D. A., Dube, O. P., Tarazona, J. & Velichko, A. A. in *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds O.F. Canziani M.L. Parry, J.P. Palutikof, & P.J. van der Linden and C.E. Hanson) 211-272 (Cambridge University Press, 2007).

130 Zeebe, R. E. History of Seawater Carbonate Chemistry, Atmospheric CO2, and Ocean Acidification. *Ann. Rev Earth Plan Sc.* **40**, 141-165 (2012).

131 Cao, L. & Caldeira, K. Atmospheric CO_2 stabilization and ocean acidification. *Geophysical Research Letters* **35**, L19609 (2008).

132 Veron, J. E. N., Hoegh-Guldberg, O., Lenton, T. M., Lough, J. M., Obura, D. O., Pearce-Kelly, P., Sheppard, C. R. C., Spalding, M., Stafford-Smith, M. G. & Rogers, A. D. The coral reef crisis: The critical importance of <350 ppm CO2. *Marine Pollution Bulletin* **58**, 1428-1436 (2009).

133 Hare, W., Cramer, W., Schaeffer, M., Battaglini, A. & Jaeger, C. Climate hotspots: key vulnerable regions, climate change and limits to warming. *Regional Environmental Change* **11**, 1-13, doi:10.1007/s10113-010-0195-4 (2011).

134 Becker, M., Meyssignac, B., Letetrel, C., Llovel, W., Cazenave, A. & Delcroix, T. Sea level variations at tropical Pacific islands since 1950. *Global and Planetary Change* **80, 81**, 85-98, doi:10.1016/j.gloplacha.2011.09.004 (2012).

The Loss and Damage in Vulnerable Countries Initiative

Accepting the reality of unmitigated climate change, the UNFCCC negotiations have raised the profile of the issue of loss & damage to adverse climate impacts. At COP-16, Parties created a Work Programme on Loss and Damage under the Subsidiary Body on Implementation (SBI). The goal of this work programme is to increase awareness among delegates, assess the exposure of countries to loss and damage, explore a range of activities that may be appropriate to address loss and damage in vulnerable countries, and identify ways that the UNFCCC process might play in helping countries avoid and reduce loss and damage associated with climate change. COP-18, in December 2012, will mark the next milestone in furthering the international response to this issue.

The "Loss and Damage in Vulnerable Countries Initiative" supports the Government of Bangladesh and the Least Developed Countries to call for action of the international community.

The Initiative is supplied by a consortium of organisations including:

Germanwatch

Munich Climate Insurance Initiative

United Nations University – Institute for Human and Environment Security

International Centre for Climate Change and Development

Kindly supported by the Climate and Development Knowledge Network (CDKN)

For further information: **www.loss-and-damage.net**

Germanwatch

Following the motto "Observing, Analysing, Acting", Germanwatch has been actively promoting North-South equity and the preservation of livelihoods since 1991. In doing so, we focus on the politics and economics of the North with their worldwide consequences. The situation of marginalised people in the South is the starting point of our work. Together with our members and supporters as well as with other actors in civil society we intend to represent a strong lobby for sustainable development. We endeavour to approach our aims by advocating fair trade relations, responsible financial markets, compliance with human rights, and the prevention of dangerous climate change.

Germanwatch is funded by membership fees, donations, grants from the "Stiftung Zukunftsfähigkeit" (Foundation for Sustainability), and by grants from a number of other public and private donors.

You can also help to achieve the goals of Germanwatch and become a member or support our work with your donation:

Bank fuer Sozialwirtschaft AG
BIC/Swift: BFSWDE33BER
IBAN: DE33 1002 0500 0003 212300

For further information, please contact one of our offices:

Germanwatch – Berlin Office
Schiffbauerdamm 15, 10117 Berlin, Germany
Ph.: +49 (0) 30 - 28 88 356-0, Fax: -1
E-mail: info@germanwatch.org

Germanwatch – Bonn Office
Kaiserstraße 201, 53113 Bonn, Germany
Ph.: +49 (0) 228 - 60492-0, Fax: -19
E-mail: info@germanwatch.org

For further information: **www.germanwatch.org**