

The impacts of climate change on the risk of natural disasters

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Human emissions of greenhouse gases are already changing our climate. This paper provides an overview of the relation between climate change and weather extremes, and examines three specific cases where recent acute events have stimulated debate on the potential role of climate change: the European heatwave of 2003; the risk of inland flooding, such as recently in Central Europe and Great Britain; and the harsh Atlantic hurricane seasons of 2004 and 2005. Furthermore, it briefly assesses the relation between climate change and El Niño, and the potential of abrupt climate change. Several trends in weather extremes are sufficiently clear to inform risk reduction efforts. In many instances, however, the potential increases in extreme events due to climate change come on top of alarming rises in vulnerability. Hence, the additional risks due to climate change should not be analysed or treated in isolation, but instead integrated into broader efforts to reduce the risk of natural disasters.

Keywords: climate change, climate variability, disaster, floods, heatwaves, natural hazards, risk, tropical cyclones

1. Introduction

Over the past two decades, evidence has mounted that the global climate is changing, and that anthropogenic greenhouse gas emissions are largely to blame. While changes in average conditions can have serious consequences by themselves, the main impacts of global climate change will be felt due to changes in climate variability and weather extremes. This paper provides an overview of current knowledge of climate change and its effects on climate variability and extreme weather that could lead to natural disasters, paying particular attention to the potential to apply the information to disaster risk reduction.

Rather than reviewing the entire scientific literature on climate change, climate variability and extreme events, much of the science presented in this paper is drawn from the most recent assessment of the Intergovernmental Panel on Climate Change (IPCC). The World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established this panel in 1988, to respond to policymakers' requests for an objective assessment of the best scientific, technical and socio-economic information on climate change, primarily in peer-reviewed scientific literature. That vast knowledge base is summarised by hundreds of top experts from all regions of the world in a way that offers a balanced synopsis of the main viewpoints, and that is policy-relevant, but not policy-prescriptive. Governments review these scientific assessments, and, along with the lead authors, approve the 'summaries for policymakers' line by line. As such, the reports provide the most comprehensive overview of the scientific

consensus and analysis of uncertainties available. They are widely used as a basis for climate change debates, including in the context of the 1992 United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol. Unless other references are provided, all numbers on observations and projections of climate change are based on IPCC, 2001a, while further details can be found in the full reports of the IPCC's *Third Assessment Report* (IPCC, 2001b; 2001c; 2001d; 2001e), released in 2001. The *Fourth Assessment Report* will be completed in 2007, and is expected to include more information on extreme weather events, as well as on adaptation to climate change.

Section 2 describes the general state of climate change science: how much climate change has been observed; to what extent can we attribute it to human greenhouse gas emissions; and what are the main projections for the future, particularly in terms of global temperature, sea-level rise and regional patterns of changes in temperature and precipitation. Section 3 contains a discussion of the relationship between observed and projected climate change and the risk of extreme weather events.

Sections 4, 5 and 6 look at three specific examples of extreme weather events that have attracted significant attention in recent years, and have raised the question of a potential link to climate change: the 2003 heatwave in Europe; the increasing risk of inland flooding, such as in recent years in Central Europe and Great Britain; and tropical cyclones, particularly the 2004 and 2005 harsh Atlantic hurricane seasons.

Section 7 analyses the potential effect of global climate change on interannual variability in the climate system, such as El Niño (which strongly influences disaster risk). Section 8 considers the risk that global warming could trigger abrupt climate changes, such as a shutdown of the oceans' thermohaline circulation (THC) or the disintegration of the West Antarctic ice sheet.

Section 9 briefly evaluates some of the implications of scientific knowledge on climate change for disaster risk reduction efforts. Section 10 offers some conclusions.

2. Global climate change

Anthropogenic climate change, or 'global warming', is caused by increasing concentrations of greenhouse gases. These gases trap the heat in our atmosphere by preventing radiation from escaping into space. The main greenhouse gas, carbon dioxide (CO₂), is emitted when fossil fuels, like coal and oil, are burned. Since the industrial revolution, fossil fuel use has increased very quickly. Due to these emissions, as well as changes in agriculture and land use, atmospheric greenhouse gas concentrations have risen sharply. For instance, the concentration of CO₂ in the atmosphere has increased by around one-third, from 280 parts per million (ppm) in 1750 to 368 ppm in 2000. This is the highest level in at least the past 420,000 years and likely the past 20 million years (IPCC, 2001c, p. 39).

The atmosphere responds to the rising greenhouse gas concentrations with a higher average temperature. Indeed, global mean surface temperatures have risen by approximately 0.6 degrees over the past century, with land areas warming faster than the oceans. The rise in Northern Hemisphere surface warming is greater than during any other

century in the past thousand years. Globally, the 1990s were likely the warmest decade of the past millennium (IPCC, 2001a), and nine out of the 10 warmest years on record occurred between 1995 and 2004 (with 1998, 2002, 2003 and 2004 being the warmest) (WMO, 2004). These changes in temperatures have had a range of secondary effects on hydrological systems and terrestrial and marine ecosystems. Examples include an increase in the global mean sea level (one to two millimetres per year over the course of the twentieth century), widespread retreat of glaciers, a decrease in snow cover, thawing of permafrost, shifts of plant and animal ranges (poleward, and upward in elevation), earlier flowering of plants, bird breeding seasons and emergence of insects, and increased frequency of coral bleaching events, particularly during El Niño episodes.

There is strong evidence that this observed warming can be attributed to human greenhouse gas emissions. The current scientific consensus is that 'most of the warming over the last 50 years is attributable to human activities' (IPCC 2001a, p. 5). Given that human emissions to date have already initiated such global climate change, and most greenhouse gases stay in the atmosphere for at least several decades, that climate change is bound to continue. Moreover, human emissions are still increasing, and are unlikely to stabilise anytime soon. Hence, the global warming observed over the past century is projected to accelerate over coming decades. Depending on the presumptions regarding future emissions, and taking account of different outcomes among a range of state-of-the-art climate models, the expected range in global temperature rise is 1.4–5.8 degrees Celsius until 2100, which is roughly between two and 10 times the rate of change observed over the past century. Such temperature rise could result in a global mean sea-level rise of between four and 88 centimetres. Even in the most optimistic emission scenarios, which could only be achieved by a massive transition to alternative energy sources, climate change will continue for several decades and even centuries, both because of greenhouse gases that have already been emitted into the atmosphere, and because of the delayed response of the oceans to the warming of the atmosphere. While the general direction of change is one of a warming atmosphere, there have been and will be significant differences between various regions on earth. Most generally, polar regions warm faster than tropical areas, and land areas warm faster than oceans. With respect to precipitation, the general projection is that the hydrological cycle will become more intensive. This results, on average, in a wetter climate. Once again, though, there are substantial differences between regions. (For further information on regional impacts of climate change, see the IPCC *Third Assessment Report* (IPCC, 2001b; 2001c; 2001d).)

As with all weather phenomena, the impacts of these changes will depend on the systems in which they occur. For instance, in some areas, global warming will initially boost agricultural productivity. In many areas, it will also reduce demand for energy for heating in winter. However, as climate change progresses, the balance of the impacts will become more and more negative, and there will be more and more irreversible impacts, such as loss of ecosystems. For human systems, much will depend on our ability to adapt to the changes. Changes in crops, infrastructure designs and many other aspects of society can greatly increase resilience to adverse weather, as well as increase the benefits of climate change. Yet capacity to adapt to climate change is much greater in

developed than in developing countries, due to differences in expertise, technology, institutional capacity and wealth. Ironically, the regions that have contributed least to rising greenhouse gases will suffer the greatest consequences.

3. Projections of extremes

The previous section outlined the general characteristics and projections of global climate change. This section examines what those broad changes mean for extreme weather events.

Some changes in extreme weather have already been observed. The general increase in temperature has resulted in a rise in the number of hot days, and a decrease in the number of cold/frost days, for nearly all land areas. At mid and high northern latitudes, the observations also point up an increase in heavy precipitation events. In some regions, such as parts of Africa and Asia, the frequency and intensity of droughts have increased over the past few decades. These changes are consistent with a general intensification of the hydrological cycle.

Projections for the coming century show that the number of hot and very hot days will continue to rise, and that the number of cold and very cold days will continue to decrease over nearly all land areas. Additionally, the intensity and frequency of extreme precipitation events are very likely to increase over many areas, and the return period of extreme rainfall events is projected to decline, resulting in more numerous floods and landslides. Mid-continental areas will generally become dryer, which is likely to increase the risk of summer droughts and wild fires. Table 1 provides an overview of such impacts.

While changes in temperature extremes are generally quite certain, and in many areas, changes in heavy precipitation or the occurrence of droughts can also be projected with reasonable confidence, projections for relatively small-scale atmospheric phenomena, such as storms, are subject to greater uncertainty (see also Section 6). There are no reliable projections for phenomena at even smaller scales, including thunderstorms, tornadoes, hailstorms and lightning.

In all cases, questions remain as to what the projections mean with regard to local scale. Climate models generally calculate the weather and the climate on grids of a few degrees latitude and longitude, or a couple of hundreds of kilometres across. While they perform relatively well in terms of modelling large patterns in the atmosphere, and incorporate all large-scale features of the earth's surface, like mountain ranges, they do not represent smaller-scale phenomena, such as differences in climate between two sides of a mountain. As a consequence, the general patterns obtained from climate models always have to be interpreted in the context of the local geography and meteorology.

Furthermore, all applications have to take account of uncertainties in the information. Some of those are related to uncertainties in the climate models and future emissions, others to downscaling to the local scale, and still others to the lack of consistent data to verify the model at that local scale (this issue is particularly pressing in developing countries, where meteorological data collection has weakened in recent years). In the

Table 1 Examples of projected changes in extreme climate phenomena, with examples of projected impacts

Projected changes during the twenty-first century in extreme climate phenomena and their likelihood	Representative examples of projected impacts (all high confidence of occurrence in some areas)
Higher maximum temperatures; more hot days and heatwaves over nearly all land areas (very likely)	<ul style="list-style-type: none"> • Increased incidence of death and serious illness in older age groups and urban poor • Increased heat stress in livestock and wildlife • Shift in tourist destinations • Increased risk of damage to a number of crops • Increased electric cooling demand and reduced energy supply reliability
Higher (increasing) minimum temperatures; fewer cold days, frost days and cold waves across nearly all land areas (very likely)	<ul style="list-style-type: none"> • Decreased cold-related human morbidity and mortality • Decreased risk of damage to a number of crops, and increased risk to others • Extended range and activity of some pest and disease vectors • Reduced demand for heating energy
More intense precipitation events (very likely in many areas)	<ul style="list-style-type: none"> • Increased flood, landslide, avalanche and mudslide damage • Increased soil erosion • Increased flood runoff could increase recharge of some floodplain aquifers • Increased pressure on government and private flood insurance systems and disaster relief
Increased summer drying over most mid-latitude continental interiors and associated risk of drought (likely)	<ul style="list-style-type: none"> • Decreased crop yields • Increased damage to building foundations caused by ground shrinkage • Decreased water resource quantity and quality • Increased risk of forest fire
Increase in tropical cyclone peak wind intensities, and mean and peak precipitation intensities (likely over some areas)	<ul style="list-style-type: none"> • Increased risks to human life, risk of infectious disease epidemics and many other risks • Increased coastal erosion and damage to coastal buildings and infrastructure • Increased damage to coastal ecosystems, such as coral reefs and mangroves
Intensified droughts and floods associated with El Niño events in many different regions (likely) (see also under droughts and intense precipitation events)	<ul style="list-style-type: none"> • Decreased agricultural and rangeland productivity in drought- and flood-prone regions • Decreased hydro-power potential in drought-prone regions
Increased Asian summer monsoon precipitation variability (likely)	<ul style="list-style-type: none"> • Increase in flood and drought magnitude and damages in temperate and tropical Asia
Increased intensity of mid-latitude storms (little agreement between current models)	<ul style="list-style-type: none"> • Increased risks to human life and health • Increased property and infrastructure losses • Increased damage to coastal ecosystems

Note: Table based on IPCC 2001a, Table SPM-1. The descriptions of likelihood refer to the collective confidence of the IPCC authors in the validity of a conclusion based on observational evidence, modelling results and theory: virtually certain (greater than 99% chance); very likely (90–99% chance); likely (66–90% chance); medium likelihood (33–66% chance); unlikely (10–33% chance); very unlikely (1–10% chance); and exceptionally unlikely (0–1% chance) (these likelihood descriptions apply to all results from IPCC Working Group I, in IPCC, 2001a; 2001b; 2001c).

case of extremes, the models only provide estimates of trends in phenomena that are by themselves stochastic in nature. While we can project that a one-in-30-year flood may in future become a one-in-10-year event, it may still take 50 years for the next flood to arrive (making it very difficult to validate model projections with real life observations). In most instances, we do not even know exactly how the distribution of extremes is changing, just the direction of the trend. Nevertheless, beyond the general trends highlighted in Table 1 and our best efforts to supply good local information on possible trends in extremes, there is also a general message: the climate system is changing, so uncertainty about extremes is rising.

The following sections assess three specific recent examples of extreme weather that have been linked to climate change.

4. Heatwaves

The European summer of 2003 was unusually hot. The prolonged and intense heat killed between 22,000 and 35,000 people, particularly elderly individuals, and caused economic losses of over USD 13 billion (IFRC, 2004). The connection to climate change was raised repeatedly. And indeed, while no single event can be directly attributed to climate change, the indirect, probabilistic evidence that was gathered in various subsequent publications is strong. In particular, Stott et al. (2004) showed that just a half a degree increase in the average summer temperature, as over the past century, for example, strongly influences the probability of the occurrence of a dramatic heatwave, such as in 2003. In fact, they estimated that it is very likely (more than 90% confidence level) that human-induced climate change has already at least doubled the risk of a heatwave like that in 2003, and that by the 2040s, every other summer could well be as hot as the one of 2003. According to some emission scenarios, at the end of the twenty-first century a summer like 2003 would be considered a cold one (Stott et al., 2004).

However, heatwaves only become disasters due to societies' inability to respond properly to the meteorological conditions. Consequently, the best way to deal with the increasing risks of heatwaves is to improve preparedness and early warning. Heatwaves can be predicted at least three days in advance, and societies must be ready to read that signal and take action. This requires better interaction between the institutions that produce weather forecasts and those who need to act on them, including joint discussion on when a heatwave warning needs to be issued—based on the effects of the weather rather than meteorological statistics—clear channels of communication, well-designed plans to follow once such a warning is issued, and the availability of human and physical resources to mitigate the heatwave's effects, particularly on the most vulnerable groups in society.

5. Floods

Given the general projections of increasing precipitation and peak precipitation over many areas, several unusual flood events have triggered discussions about a potential

link with climate change. Recent examples in Europe include the record precipitation and consequent flooding in the winter of 2000–01 in England and Wales (Marsh, 2001) and the even larger-scale riverine flood events of the Oder (1997), Elbe (2002) and Rhone (2002). Clearly, the risk of such flood events is influenced not only by the intensity of precipitation in the river basin, but also by the flow regime, which is strongly affected by land use in the watershed area. Moreover, heavy flood events are by definition rare, so that it is difficult to separate ‘freak events’ from real changes in the probability of a particular event. These two factors make it difficult to attribute changes in flood occurrence firmly to global warming.

However, studies using climate models to produce ‘probabilistic’ projections of future precipitation intensity over the area of major river catchments are providing an indication of what to expect. Instead of using one climate model run to provide a projection of average conditions during a particular period, these studies use several runs, or results of several different models, and use the whole set of results to generate statistical probabilities of the occurrence of particular extreme events. Employing such an approach, Palmer and Räisänen (2002) found that the probability of a very wet winter in the UK (more than two standard deviations above the normal, which under the current climate has a probability of around 2.5%, or a 40-year return period) is estimated to increase by a factor of five over the next 50–100 years (to a probability of 12.5%, or an eight-year return period), increasing the risk of events like the 2001–01 floods. In addition, their results showed that the probability of extremely wet Asian monsoon seasons would increase in a similar fashion, with severe implications for flooding in Bangladesh.

Particular problems associated with these studies include the need to produce large numbers of climate simulations to generate the statistics. Given the large computational resources required to run these advanced climate models (long calculations, often lasting several weeks, on the world’s most powerful supercomputers), this problem is not easily overcome. Moreover, the need for a large number of calculations collides with the need to run the climate models at a much higher resolution. The current climate models provide information at a scale of approximately 100 by 100 kilometres at most. This would have to be brought down to about 10 by 10 kilometres to be able to couple it to a local basin hydrological model to calculate specific flood risks. Such a 10-fold increase in resolution not only requires better validation of climate models at the local scale, but would also increase the computation time by at least a factor of 100, making it impossible to generate the number of model simulations required to produce reliable statistics.

Besides, in general, despite some climate research pointing up serious concerns regarding the rising frequency of flood events in particular areas, one should be careful not to attribute all current extreme events to climate change. For instance, in an 80–150-year analysis of observations of flood occurrence in the Oder and Elbe rivers (which generated heavy flooding in 1997 and 2002, respectively), Mudelsee et al. (2003) showed that winter flooding has actually decreased, while summer flooding has remained essentially unchanged. It is interesting to note that the reduction in winter-time flooding can possibly be linked to global warming—warmer and/or more polluted

rivers result in a reduction in strong freezing events, which create water barriers, whose breaking up triggers enhanced flooding.

In conclusion, in many areas, riverine flood risks may well be influenced by climate change, and the general tendency is towards higher flood risk. However, there is no generic answer in relation to the extent or even the direction of the change, other than that there is generally increasing uncertainty. Location-specific flood risk analyses should take account of all risk-related trends, including geographic changes in the catchment area, changes in exposure of assets and population, as well as climate change.

6. Tropical cyclones

Tropical cyclones, typhoons and hurricanes all pertain to the same phenomenon: weather systems with strong winds that circulate around low-pressure areas, with a central 'eye' that has a diameter of typically 20–150 kilometres. Tropical cyclones can form above warm seas with temperatures of at least 26.5° Celsius, and can last for at least two weeks. However, they rapidly lose power when they move inland.

The year 2004 was the most costly hurricane season for the US, with five land-falling hurricanes causing record economic damage of at least USD 42 billion (National Climatic Data Center, 2004). By October, the 2005 hurricane season had already broken that record, mainly due to Hurricane Katrina, which appears to have been the most costly hurricane ever, with damage estimates in excess of USD 100 billion (Graumann et al., 2005). In addition, 2005 witnessed the highest number of hurricanes and named storms in any season, a record number of the most intense ('category 5') hurricanes, and the most intense hurricane ever recorded (Wilma) (National Climatic Data Center, 2005). The harsh 2004 and 2005 hurricane seasons seem to be consistent with a trend: the frequency and particularly the intensity of tropical cyclones in the Atlantic have been on the rise since 1995. Moreover, Emanuel (2005) showed that worldwide, the destructiveness of tropical cyclones has increased over the past 30 years, due to an increase in their average intensity and lifetime, and Webster et al. (2005) showed that the number of very intense category 4 and 5 cyclones has nearly doubled in the period since 1970.

These events and analyses have raised the question whether climate change is affecting the risk of tropical cyclones.

Yet, contrary to heatwaves, which simply represent the tail end of a temperature distribution that shifts towards more frequent high-temperature episodes when the average temperature increases, cyclones are the product of much more complex atmospheric interactions, and the link to global temperature rise is much more subtle. Regarding the frequency and location of tropical cyclones, 'there is no sound theoretical basis for drawing any conclusions about how anthropogenic change affects hurricane numbers or tracks, and thus how many hit land' (Trenberth, 2005). However, Trenberth (2005) also points out that we do know that global warming is already changing environmental conditions in the areas where tropical storms occur, providing more energy to fuel the storms, which can make them more intense (in terms of wind

speed and rainfall). In 2001, the IPCC (2001c) projected that over some areas, there would likely be increases in the tropical cyclone peak wind speed of 5–10%, and in precipitation of 20–30%, over the course of the coming century (faster or slower depending on the rate of global temperature change). In the short term, such changes remain very difficult to detect in the context of high interannual and multi-decadal variability in tropical cyclone occurrence (linked to, for instance, the El Niño/Southern Oscillation (ENSO), the stratospheric quasi-biennial oscillation and multi-decadal oscillations in the North Atlantic). In fact, Emanuel (2005) notes that such variability may well explain a large portion of the increase in the potential destructiveness of cyclones over the past 30 years.

For now, rising vulnerability to tropical cyclones is a concern in itself, and is largely responsible for the large amount of damage caused, for instance, during the 2004 Atlantic hurricane season (see, for example, Pielke et al., 2005). Hence, while climate change may be exacerbating the hazards (particularly in terms of wind speed and precipitation intensity), the key solution to the problem lies in addressing known vulnerabilities to cyclones as they currently occur. On top of that, risk reduction programmes may need to factor in sea-level rise, which results in much higher storm surge damage due to a particular cyclone. Such an effect, which will particularly affect low-lying coasts and islands, can already be factored into coastal zone management and infrastructure planning. Furthermore, cyclone preparedness programmes could utilise seasonal tropical cyclone forecasts, which incorporate at least some of the effects of global climate change (for instance, the possible effect of rising tropical sea surface temperatures), as well the influence of many other variables, including the effects of interannual and interdecadal variability.

7. El Niño and other variability in the climate system

The variability of our climate is not limited to day-to-day changes in the weather. Instead, the climate system contains several types of large-scale variability, which influence average weather patterns in a similar way as the annual seasons (winter, spring, summer and autumn) or monsoon and dry seasons. Rather than occurring annually however, these changes take place every few years, decades or even centuries, across large parts of the globe. Some of these patterns involve only the atmosphere, while others include a coupling to the ocean circulation. Examples include El Niño/La Niña and the Southern Oscillation, Arctic Oscillation, North Atlantic Oscillation, Antarctic Oscillation and the stratospheric Quasi-Biannual Oscillation. If global climate change were to affect these modes of variability, it could have major implications for the occurrence of extreme weather events.

The most well-known examples of interannual variability, possibly impacting the most on the occurrence of natural disasters, are El Niño and its counterpart La Niña, both part of a coupled ocean–atmosphere oscillation called the El Niño/Southern Oscillation. ENSO is a quasi-periodic event that occurs every three to seven years, sometimes stronger, sometimes weaker, as a result of a complex set of interactions

between the atmosphere and the tropical Pacific Ocean. Both phases have a range of typical effects on weather patterns in many areas of the world. For example, El Niño increases the probability of exceptionally heavy rains over the deserts of Peru and droughts across the rainforests of Indonesia. La Niña, meanwhile, may result in unusually heavy rainfall in Australia and parts of Asia, as well as warmer and dryer conditions in large parts of South America. (For a more complete overview of El Niño and La Niña and their impacts, see, for instance, IRI, 2005).

The 1997–98 El Niño was one of the strongest on record, with structural losses of USD 36 billion, 21,000 reported fatalities, and another 130 million people affected (Sponberg, 1999). Partly triggered by that severe 1997–98 El Niño, there has been a lot of debate on the potential impact of global warming on the frequency or intensity of ENSO events. However, despite great improvements in modelling capacity, only a handful of coupled ocean–atmosphere models are able to simulate a realistic contemporary ENSO, hampering our ability to generate reliable projections of what will happen to ENSO during the coming century. The IPCC's *Third Assessment Report* concluded that climate models have various shortcomings in terms of their ability to simulate ENSO, and showed that climate models disagreed about changes in the frequency or the intensity of the ENSO cycle itself. However, the report also noted that global warming might result in more El Niño-like mean conditions in the tropical Pacific (IPCC, 2001c, pp. 567–568). In a more recent study, Van Oldenborgh et al. (2005) analysed results from the main climate models that will be used in the IPCC's *Fourth Assessment Report*. Six of these models were able to represent realistically the current ENSO cycle, and only these six were used to make projections into the future. These models exhibited no change in the average state of the ENSO cycle, or a small shift towards El Niño-like conditions, and showed no significant change in the frequency or intensity of the ENSO cycle itself. This indicates that, based on current climate models, global warming will probably have relatively little influence on the frequency or intensity of El Niño and La Niña episodes.

In recent years, improved computer models, larger supercomputers and better observing systems have dramatically increased the quality of probabilistic seasonal forecasts of the weather patterns that accompany El Niño and La Niña. Regardless of global climate change, these seasonal forecasts may provide a useful piece of climate information that can help to anticipate and mitigate the risk of natural disasters, particularly in regions affected by ENSO.

8. Abrupt climate changes

So far, this paper has discussed changes in extreme events and weather patterns that may accompany a gradual rise in the global average temperatures due to rising greenhouse gas concentrations. However, some elements of the global climate system could also change abruptly, with potentially catastrophic changes occurring over a period of only a few years or decades. Two well-known examples of catastrophic changes are a shutdown of the thermohaline circulation and a disintegration of the West Antarctic ice sheet.

The THC is a global system of water flows through the earth's oceans, which play an important role in global temperature distribution. It is driven by changes in the temperature and salinity (saltiness) of the water. In polar regions, global warming increases sea surface temperatures. At the same time, increased precipitation and the melting of glaciers in those regions also reduce the water's salinity. Both of these processes are expected to weaken the thermohaline circulation. Some models suggest that after 2100, the THC could shut down completely and possibly irreversibly, which would have major consequences for temperatures across Europe, for example.

Concerns have also been raised about the potential disintegration of the West Antarctic ice sheet, with potentially severe ramifications for global sea-level rise. During the coming century, this appears unlikely, and the Antarctic ice sheet as a whole is likely to grow rather than to melt (because of increases in snowfall). Over the next millennium however, melting of the West Antarctic ice sheet could contribute about three metres to global sea-level rise.

Overall, the general scientific consensus is that while the risk of abrupt and catastrophic changes in the climate system is rising, such large changes are still highly unlikely to occur in the coming century. With respect to disaster risk reduction, the possibility of such events can generally be neglected. However, while currently small, the probability of abrupt climate change will increase along with the increasing rate, magnitude and duration of global warming. In that sense, the risk of such abrupt and catastrophic changes is yet another argument to take the risk of global climate change very seriously, particularly from the perspective of the 'precautionary principle' set out in the UNFCCC.

9. Applying information on climate change, climate variability and extreme weather events

This paper is limited to describing some elements of the science on climate change and its relation to climate variability extreme events. It barely touches on the other element of the risk equation: the vulnerability of the systems being affected by climate-related hazards. Other papers in this special issue discuss this topic in-depth. It is important to highlight, though, that climate change is only one factor influencing the risk of natural hazards. Response strategies, therefore, should consider all the options in order to mitigate such risks. In the case of climate change, this includes addressing the root cause of the increasing risk: the emission of greenhouse gases. However, it also includes, prominently, the reduction of vulnerability to current and changing climate variability and weather extremes, based primarily on current experience in disaster risk reduction.

Beyond this expanded mandate, the implication of climate change for disaster risk reduction is simply to take account of the scientific information on climate trends, particularly regarding extremes. This means that organisations working on disaster risk reduction need to establish linkages with institutes that can provide them with that information, such as national meteorological offices or international centres of expertise. These scientific institutes should also reach out to the disaster risk reduction

community, and assist in the optimal application of the climate information they produce. In some instances, the information will indicate that particular hazards might become more frequent or more intense; disaster risk reduction efforts could plan for that. Such linkages may also provide access to the rapidly improving international capacity in seasonal forecasting, which provides increasingly reliable probabilistic forecasts of average temperature and rainfall, as well as risks of extremes, with a lead time of a few months up to a year.

While such information is important, climate change will also create surprises, as part of the generally increased variability. After a severe drought has hit a particular region, and especially if trends also suggest greater drought risk, it makes sense to start reducing vulnerability to droughts, making use of the window of opportunity for risk reduction that opens after a disaster has happened. However, the next disaster might also be an unprecedented flood. Disaster risk reduction efforts should, particularly in their public communications strategies, take account of the possibility of such surprises, and be careful not to see short-term trends in one category of disasters as providing a consistent projection of future climate change.

Finally, while this paper has focused on weather extremes, several gradual trends also have significant impacts on natural disasters. For one, sea-level rise—projected to be between nine and 88 centimetres until 2100—will greatly affect disaster risks in many coastal areas, partly because it will increase the physical risk of a particular amount of flooding, but also because it (and broader climate changes) may reduce the resilience of coastal (eco)systems, such as coral reefs. In other areas of the world, climate changes will exacerbate water shortages and decrease potential crop yields. In such cases, especially when systems are already stretched to their limits of tolerance (due to previous disasters, conflicts, HIV/AIDS or other factors), a relatively mild drought may suddenly have very considerable impacts.

In the end, the key message is that disaster risk reduction must embed the new information on climate change in a much broader analysis, which primarily assesses all key elements in vulnerability to these hazards, as well as response options to address that vulnerability. Climate change is just one new element to be included in that analysis, and does not require doing much different, just doing it better, taking account of the best information available.

10. Conclusions

- The global climate is already changing, and will continue to change over coming decades and centuries. In many places, local trends in average temperature and precipitation due to climate change are already being observed, and fairly reliable projections for the future can improve planning decisions.
- However, climate change is not just about gradual changes. Key impacts of climate change will be due to changes in climate variability and weather extremes, such as those listed in Table 1. Many of these trends in variability and weather extremes are clear enough to warrant attention in regional and local risk reduction strategies.

- To benefit from good information on such local information on climate change, organisations working on disaster risk reduction and development will need to establish linkages with new partners, such as national meteorological offices or global centres of expertise on climate research. In addition, some methods and tools for disaster risk assessment may need to be adjusted to address better hazard trends.
- Yet, while general patterns and trends can be projected with reasonable confidence, some of the information on precise changes in risks, particularly on the local scale and in relation to small-scale atmospheric phenomena, will remain relatively uncertain. Climate change does not just cause changes in known hazard risks, but also raises the level of uncertainty, and will generate surprises.
- Disaster risk reduction and more robust development planning are crucial in adapting to the increasing risks associated with climate change. This is particularly important in the face of mounting vulnerability to natural hazards, as reflected, for instance, in rising numbers of people affected and escalating levels of economic damage. In almost all cases, climate change is just an additional factor to consider, which can be embedded in existing risk reduction strategies.

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