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The missing economic risks in assessments of climate change impacts

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Policy insight

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Summary

- Economic assessments of the potential future risks of climate change have been omitting or grossly underestimating many of the most serious consequences for lives and livelihoods because these risks are difficult to quantify precisely and lie outside of human experience.
- Political and business leaders need to understand the scale of these 'missing risks' because they could have drastic and potentially catastrophic impacts on citizens, communities and companies.
- Scientists are growing in confidence about the evidence for the largest potential impacts of climate change and the rising probability that major thresholds in the Earth's climate system will be breached as global mean surface temperature rises, particularly if warming exceeds 2°C above the pre-industrial level.
  These impacts include:
    - Destabilisation of ice sheets and glaciers and consequent sea level rise
    - Stronger tropical cyclones
    - Extreme heat impacts
    - More frequent and intense floods and droughts
    - Disruptions to oceanic and atmospheric circulation
    - Destruction of biodiversity and collapse of ecosystems
- Many of these impacts will grow and occur concurrently across the world as global temperature climbs.
- Some of these impacts involve thresholds in the climate system beyond which major impacts accelerate, or become irreversible and unstoppable.
- When a threshold is breached, it might cause one or more other thresholds to be exceeded as well, leading to a cascade of impacts.
- Many of these impacts could exceed the capacity of human populations to adapt, and would significantly affect and disrupt the lives and livelihoods of hundreds of millions, if not billions, of people worldwide.
- These impacts would also undermine economic growth and development, exacerbate poverty and destabilise communities.
- Economic assessments fail to take account of the potential for large concurrent impacts across the world that would cause mass migration, displacement and conflict, with huge loss of life.
- Economic assessments that are expressed solely in terms of effects on output (e.g. gross domestic product), or that only extrapolate from past experience, or that use inappropriate discounting, do not provide a clear indication of the potential risks to lives and livelihoods.
- It is likely that there are additional risks that we are not yet anticipating simply because scientists have not yet detected their possibility, as we have entered a period of climate change that is unprecedented in human history.
- Some advances are being made in improving economic assessments of climate change impacts but much more progress is required if assessments are to offer reliable guidance for political and business leaders on the biggest risks.
- The lack of firm quantifications is not a reason to ignore these risks, and when the missing risks are taken into account, the case for strong and urgent action to reduce greenhouse gas emissions becomes even more compelling.

1. Introduction

As the fifth anniversary of the finalisation of the United Nations Paris Agreement approaches, and countries explore how to increase the ambition of their pledges for reducing greenhouse gas emissions in their nationally determined contributions, political and business leaders across the world are formulating and assessing strategies for action on climate change. In order to make well-informed decisions, leaders need to understand clearly the nature and magnitude of the risks to lives and livelihoods that are being created by climate change.

Unfortunately, much of the technical advice and recommendations that leaders have been receiving about these risks incorporate assessments of the economic implications that omit or underplay the largest potential impacts of climate change. Indeed, economic assessments of climate change impacts currently fail to convey the scale and magnitude of what is at stake for the lives and livelihoods of individuals, infrastructures, Indigenous Peoples and critical ecosystems.

This policy insight seeks to draw attention to these missing and under-represented risks by identifying some of the most important future risks that are typically missing from economic assessments. We also discuss how populations might fare in light of their potential to adapt in the face of these risks.

When the risks are taken into account, the case for strong, deliberate and urgent action to reduce greenhouse gas emissions becomes even more compelling.

2. Context: unprecedented and underplayed risks

The concentration of carbon dioxide in the atmosphere is now about 45 per cent higher than it was before major industrialisation began in the 18th century. It is estimated that the last time that the carbon dioxide concentration was at today's level was about 3 million years ago during the Pliocene Epoch, when compared with today the global climate was at least 3°C warmer, the polar ice caps were much smaller and global sea level was 10 to 20 metres higher. Modern humans first appeared on Earth less than 250,000 years ago. As a species, therefore, we have no experience of a climate as warm as the Pliocene's, towards which we are currently heading.

Global mean surface temperature has increased by about 1°C since the end of the late 19th century as a result of an increased concentration of greenhouse gases, especially carbon dioxide, in the atmosphere, caused by human activities – primarily the burning of fossil fuels. A range of associated climate consequences have already been observed and recorded: accelerating mass ice loss from many glaciers and the polar ice sheets, a global rise in sea level, shifts in the pattern of snow- and rainfall in different regions (more intense and frequent dryness or precipitation), and increased frequency and intensity of heatwaves. These are some examples of the consequences that are growing in magnitude and are having an increasing impact on human and wildlife populations.

Human populations are already being forced to adapt to these impacts but there are limits to their capacity to do so. Human civilisation, with grain-based agriculture, settlements and surpluses, has developed over the past 10,000 years – since the end of the last Ice Age – during which the climate has been relatively stable and global mean surface temperature was likely never more than 1.5°C warmer than its pre-industrial level. At current rates of warming, the annual average global mean surface temperature could be regularly 1.5°C higher than its pre-industrial level within the next 40 years, according to the Intergovernmental Panel on Climate Change (IPCC). It should be noted that the aggregate global greenhouse gas emissions expected in 2030 if all countries implement the pledges for emissions contained in their nationally determined contributions to the Paris Agreement would be consistent with a pathway that results in a global mean surface temperature that is about 3°C higher by 2100 than its pre-industrial level, with further warming in the 22nd century.

However, recent reports by the IPCC have exposed mismatches between the estimates of the potential physical and economic impacts of climate change. For instance, the Summary for Policymakers of the Synthesis Report of the IPCC Fifth Assessment Report, published in November 2014, stated: "Without additional mitigation efforts beyond those in place today, and even with adaptation, warming by the end of the 21st century will lead to high to very high risk of severe, widespread and irreversible impacts globally (*high confidence*)" (p17).

It also stated: "The risks associated with temperatures at or above 4°C include substantial species extinction, global and regional food insecurity, consequential constraints on common human activities and limited potential for adaptation in some cases (*high confidence*). Some risks of climate change, such as risks to unique and threatened systems and risks associated with extreme weather events, are moderate to high at temperatures 1°C to 2°C above pre-industrial levels" (p19).

But the report's conclusions about the economic impacts were much more muted: "Aggregate economic losses accelerate with increasing temperature (*limited evidence, high agreement*), but global economic impacts from climate change are currently difficult to estimate. From a poverty perspective, climate change impacts are projected to slow down economic growth, make poverty reduction more difficult, further erode food security and prolong existing and create new poverty traps, the latter particularly in urban areas and emerging hotspots of hunger (*medium confidence*)" (p16).

The Summary for Policymakers of the IPCC Special Report on 'Global Warming of 1.5°C', published in October 2018, concluded: "Exposure to multiple and compound climate-related risks increases between 1.5°C and 2°C of global warming, with greater proportions of people both so exposed and susceptible to poverty in Africa and Asia (*high confidence*)" (p10). However, the assessment of the economic risks is much more cautious: "Risks to global aggregated economic growth due to climate change impacts are projected to be lower at 1.5°C than at 2°C by the end of this century (*medium confidence*)" (p9). The report also notes: "Here, impacts on economic growth refer to changes in gross domestic product (GDP). Many impacts, such as loss of human lives, cultural heritage and ecosystem services, are difficult to value and monetize" (p9).

Limitations in current assessments of climate system thresholds and human adaptive capacity

The vague statements about the economic risks in the IPCC reports reflect the limitations of published studies that are based on analyses that exclude the largest potential impacts of climate change.

Many of the missing economic risks in climate change assessments result from a lack of skill in modelling thresholds in the climate system and/or thresholds in the capacity for human societies to adapt to the impacts. These thresholds may mean that impacts become irreversible, unstoppable or accelerate. Many of these risks cannot be extrapolated from the climate of the recent past and lie outside the experience of modern humans, so therefore are inferred from evidence of similar occurrences in the geological record or from other scientific evidence. Our changing climate is interacting in complex ways with our dynamic and globalised human societies. Our capacity to assess future impacts and to plan effective and robust responses is severely challenged by the complex interactions between climate change, natural climate variability, demographic shifts, political processes, economic insecurity and land-use practices.

Overall, such assessments frequently omit, do not model, or merely note the existence of the largest risks because those risks are uncertain and lie outside the bounds of human experience. As a result, they tend to focus the attention of policymakers on smaller risks that are easier to quantify and are considered most likely, instead of highlighting the biggest potential risks to lives and livelihoods.

The enormous uncertainty around these complex interactions means that they are likely to remain active areas of research for many years. There have been recent attempts to incorporate some of these risks, such as destabilisation of the Greenland ice sheet, into economic assessments, but they have not taken account of the full range of impacts, nor the potential for multiple impacts to occur concurrently.

At present, the probabilities of most, but not all, of these types of catastrophic global impacts occurring in the near future are thought by most scientists to be relatively low, although not negligible, and they are expected to rise with global temperature. Scientists are not able to precisely quantify these probabilities but some may not be small, particularly if global mean surface temperature rises by more than 2°C above its pre-industrial level. Long-term planning requires risk scenarios that include these dangerous possibilities.

3. The greatest potential risks from climate change

In this section we provide an overview of the risks posed by climate change that carry some of the greatest consequences for human populations and wildlife:

- Destabilisation of ice sheets and glaciers and consequent sea level rise
- Stronger tropical cyclones
- Extreme heat impacts
- More frequent and intense floods and droughts
- Disruptions to oceanic and atmospheric circulation
- Destruction of biodiversity and collapse of ecosystems

Destabilisation of ice sheets and glaciers and consequent sea level rise

The major polar land-based ice sheets on West Antarctica and Greenland together hold enough water to raise global sea level by about 13 metres. Both are currently losing mass due to a combination of melting and destabilisation, and hence are already contributing to the rise in global sea level – along with an increasing amount of meltwater from glaciers and thermal expansion of seawater.

The West Antarctic and Greenland ice sheets formed over hundreds of thousands of years, so current losses of mass are likely to be irreversible on today's policymaking timescales. But a further critical point is that there are thought to be thresholds beyond which destabilisation of major parts of the ice sheets becomes inevitable. The physical mechanisms controlling the stability of the ice sheets are poorly understood. Melting at the base of an ice sheet may allow the overlying mass to move. In addition, ice shelves surrounding the ice sheets may disintegrate, allowing glaciers to flow unchecked, with increased calving of icebergs into the surrounding seas. Some scientists believe that these thresholds have already been reached for parts of the West Antarctic ice sheet.

The pace of destabilisation, and hence the rate of consequent sea level rise, is not well understood. It is expected that it would take several thousand years for the Greenland and West Antarctic ice sheets to disintegrate completely, and most assessments assume less than one metre of total sea level rise over the course of this century. However, there are significant uncertainties about how quickly the constituent parts of the ice sheets might become unstable. Some estimates suggest that the destabilisation of the ice sheets could contribute to a total sea level rise of about two metres by the end of this century, and possibly six metres by 2300.

The risks of melting ice for human populations: flooding, contamination of fresh water and displacement

The incidence of flooding and inundation along coastlines will increase as sea level continues to rise, increasing the likelihood of populations being displaced or migrating away from high-risk areas. Some low-lying countries and small island nations face a threat to their very existence in the long term as their lands are inundated.

It is estimated that more than 600 million people currently live on land with an elevation of 10 metres or less above sea level along the world's coastlines. This population could increase to more than 1 billion by 2050. Most of these people will experience the impacts of sea level rise through increases in the heights of high tides. Many will be exposed to elevated storm surges, which will threaten lives and property and contaminate freshwater supplies further inland, affecting many more hundreds of millions. One recent study (by Nicholls et al., 2018) estimated that between 3 and 6 million people suffered from coastal flooding in 2015. It concluded that an additional 35 to 125 million people could need protection from coastal flooding by 2100 even if the rise in global mean surface temperature is limited to 2°C.

Many growing cities and significant infrastructure such as airports and ports are located at low elevations along coastlines. In 2005, there were 136 coastal cities with more than 1 million people, together home to 400 million people. Some of these cities are suffering from subsidence because they are built on the soft sediments of deltas at the mouths of rivers, and so are exposed to enhanced rates of local sea level rise and salt water intrusion. The fertile lands of deltas in the mid and low latitudes are home to about 500 million people worldwide, with a concentration in South, Southeast and East Asia (the Ganges–Brahmaputra delta has a particularly high population density).

With the concentrations of people and assets in cities, it is usually considered to be economically worthwhile to provide sea defences. These defences will need to be strengthened to provide protection against sea level rise. However, some cities will no longer be feasible, viable or economic to protect as sea level continues to rise. Meanwhile, misjudgements about the level of defence required could lead to heavy loss of life and damage. The incidence of flooding and inundation along coastlines will increase as sea level continues to rise, increasing the risks of populations being displaced or migrating away from high risk areas. Some low-lying countries face a threat to their very existence in the long term as their lands are inundated.

While the volume of ice contained in the world's glaciers is significantly less than that within the polar ice sheets, their losses are already making a substantial contribution to global sea level rise. However, the biggest risk associated with the melting of glaciers is the prospect of their no longer providing a stable and predictable source of water for large human populations. In particular, the glaciers of the Himalayas are the source for many of the great rivers of South, Southeast and East Asia and their disappearance could disrupt the supply of water, and hence the viability of communities and livelihoods, for hundreds of millions of people. This process is generally ignored in economic assessments.

It should also be noted that the degradation of the land-based and sea ice sheets exposes darker land and ocean surfaces that absorb more of the Sun's radiation, increasing local warming as the reflective albedo effect of ice is lessened.

Stronger tropical cyclones

Tropical cyclones have devastating impacts when they hit land. They have been responsible for large loss of life, damage to property and interruption to business through the impact of strong winds, storm surges and heavy rainfall. The latest research suggests that there could be fewer tropical cyclones overall with global warming, but the frequency of strong storms will increase, primarily as a result of higher sea surface temperatures. There has been an increase in the average annual number of strong hurricanes in the North Atlantic since 1970.

In addition, the amount of heavy rainfall is likely to increase, as a warmer atmosphere can hold more water. Stronger storms are likely to generate bigger surges and, coupled with rising sea levels, will pose a growing threat to low-lying coastal areas.

Further urbanisation and development of coastlines that are already prone to tropical cyclones is likely to cause substantial magnification of the risks. The costs of preventing and recovering from damage are likely to grow and may become an unsustainable financial and economic burden, manifested, for instance, through a lack of affordable insurance.

Many parts of the world are reducing the loss of life from tropical cyclones through better weather forecasting and early warning systems. Improvements in the resilience of buildings and infrastructure can offset at least some of the likely rise in the potential destructiveness of tropical cyclones but there may be limits to adaptive capacity, particularly in developing countries, and miscalculations about resilience are likely to prove devastating.

It seems likely that the geographical reach of tropical cyclones could grow as sea surface temperatures increase around the world and a wider expanse of oceans reach the critical threshold of 26.5°C, beyond which their formation becomes more likely. Tropical cyclones could prove particularly devastating for coastal communities that do not currently experience them and have not developed resilience against them.

Extreme heat impacts

Summer heatwaves can prove deadly, particularly for those with underlying health problems such as respiratory diseases. An extreme heatwave in northern Europe in August 2003 killed more than 70,000 people, hitting the elderly and infirm the hardest. Cities are particularly exposed to heatwave conditions because the urban heat island effect means temperatures can be many degrees higher than in surrounding rural areas.

One study (by Dosio et al., 2018) found that more than a third of the world's population will be exposed to severe heatwaves (defined according to the Heat Wave Magnitude Index) at least once every five years, even if the rise in global mean surface temperature is limited to 2°C.

Human populations living in the Tropics may be accustomed to high temperatures but they face a rising risk from a lethal combination of heat and humidity. At high temperatures, the human body cools itself through sweat. However, at a so-called 'wet bulb temperature' (WBT) of 35°C or more, sweat no longer evaporates from the surface of the skin and the body cannot cool down. Under such circumstances, the core temperature of the body rises, leading to illness and, eventually, death. A WBT of 35°C would result from a combination of factors, roughly equivalent to an ambient temperature of 46°C and humidity of 50 per cent. It is estimated that a healthy human could survive a maximum of six hours in these conditions.

A wet bulb temperature of 35°C has never been recorded, but parts of the world have exceeded a WBT of 31°C, which is already extremely dangerous to any human who is exposed to it for more than a short period of time. The hottest WBTs in the world occur in the Persian/Arabian Gulf, in the northern parts of South Asia, and in Eastern China.

There is strong evidence that even in workplace temperatures that are high but not extreme, workers are less productive and work more slowly.

As the frequency and intensity of heatwave conditions increase with climate change, outdoor activities such as farming and construction work will become more dangerous. While adaptive measures such as air conditioning can reduce the impacts of hot weather extremes, these will be too expensive to install and maintain for poor people – meaning the majority of the population in many locations. Regions that experience a combination of high temperatures and high humidity will become essentially uninhabitable; this could include parts of southern Asia that are currently densely populated (many areas of which will also be affected by flooding and inundation). This would likely lead to movements of large populations, and potential political destabilisation.

High temperatures, particularly if combined with drought conditions, can also kill crops and damage yields, resulting in price spikes and reductions in food security.

Release of greenhouse gases from sinks

The rise in global mean surface temperature could cause the release of carbon dioxide and methane from land and ocean sinks, which would accelerate the rise in atmospheric levels of greenhouse gases. The thawing of permafrost regions would release large volumes of carbon dioxide: the world's permafrost is estimated to hold twice as much carbon dioxide as is currently present in the atmosphere. Warming of the Southern Ocean could have a profound impact on atmospheric concentrations of carbon dioxide, too. At present the Ocean is a net sink but further warming could release large amounts of carbon dioxide, turning it into a source. The temperature thresholds at which these releases will occur is unknown, but if they are reached, much of the Earth's subsequent warming could be beyond human control.

More frequent and intense floods and droughts

Climate change is making some parts of the world much wetter or much drier – the direction of the change can be difficult to predict and as a result, the impact on hydrological conditions is often omitted from economic assessments. Rainfall is already increasing in many regions as a warmer atmosphere can hold and release more water. However, some regions are experiencing reductions in rainfall as weather patterns change, leading to drought conditions, which are exacerbated by higher rates of evaporation in a warmer climate.

An increase in the frequency and intensity of rainfall creates a greater risk of surface water and river flooding. Floods can obviously directly threaten lives and properties but they can also create much more widespread impacts by submerging crops and drowning livestock. Urban areas can become more susceptible to flooding and contamination of water supplies if sewerage and drainage infrastructure is unable to cope with higher volumes or sudden deluges of rainfall.

An increase in the intensity of drought conditions can pose a major threat to populations that are already experiencing water stress. Hundreds of millions of people are already at risk from shortages of water for drinking and agricultural use. Increased dryness can also raise the probability of wildfires. Over the long term, extended dryness can promote desertification, with large areas rendered essentially uninhabitable because they cannot sustain vegetation. Many existing deserts are already expanding and new deserts will form.

Disruptions to oceanic and atmospheric circulation

The warming of the oceans, land and atmosphere that is resulting from climate change could have major impacts on existing patterns of oceanic and atmospheric circulation. This could result in profound changes in climate patterns, including the location, frequency and intensity of extreme weather events.

For instance, the melting of ice from northern polar regions, particularly Greenland, is causing more cold freshwater to drain into the North Atlantic Ocean. This influx could disrupt the Atlantic Meridional Overturning Circulation (AMOC), of which the Gulf Stream – which transports heat and moisture northwards from the tropical part of the Atlantic Ocean – is part. Serious weakening or even shut-off of the Gulf Stream would have profound implications for the landmasses around the North Atlantic – including a strong drying effect on the UK, which would vastly reduce the availability of viable arable land. It could also have important global effects, such as a southward shift of the tropical rainfall belt, as well as increasing warming of the Southern Ocean and Antarctica.

There have also been suggestions that climate change is having an impact on the strength and position of the high-speed winds of the Northern Hemisphere jet stream, which strongly influences weather systems across North America, Europe and Asia. The extent of an impact, and the potential consequences, have not yet been established.

The effects of climate change on other large-scale climate processes are still unclear but could prove significant. These processes include the El Niño Southern Oscillation (ENSO), which has been linked to droughts, crop failure, conflict and ecosystem disruptions.

Climate change is also expected to affect the occurrence of the monsoon rains in Asia and Africa. The monsoon rains are critical to agriculture and water supply in these continents but shifts in their timing can cause flood risk or drought that can become unmanageable and a threat to hundreds of millions of people, particularly if they lead to losses of crops and livestock or destruction of homes and infrastructure. Climate change is likely to mean monsoon systems affect larger areas over longer timescales, and rainfall during monsoon season is likely to intensify while becoming less predictable. The largest effect, which is already being observed today, is an increase in the year-to-year variability of the monsoon strength and the associated extremes of rainfall, which will have serious consequences for human development in regions with poor communities that are already struggling to adapt to climate change.

Destruction of biodiversity and collapse of ecosystems

As the climate warms, many plant and animal species will attempt to move to higher altitudes or higher latitudes. For some species this may not be possible, and they will face an increased risk of decline and potential extinction. Species that are adapted to the Arctic and Antarctic environments are at particular risk.

Oceans

Major changes to the distribution of species could have fundamental implications for the marine food web. The decline or loss of critical ‘keystone’ species – those that have a fundamental role in the functioning of food chains and webs – such as Antarctic krill could cause major disruptions in some areas and undermine the productivity of fisheries. The migration of plant and animal species will have profound potential implications for the supply of food and other resources for the human population.

Rising ocean temperatures are already having demonstrable impacts. Warming seas are exposing many coral reefs in tropical regions to a higher risk of experiencing bleaching and death from heat stress. A continuing rise in global ocean temperatures is expected to lead to the eventual loss of the majority of the world’s tropical reefs.

Many marine wildlife species are responding to the rise in temperatures by migrating closer to the poles, disrupting the delicate balance between species as they leave one habitat for another. In addition, ocean acidification, resulting from the greater absorption of carbon dioxide by the oceans, is likely to have an adverse impact on many shellfish species that utilise calcium carbonate. Changes in the abundance and distribution of marine species will have profound impacts on the availability of food and other marine resources upon which many coastal populations currently depend.

Forests

Shifts in temperature and rainfall patterns may also have devastating impacts for the world’s forests. In particular, there is evidence that rainforests and boreal forests could experience widespread die-off, decimating biodiversity in those regions and causing drying of regional climates. The loss of forests would also have serious implications for carbon dioxide levels in the atmosphere, as the world would be losing a major carbon sink while burnt or cleared trees would emit carbon too. Some experts have concluded that the interaction between deforestation, climate change and widespread use of fire mean that the eastern, southern and central parts of the world’s largest rainforest, the Amazon, could flip to non-forest ecosystems if the loss of forest reaches between 20 and 40 per cent or warming reaches about 4°C. Over the past 60 years almost 20 per cent of the Amazon rainforest has been lost and warming has reached 1°C.

Impacts on farming

Climate change will have very important implications for agriculture, particularly the sustainability of crops and livestock. The rise in atmospheric levels of carbon dioxide can boost the growth of vegetation but any associated benefits may be undermined by changes in temperature and rainfall. Extreme heat and dryness can kill livestock and harm their ability to reproduce. It can also kill crops and reduce yield quantities and quality. Of particular concern is the impact on the global staple crops of wheat, soy, maize and rice. While it may be possible to find plants and animals better able to withstand warmer, drier conditions, poor farmers may not be able to afford investments in such substitutes. Disruptions to food security can lead to malnutrition and hunger, particularly for children.

Vector-borne disease

As with all plant and animal species, pests, parasites and disease-carriers are also likely to move in response to the changing climate. This means that, for instance, diseases such as malaria that are spread by insect vectors will start to threaten human populations that are not currently exposed to them. The migration of these plants and animals could also have significant indirect impacts if they affect crops and livestock. Emerging diseases will spread more easily within populations that have not developed resistance through previous exposure, with potentially huge societal and economic consequences.

4. The limits of adaptation and migration

Many of the impacts of climate change result in amplification of risks to which human populations are already exposed, as well as the creation of new risks. Indeed, the growing impacts of climate change are affecting more and more people around the world, with multiple impacts producing concurrent effects and therefore disrupting and damaging lives and livelihoods in many locations. Climate change impacts have also been shown to adversely affect economic development and growth by damaging capital, productivity and investment.

Many communities have developed resilience to the risks that occur today, by utilising existing knowledge and changing their behaviour, through engineering solutions, such as building sea walls and flood defences, and through systems that prevent loss of life, such as early warnings for extreme weather events. Unsurprisingly, resilience is generally greater among wealthy populations than poor populations: wealthier people can afford additional protections that prevent damages or facilitate more rapid recovery afterwards.

While human populations will be able to adapt to these risks, there are likely to be limits that may be exceeded. As an example, coastal communities living on river deltas in the Tropics are facing a growing threat from storm surges at higher elevations than were previously exposed to this hazard, as a result of rising sea levels. Early warning systems and emergency shelters can help to protect lives, and stronger or reinforced sea defences and building construction can prevent damage to property. However, recent experience has shown that even communities in high-income countries are unable to prevent severe losses from extreme storm surges that overcome the limits of engineering for buildings and infrastructure. These events generally cause more economic damage in absolute terms in higher-income countries but cause more devastating loss of life in developing countries.

Population displacement and migration

Experience has shown that in both developed and developing countries poor or disadvantaged people find it more difficult to escape extreme weather events than do people who are better-off. Where a community or region is exposed to very severe or repeated extreme weather events, some populations may be displaced, while wealthier people may migrate and relocate to safer areas, leaving behind poorer people who are exposed to significant risks including loss of livelihood or threats to food or water security. These populations are also likely to find it more difficult in the long term to raise their living standards and escape poverty and the worst aspects of climate change.

Populations can also be displaced in regions experiencing slow-onset impacts such as inundation from sea level rise and desertification from longer and more frequent periods of dryness. Recent human history has shown that periods of intense or extended drought can undermine food security in poor communities and increase the risk of famine and large population movements.

Although migration often has benefits, the potentially enormous scale of population movements driven by climate change could cause cascading instabilities in regions that are not well prepared. Threats to livelihoods can lead to conflicts over land – between herders and farmers, for example – or over scarce water resources, from the scale of a single community to multiple countries, with transboundary conflict occurring particularly in relation to dam construction.

Recent human history shows that such instabilities caused by the displacement or migration of large populations can escalate, triggering more serious conflict and war. It is for this reason that many countries recognise climate change as a threat multiplier that could undermine political stability and human security around the world. Yet population displacement, conflict and death are often overlooked in economic assessments of climate change impacts.

Breaching of thresholds and cascading effects

Adaptation will become even more critical if major climatic thresholds are reached, leading to unstoppable, irreversible or accelerating impacts. The exceedance of one threshold may trigger another. For instance, the loss of ice from the Greenland ice sheet could trigger a critical threshold in the AMOC, together causing a rise in sea level and heat accumulation in the Southern Ocean, which would accelerate ice loss from the East Antarctic ice sheet.

Adaptation can be even more challenging because these impacts create cascading effects within human societies as well. For instance, drought may threaten water security, disrupt food supply chains and lead to internal migration that stresses existing social, economic and political conditions. This can incite conflict or cause an increase in international migration which, in turn, may fuel further disruptions to water and food security, natural resources, and social, economic and political conditions.

The occurrence of these types of cascading impacts has both regional and global consequences. The Syrian crisis and exodus, the disappearance of Lake Chad and accompanying disruption and conflict, and historic collapses of whole civilisations all provide cautionary examples of what happens when a series of complex, cascading risks are exacerbated by climate change.

The biggest risks from climate change, however, would result from impacts that are unprecedented in human history: sea level rise of several metres or major disruption to the monsoon rains and river flows in India. The capacity of human populations to adapt to impacts and disruptions on a scale of this kind is largely untested and uncertain.

5. Why the risks have been missed, omitted or unquantified

The biggest risks from climate change are associated with consequences that are unprecedented in human history and cannot simply be extrapolated from the recent past. As such they are uncertain and difficult for scientists to quantify in physical terms. Furthermore, the resulting consequences for lives and livelihoods can be difficult to determine because they involve assumptions about the resilience of populations, their capacity for adaptation and their ability to move in a crowded world. The cascading risks that can result from these impacts can be difficult to predict precisely and to capture in simulations using current models. These uncertainties mean that the impacts are difficult to represent in terms of costs and benefits and are therefore often ignored or omitted from economic models. In essence, they are assigned a probability of zero even though it is understood that to do so is incorrect.

Some of the physical processes that are not well understood, in terms of both occurrence and impact, and therefore are not adequately included in assessments are:

- Ice sheet and ice shelf hydrology and dynamics
- Severe storms and floods – including tornados, tropical cyclones and heavy rainfall events
- Coastal erosion and its impact on infrastructure
- Cascading ecosystem losses
- Feedback loops that accelerate climate change – including permafrost thaw and forest die-off
- Extreme heatwaves, droughts and associated wildfires

Other processes that need to be better represented in models include:

- The determinants of agricultural productivity and consumption demand
- Health impacts of climate change and labour productivity effects
- Responses to extreme events – such as food shocks and destruction of assets
- Health impacts from extreme events – such as wildfires and disease outbreaks and their interactions with air pollution
- Political responses – such as changes in trade policies that can affect food security and prices
- Adaptation responses – such as agricultural breeding, urban planning and land-use management

Models also struggle to represent compound events, such as sea level rise and storm surge impacts on exposed coastal populations, heatwaves and droughts, and pest and disease outbreaks. Other linked hazards that are not well represented include compound extremes (e.g. a coastal flood event striking a region already facing a river flood), sequential extremes (e.g. a drought event followed by a heatwave), and concurrent extremes (e.g. multiple breadbasket failures). Recent research indicates that compound, sequential and concurrent extremes would lead to more substantial aggregate impacts.

Even when the economic consequences of these impacts can be represented in policy assessments, they may be downplayed if they are not due to occur imminently. Inappropriate discounting by economists can lead very significant future impacts – such as long-term sea level rise during the 22nd century – to be treated as if they are relatively trivial compared with current impacts.

In addition, economic assessments often present consequences in terms of the impact on gross domestic product only, a measure of economic output that is too narrow to be able to convey the true nature and scale of damage to lives and livelihoods.

Finally, some risks are likely to be missed simply because scientists have not yet detected their possibility. As we have entered a period of climate change that is unprecedented in human history, there may be additional impacts that have not yet emerged and that we are not yet anticipating.

Some advances are being made in improving economic assessments of climate change impacts, but much more progress is required if these assessments are to offer reliable guidance for political and business leaders about the biggest risks. Some of the risks are difficult to model satisfactorily, but more progress might be made. Other risks are currently impossible to assess numerically, which economists need to acknowledge with greater openness and clarity.

Bibliography

Abel GJ, Brottrager M, Cuaresmac JC, Muttarak R (2019) Climate, conflict and forced migration. *Global Environmental Change*, 54: 239-249

Bamber JL, Oppenheimer M, Kopp RE, Aspinall WP, Cooke RM (2019) Ice sheet contributions to future sea-level rise from structured expert judgment. *Proceedings of the National Academy of Sciences*, 116(23): 11195-11200

Cai Y, Lenton TM, Lontzek, TS (2016) Risk of multiple interacting tipping points should encourage rapid CO_2 emission reduction. *Nature Climate Change*, 6: 520–525

Dietz S, Bowen A, Doda B, Gambhir A, Warren R (2018) The economics of 1.5°C climate change. *Annual Review of Environment and Resources*, 43: 455-480

Dietz S, Stern N (2015) Endogenous growth, convexity of damage and climate risk: How Nordhaus' framework supports deep cuts in carbon emissions. *The Economic Journal*, 125: 574-620

Donat MG, Lowry AL, Alexander LV, O'Gorman PA, Maher N (2016) More extreme precipitation in the world's dry and wet regions. *Nature Climate Change*, 6: 508-513

Dosio A, Mentaschi L, Fischer EM, Wyser K (2018) Extreme heat waves under 1.5 °C and 2 °C global warming. *Environmental Research Letters*, 13: 054006

Dumitru OA, Austermann J, Polyak VJ, Fornós JJ, Asmerom Y, Ginés J, Ginés A, Onac BP (2019) Constraints on global mean sea level during Pliocene warmth. *Nature*, https://doi.org/10.1038/s41586-019-1543-2

Farmer JD, Cameron Hepburn C, Mealy P, Teytelboym A (2015) A third wave in the economics of climate change. *Environmental and Resource Economics*, 62(2): 329-357

Intergovernmental Panel on Climate Change (IPCC) (2014) Summary for Policymakers. In: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri RK, Meyer LA (eds.)]. IPCC, Geneva, Switzerland, 31pp

Intergovernmental Panel on Climate Change (IPCC) (2018) Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR., Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M, Waterfield T (eds.)], 24pp

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (2019) *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Díaz S, Settele J, Brondizio ES, Ngo HT, Guèze M, Agard J, Arneth A, Balvanera P, Brauman KA, Butchart SHM, Chan KMA, Garibaldi LA, Ichii K, Liu J, Subramanian SM, Midgley GF, Miloslavich P, Molnár Z, Obura D, Pfaff A, Polasky S, Purvis A, Razzaque J, Reyers B, Roy Chowdhury R, Shin YJ, Visseren-Hamakers IJ, Willis KJ, Zayas CN (eds.). IPBES secretariat, Bonn, Germany. 43pp

Knutson T, Camargo SJ, Chan JC, Emanuel K, Ho C, Kossin J, Mohapatra M, Satoh M, Sugi M, Walsh K, Wu L (2019) Tropical cyclones and climate change assessment: Part II. projected response to anthropogenic warming. *Bulletin of the American Meteorological Society*, https://doi.org/10.1175/BAMS-D-18-0194.1

Lenton TM, Ciscar J-C (2013) Integrating tipping points into climate impact assessments. *Climatic Change*, 117(3): 585-597

Lovejoy TE, Nobre C (2018) Amazon tipping point. *Science Advances*, 4(2): eeat 2340

Lozier MS, Li F, Bacon S, Bahr F, Bower AS, Cunningham SA, De Jong MF, De Steur L, Deyoung B, Fischer J, Gray SF, Greenan BJW, Holliday NP, Houk A, Houpert L, Inall ME, Johns WE, Johnson HL, Johnson C, Karstensen J, Koman G, Le Bras IA, Lin X, MacKay N, Marshall DP, Mercier H, Oltmanns M, Pickart

RS, Ramsey AL, Rayner D, Straneo F, Thierry V, Torres DJ, Willikams RG, Wilson C, Yang J, I. Yashayaev I, Zhao J (2019) A sea change in our view of overturning in the subpolar North Atlantic. *Science*, 363(6426): 516-521

Mann, ME, Rahmstorf S, Kornhuber K, Steinman BA, Miller SK, Petri S, Coum D (2018) Projected changes in persistent extreme summer weather events: the role of quasi-resonant amplification. *Science Advances*, 4(10): eaat3272

Merkens J-L, Reimann L, Hinkel j, Vafeidis AT (2016) Gridded population projections for the coastal zone under the Shared Socioeconomic Pathways. *Global and Planetary Change*, 145: 57-66

Nicholls RJ, Brown S, Goodwin P, Wahl T, Lowe J, Solan M, Godbold JA, Haigh ID, Lincke D, Hinkel J, Wolff C, Merkens J-L (2018) Stabilization of global temperature at 1.5°C and 2.0°C: implications for coastal areas. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376(2119): 20160448

Nobrea CA, Sampaiob G , Bormac LS , Castilla-Rubiod JC, Silvae JS, Cardosoc M (2016) Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *Proceedings of the National Academy of Sciences*, 113(39): 10759–10768

Nordhaus W (2019) Economics of the disintegration of the Greenland ice sheet. *Proceedings of the National Academy of Sciences*, 116(25): 12261-12269

Schellnhuber HJ, Rahmstorf S, Winkelmann R (2016) Why the right climate target was agreed in Paris. *Nature Climate Change*, 6: 649–653

Steffen W, Rockström J, Richardson K, Lenton TM, Folke C, Liverman D, Summerhayes CP, Barnosky AD, Cornell SE, Crucifix M, Donges JF, Fetzer I, Lade SJ, Scheffer M, Winkelmann R, Schellnhuber HJ (2018) Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences*, 115(33): 8252-8259

Stern N (2013) The structure of economic modeling of the potential impacts of climate change: grafting gross underestimation of risk onto already narrow science models. *Journal of Economic Literature*, 51(3): 838-859

Stoerk T, Wagner G, Ward RET (2018) Policy brief—Recommendations for improving the treatment of risk and uncertainty in economic estimates of climate impacts in the sixth Intergovernmental Panel on Climate Change assessment report. *Review of Environmental Economics and Policy*, 12(2): 371–376

United Nations Environment Programme (2018) *The Emissions Gap Report 2018*. United Nations Environment Programme, Nairobi. 85p

Watts N, Amann M, Arnell N, Ayeb-Karlsson S, Belesova K, Berry H, Bouley T, Boykoff M, Byass P, Cai W, Campbell-Lendrum D, Chambers J, Daly M, Dasandi N, Davies M, Depoux A, Dominguez-Salas P, Drummond P, Ebi KL, Ekins P, Montoya LF, Fischer H, Georgeson L, Grace D, Graham H, Hamilton I, Hartinger S, Hess J, Kelman I, Kiesewetter G, Kjellstrom T, Kniveton D, Lemke B, Liang L, Lott M, Lowe R, Sewe MO, Martinez-Urtaza J, Maslin M, McAllister L, Mikhaylov SJ, Milner J, Moradi-Lakeh M, Morrissey K, Murray K, Nilsson M, Neville T, Oreszczyn T, Owfi F, Pearman O, Pencheon D, Pye S, Rabbaniha M, Robinson E, Rocklöv J, Saxer O, Schütte S, Semenza JC, Shumake-Guillemot J, Steinbach R, Tabatabaei M, Tomei J, Trinanes J, Wheeler N, Wilkinson P, Gong P, Montgomery H, Costello A (2018) The 2018 report of the Lancet Countdown on health and climate change: shaping the health of nations for centuries to come. *The Lancet*, 392(10163): 2479-2514

Zhisheng A, Guoxiong W, Jianping L, Youbin S, Yimin L, Weijian Z, Yanjun C, Anmin D, Li L, Jiangyu M, Hai C, Zhengguo S, Liangcheng T, Hong Y, Hong AO, Hong C, Juan F (2015) Global monsoon dynamics and climate change. *Annual Review of Earth and Planetary Sciences*, 43: 29-77