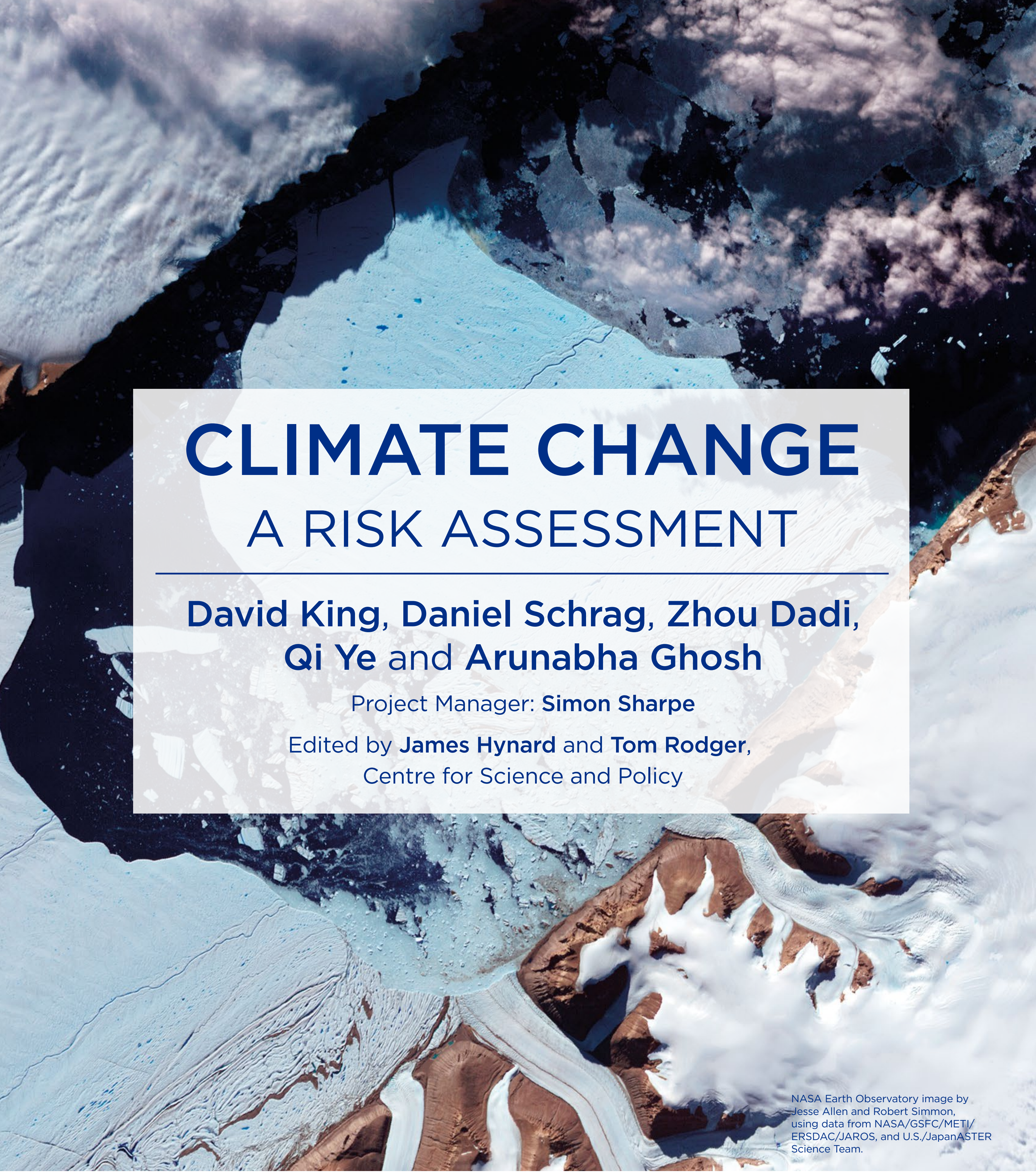


CLIMATE CHANGE

A RISK ASSESSMENT

David King, Daniel Schrag, Zhou Dadi, Qi Ye and **Arunabha Ghosh**

Project Manager: **Simon Sharpe**

Edited by **James Hynard** and **Tom Rodger**, Centre for Science and Policy

NASA Earth Observatory image by Jesse Allen and Robert Simmon, using data from NASA/GSFC/METI/ERSDAC/JAROS, and U.S./JapanASTER Science Team.

Hosts of the project workshops

Harvard University Center for the Environment

Tsinghua University

EEW Council on Energy, Environment & Water

Centre for the Study of Existential Risk, University of Cambridge

Sponsors

Foreign & Commonwealth Office

China National Expert Committee on Climate Change

skoll global threats fund

Global Challenges Foundation

Institute and Faculty of Actuaries

Willis

ABOUT THE AUTHORS

Sir David King is the UK Foreign Secretary's Special Representative for Climate Change, and was formerly the UK Government's Chief Scientific Adviser. He has authored over 500 papers on chemical physics and on science and policy, and his university positions have included Professor of Physical Chemistry at Cambridge University, and Founding Director of the Smith School of Enterprise and the Environment at Oxford University.

Professor Daniel P. Schrag is Director of the Harvard University Center for the Environment, and serves on the US President's Council of Advisors on Science and Technology. He is the Sturgis Hooper Professor of Geology and Professor of Environmental Science and Engineering, and studies energy technology and policy as well as geochemistry and climatology. He has received several honors including a MacArthur Fellowship.

Professor Zhou Dadi is a member of the China National Expert Committee on Climate Change, and was formerly Director General of the Energy Research Institute of the National Development and Reform Commission of the Government of China. He is a specialist in energy economics and energy systems analysis, sustainable energy strategy, energy conservation, and climate change policy.

Professor Qi Ye is Director of the Brookings-Tsinghua Centre for Public Policy at the School of Public Policy and Management, Tsinghua University, and a Senior Fellow of the Brookings Institution. He is an expert on China's policies on climate change, the environment, energy, natural resources, biodiversity, and on the theory and practice of sustainable development.

Dr Arunabha Ghosh is the CEO of the Council on Energy, Environment and Water (CEEW), one of India's top-ranked climate think-tanks. He is an expert in climate, energy, water and environment policy, economics and governance, has presented to parliaments including those of India, Europe and Brazil, and to heads of state, and has previously worked at Princeton and Oxford Universities, United Nations Development Programme and World Trade Organization. He is a founding Board member of the Clean Energy Access Network and on the Board of the International Centre for Trade and Sustainable Development.

This report was edited and produced by the Centre for Science and Policy (CSaP) at the University of Cambridge. CSaP's mission is to promote the use of expertise and evidence in public policy by convening its unique network of academics and policy makers.

STATUS OF THIS REPORT

Sir David King led this project in his official capacity as the UK Foreign Secretary's Special Representative for Climate Change. The Foreign and Commonwealth Office commissioned this report as an independent contribution to the climate change debate. Its contents represent the views of the authors, and should not be taken to represent the views of the UK Government.

ACKNOWLEDGMENTS

The authors wish to thank all of those who contributed their time and expertise to this project, including the contributing authors to this report, and also those participants in our meetings whose names are not listed here, but whose valuable insights have contributed to our analysis.

We wish to thank the sponsors of the project, including the UK Foreign and Commonwealth Office, the China National Expert Committee on Climate Change, the UK Government Office for Science, the Skoll Global Threats Fund, Global Challenges Foundation, the UK Institute and Faculty of Actuaries, and Willis Research Network, for their generous support. Special thanks are also due to the UK Department of Energy and Climate Change Science team, China Meteorological Administration, the CNA Corporation, and the Climate Change Science Institute at Oak Ridge National Laboratory, for their support to specific aspects of the project.

We also wish to thank all the following individuals for their practical, intellectual and moral support, which has made this project possible: James Ballantyne, Oliver Bettis, Steven Bickers, Shourjomoy Chattopadhyay, Vaibhav Chaturvedi, Partha Dasgupta, Hem Himanshu Dholakia, John Edwards, Vaibhav Gupta, Pradyot C. Haldar, Frances Hooper, Paulette Hunter Okulo, Anil Jain, Aarti Katyal, Sindhushree Khullar, Anthony W. King, Sylvia Lee, Stephan Lewandowsky, Amy Luers, Luo Yong, Lisa Matthews, Bessma Mourad, Chris Nicholson, Harriet O'Brien, Dennis Pamlin, Bob Phillipson, Benjamin L. Preston, Aditya Ramji, Sudatta Ray, Denise Sadler, Sayantan Sarkar, Mihir Shah, Surbhi Singhvi, Morgan Slebos, Wang Mengni, Nicola Willey, Ken Wright, Zhang Jiansong, Zheng Qi, Zhu Songli.

CLIMATE CHANGE

A RISK ASSESSMENT

David King, **Daniel Schrag**, **Zhou Dadi**,
Qi Ye and **Arunabha Ghosh**

Project Manager: **Simon Sharpe**

Edited by **James Hynard** and **Tom Rodger**,
Centre for Science and Policy

Hosts of the project workshops

Harvard University Center for the Environment
Tsinghua University
CEEW Council on Energy, Environment and Water
Centre for the Study of Existential Risk, University of Cambridge

Sponsors

Foreign & Commonwealth Office
China National Expert Committee on Climate Change
skoll global threats fund
Global Challenges Foundation
Institute and Faculty of Actuaries
Willis

CONTENTS

MINISTERIAL FOREWORD

The Rt Hon. Baroness Anelay of St Johns
Minister of State, UK Foreign and Commonwealth Office

None of us should be in any doubt that climate change poses a great risk. Indeed, it is remarkable that even in the run-up to a general election, the leaders of the UK's three largest political parties came together to say that *"Climate change is one of the most serious threats facing the world today. It is not just a threat to the environment, but also to our national and global security, to poverty eradication and economic prosperity."*

In assessing the risk of climate change, the immediate questions for any country anywhere in the world are: How serious is the threat? How urgent is it? How should we prioritise our response, when we have so many other pressing, national objectives - from encouraging economic recovery to protecting our people around the world? These are all important questions, and we can only truly answer them if we assess the risk in full.

In the past, when assessing the risk of climate change, we have tended to take an approach that is, perhaps, too narrow - or incomplete. In public debate, we have sometimes treated it as an issue of prediction, as if it were a long-term weather forecast. Or as purely a question of economics - as if the whole of the threat could be accurately quantified by putting numbers into a calculator. Often, too, we have not fully assessed the indirect or systemic risks, such as those affecting international security – even though, as the UK's first national climate change risk assessment found, these could be far greater than the direct risks like coastal flooding. Assessing the threat of climate change today demands a more coordinated, more sophisticated, more holistic approach.

Taking a holistic approach to risk management goes to the heart of what the Foreign and Commonwealth Office does. It is an approach that applies as much to climate change as to, for example, preventing the spread of nuclear weapons. Earlier this year, I addressed a meeting of the Permanent Five members of the UN Security Council to discuss nuclear disarmament and non-proliferation. Assessing the risk around this vital area of security depends on understanding inter-dependent elements, including: what the science tells us is possible; what our political analysis tells us a country may intend; and what the systemic factors are, such as regional power dynamics.

The risk of climate change demands a similarly holistic assessment. So, to understand its full extent, we must: first, take into account countries' plans and policies, which together affect the future of global emissions; second, understand the science of how our climate may change; third, consider how climate change could affect the complex systems of the global economy and international security.

Finally, we must also make a judgment about how we value the risk. In other words, how much do we care about the effects of climate change? How important is it that we act to avoid them? What probability of their occurrence can we tolerate? For climate change, as for nuclear proliferation, the answers to these questions are not easily expressed in economic terms. They depend in part on how we value human life – both now, and in the future. Decisions on national security usually have implications for the budget, but they can rarely be reduced to simple equations of cost and benefit. That is why it is important that we are open and honest about any value judgments we make, so that these can be subject to public debate.

Just as our assessment of the risk needs to be holistic, so too does our response. Responding to the risk of climate change will demand technological innovation, financial investment and political leadership. Each of these elements must be brought together to produce a response that is both proportionate and effective.

We are beginning to see some positive progress. Technological innovation has dramatically cut the costs of renewable energy, increasing its share of global energy investment. In turn, more and more countries are taking policy steps to reduce their emissions and the Paris conference at the end of this year presents an opportunity to scale up our global response.

However, lest we become complacent, we must remember that in one way, climate change differs from any other subject of diplomatic negotiation: it is governed by a physical process. A process where the risk increases over time, and will continue to do so until we have entirely dealt with its cause. That is why leadership is so important – to forge ahead, to drive momentum and to show the way for others to follow.

Former British Prime Minister Margaret Thatcher showed just that kind of leadership in her early recognition of the nature and scale of the risks of climate change. In 1989, she told the UN General Assembly that rather than being the lords of all we survey, *"we are the Lord's creatures, the trustees of this planet, charged today with preserving life itself – preserving life with all its mystery and all its wonder. May we all be equal to that task."*

I am delighted that experts from the UK, US, China and India have worked together to produce this report, which makes those risks even clearer. As we consider its findings, let us remember those words from a quarter-century ago. Let us determine to be both proportionate and effective in our response. Let us show that we are, indeed, equal to the task before us.

EXECUTIVE SUMMARY

The most important decision any government has to make about climate change is one of priority: how much effort to expend on countering it, relative to the effort that must be spent on other issues. This risk assessment aims to inform that decision.

CONCLUSIONS OF THE RISK ASSESSMENT

A climate change risk assessment must consider at least three areas: the future pathway of global emissions; the direct risks arising from the climate's response to those emissions; and the risks arising from the interaction of climate change with complex human systems. Each of these areas contains large uncertainties. From our assessment, we draw the following conclusions about the most significant risks.

EMISSIONS: Without increased political commitment and an acceleration of technological innovation, global emissions are likely to follow a medium to high pathway: continuing to increase for the next few decades, and then levelling off or decreasing gradually.

- Current policies and plans for major countries and regions are, in aggregate, consistent with a medium to high emissions pathway, with emissions continuing to increase over the next few decades.
- The technological challenges to achieving a low emissions pathway are substantial, and are not being adequately addressed at present. Without an acceleration of innovation in energy technology and energy systems – including wind and solar with storage, nuclear, biofuel, petroleum-free passenger transport, carbon storage, and large-scale energy efficiency – the likelihood of following a pathway in which emissions fall rapidly and approach zero by late in the century is very low.
- High emissions pathways in which emissions continue to increase throughout the century cannot be ruled out, given the potential for extraction of large new coal reserves, as well as oil shale and methane hydrates.
- The climate responds to cumulative emissions, so any pathway that does not bring emissions close to zero will result in risk continually increasing over time.

DIRECT RISKS: The risks of climate change are non-linear: while average conditions may change gradually, the risks can increase rapidly. On a high emissions pathway, the probability of crossing thresholds beyond which the inconvenient may become intolerable will increase over time.

- For any emissions pathway, a wide range of **global temperature increases** is possible. On all but the lowest emissions pathways, a rise of more than 2°C is likely in the latter half of this century. On a medium-high emissions pathway (RCP6[1]), a rise of more than 4°C appears to be as likely as not by 2150. On the highest emissions pathway (RCP8.5), a rise of 7°C is a very low probability at the end of this century, but appears to become more likely than not during the course of the 22nd century. A rise of more than 10°C over the next few centuries cannot be ruled out.
- Humans have limited tolerance for **heat stress**. In the current climate, safe climatic conditions for work are already exceeded frequently for short periods in hot countries, and heat waves already cause fatalities. In future, climatic conditions could exceed potentially lethal limits of heat stress even for individuals resting in the shade. The probability of exposed individuals experiencing such conditions in a given year starts to become significant for a global temperature rise of around 5°C, and could exceed 50% for a global temperature rise of around 7°C, in hot areas such as northern India, southeastern China, and southeastern USA.
- **Crops** have limited tolerance for high temperatures. When critical thresholds are exceeded, yields may be drastically reduced. The probability of crossing such thresholds in a given year, for studied examples of maize in the Midwestern US and rice in southern China, appears to rise from near zero at present, to become increasingly significant with global temperature rise of more than 2°C, and in the worst cases to reach somewhere in the region of 25% (maize) and 75% (rice) respectively with global temperature rise of around 4-5°C.Biophysical limits on the extent to which such tolerance thresholds can be raised may be an important constraint on adaptation. This is one reason why high degrees of climate change could pose very large risks to global food security.
- Thresholds for **water stress** are largely arbitrary, but thresholds of 'moderate', 'chronic' and 'extreme' water shortage are widely used, based on per capita availability. The number of people exposed to extreme water shortage is projected to double, globally, by mid century due to population growth alone. Climate change could increase the risk in some regions: for example, on a high emissions pathway, the probability of the Tigris – Euphrates river basin falling into extreme water shortage could rise significantly after 2030, reaching close to 100% by 2070.
- In South and East Asia, climate change may slightly offset otherwise increasing risks of water stress, while increasing the risk of **flooding**. On a high emissions pathway, what is now a '30-year flood' could become three times more frequent in the Yellow River and Indus basins, and six times more frequent in the Ganges basin, over the course of the century, on a central estimate. In the worst case for those three river basins, such a flood could be in the region of ten times more frequent by the end of the century.
- On a high emissions pathway, the incidence of extreme **drought** affecting cropland could increase by about 50% in the US and South Asia, double globally, and triple in southern Africa, over the course of the century under central estimates. The uncertainties around these central estimates are large: for the US and South Asia, in the best case, drought incidence could halve; in the worst case, it could increase by three or four times.
- With 1m of **global sea level rise**, the probability of what is now a '100-year flood event' becomes about 40 times more likely in Shanghai, 200 times more likely in New York, and 1000 times more likely in Kolkata. Defences can be upgraded to maintain the probability of a flood at a constant level, but this will be expensive, and the losses from flooding will still increase, as the floods that do occur will have greater depth. Thresholds of adaptation beyond which 'retreat' from the sea may become more feasible than further increases in flood protection are not well defined, but the most significant limits may be sociopolitical rather than economic or technological.
- Climate models suggest that global sea level rise is unlikely to exceed 1m this century, and that a plausible worst-case scenario could result in an increase of several metres by the end of the 22nd century. However, due to inertia in the climate system, with a sustained global temperature rise of 2°C the global sea level may be committed to rise by some 10-15m as ice-sheets gradually melt, but whether this will take hundreds of years or thousands of years is deeply uncertain.
- Many elements of the climate system are capable of **abrupt or irreversible change**. Changes to monsoons or to ocean circulation patterns, die-back of tropical forests, and the release of carbon from permafrost or sub-sea methane hydrates could all cause large-scale disruption of the climate. The probabilities of such changes are not well known, but are they expected to increase as the global temperature rises.

SYSTEMIC RISKS: The risks of climate change are systemic. The greatest risks may arise from the interaction of the climate with complex human systems such as global food markets, governance arrangements within states, and international security.

- As climate change increases the frequency of extreme weather events, preliminary analysis suggests what was a '1 in 100 year' shock to global food production in the latter half of the 20th century may have become three times more likely by mid-century. If policy and market responses amplify rather than mitigate the shock, a plausible worst-case scenario in the present day could produce unprecedented price spikes on the global market, with a trebling of the prices of the worst-affected grains, compared to current levels.

- Climate change has already increased the probability of extreme events such as the Russian heat wave of 2010, and the Syrian drought of 2007-2011. These events have contributed to unrest and conflict, in combination with other factors such as food export restrictions, existing resource stress, poor governance and state fragility. At low degrees of climate change, further such risks are most likely to arise in regions where climate change is reducing already stressed resources at the same time as high rates of population growth are increasing demand.

- Security risks at high degrees of climate change seem likely to be of a different order of magnitude. Extreme water stress, and competition for productive land, could both become sources of conflict. Migration from some regions may become more a necessity than a choice, and could take place on a historically unprecedented scale. It seems likely that the capacity of the international community for humanitarian assistance would be overwhelmed. The risks of state failure could rise significantly, affecting many countries simultaneously, and even threatening those that are currently considered developed and stable. The expansion of ungoverned territories would in turn increase the risks of terrorism. The temptation for states or other actors to take unilateral steps toward climate geoengineering would be significant, and could become a further source of conflict.

VALUE: Valuing these risks is essentially a subjective exercise.

- Standard economic estimates of the global costs of climate change are wildly sensitive both to assumptions about the science, and to judgments about the value of human life. They are also likely to be systematically biased towards underestimation of risk, as they tend to omit a wide range of impacts that are difficult to quantify.

- Even if economic costs could be estimated accurately, their sum total would not be a good measure of the risks of climate change. Some of the greatest tragedies of the last century had a negligible impact on global GDP. Some of the greatest risks of climate change may be similarly non-monetary.

- Any valuation of the risks of climate change will involve subjective judgments, most notably with regard to the importance attached to the wellbeing of future generations. Such judgments should be made transparently, so that they may be publicly debated.

RECOMMENDATIONS FOR CONTINUING RISK ASSESSMENT

There is much that we can do to improve our assessment of climate change risk. This is an opportunity, as it can better inform decisions on risk reduction.

Our recommendations on risk assessment are: apply the right principles; broaden participation in the process; and report to the highest decision-making authorities.

Apply the principles of risk assessment. These include:

- **Assess risks in relation to objectives, or interests**. Start from an understanding of what it is that we wish to avoid; then assess its likelihood.

- **Identify the biggest risks**. Focus on finding out more about worst-case scenarios in relation to long-term changes, as well as short-term events.

- **Consider the full range of probabilities**, bearing in mind that a very low probability may correspond to a very high risk, if the impact is catastrophic.

- **Use the best available information**, whether this is proven science, or expert judgment. A best estimate is usually better than no estimate at all.

- **Take a holistic view**. Assess systemic risks, as well as direct risks. Assess risks across the full range of space and time affected by the relevant decisions.

- **Be explicit about value judgments**. Recognize that they are essentially subjective, and present them transparently so that they can be subject to public debate.

Risk assessments need to be made on a regular and consistent basis, so that in areas of uncertainty, any changes or trends in expert judgment are clearly visible over time. This could be facilitated by the identification and use of a consistent set of indicators in each of the three areas of risk assessment described above.

Broaden participation in the risk assessment process. Different participants are important to different stages of the process:

- **Defining objectives:** Leaders and decision-makers have a role at the beginning, in defining the objectives and interests against which risks should be assessed.

- **Information gathering:** Scientists have the lead role in understanding climate change and its direct impacts. Experts in politics, technology, economics, and other disciplines can provide information relevant to the future of global emissions, and the indirect impacts of climate change as it interacts with human systems.

- **Risk assessment:** Whereas information gathering may collect whatever is useful or interesting, risk assessment interrogates that evidence in relation to defined objectives and according to a specific set of principles. Separating these tasks may allow both to be carried out more effectively. Climate change risk assessments should involve not only scientists, but also experts in risk, who may be drawn from fields such as defence, intelligence, insurance, and public health.

Report to the highest decision-making authorities. A risk assessment aims to inform those with the power to reduce or manage the risk. Assessments of specific, local, or sectoral risks of climate change may be directed at those with specific, local or sectoral responsibility. Assessments of the risk of climate change as a whole should report directly to those with responsibility for governance as a whole. At the national level, this means the head of government, the cabinet, or the national security council. At the global level, it means institutions where heads of government meet to make decisions.

RISK REDUCTION: ELEMENTS OF A PROPORTIONATE RESPONSE

A risk assessment aims primarily to further our understanding of the problems we face; at the same time, it may provide some insight into the nature of the solutions.

The greatest risks of climate change arise when thresholds are crossed: what had been gradual becomes sudden; what had been inconvenient becomes intolerable. Similarly, the greatest reductions in risk will be achieved by crossing thresholds at which change becomes non-linear.

Political leadership can be a source of non-linear change. With existing technology, there is already the opportunity for political leadership to significantly change the trajectory of any country's emissions in the short term.

Technological innovation is a natural source of non-linear change. New technologies can emerge slowly, but then displace old ones rapidly and suddenly when some invisible threshold is crossed. Accelerating this pace of change, and bringing forward those thresholds, should be a priority in respect of the range of technologies that are needed to achieve the low carbon transition. The top priority should be to use both technological progress, and policy measures such as carbon pricing, to cross as soon as possible the threshold at which clean energy becomes cheaper than fossil energy.

In finance, small changes in rules can produce large changes in results. Adjustments to regulations and incentives to incorporate enhanced assessment of long-term risk into the financial system could significantly increase investment in technologies that serve our long-term economic interests.

The risks of climate change are amplified by feedbacks: rising temperatures melt ice; sea without ice absorbs more heat; and the temperatures rise faster. Effective risk reduction will also take advantage of positive feedbacks. Political interventions can change market sentiment, so that the market sends more investment into clean energy technologies, so that this accelerates technological progress, so that new political interventions become possible.

Just as the risks of climate change are both immediate and long-term, we must act both immediately and with a long-term view. A risk that grows over time will not be managed successfully if our horizons are short-term. Ultimately, the risks of climate change will only be under control when we have reduced global emissions to near zero. So while we must do all in our power to reduce emissions now, we must also follow a path that increases our power to do more in the future.

The risks of climate change may be greater than is commonly realized, but so is our capacity to confront them. An honest assessment of risk is no reason for fatalism. If we counter inertia with ingenuity, match feedback with feedback, and find and cross the thresholds of non-linear change, then the goal of preserving a safe climate for the future need not be beyond our reach.

Endnote

1. 'RCP' stands for 'Representative Concentration Pathway'. We refer here to the emissions pathways implicit in the greenhouse gas concentration scenarios used by the Intergovernmental Panel on Climate Change in its Fifth Assessment Report.

CLIMATE CHANGE

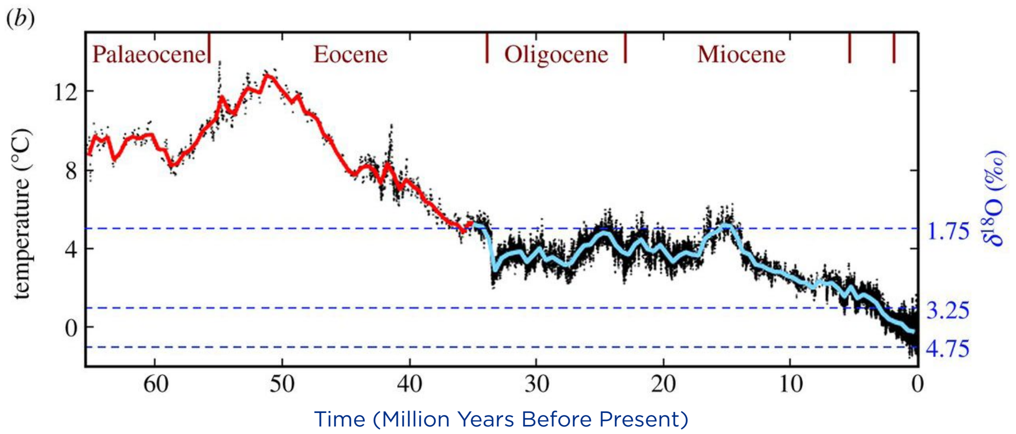
A RISK ASSESSMENT

1 INTRODUCTION

The Earth's climate has changed dramatically in the past. It has swung in and out of ice ages, at whose peak great swathes of North America, Europe and northern Asia were covered in sheets of ice three kilometres thick. It has been through periods of extreme heat, where subtropical climates existed in high northern latitudes. The height of the oceans has changed by more than a hundred metres.

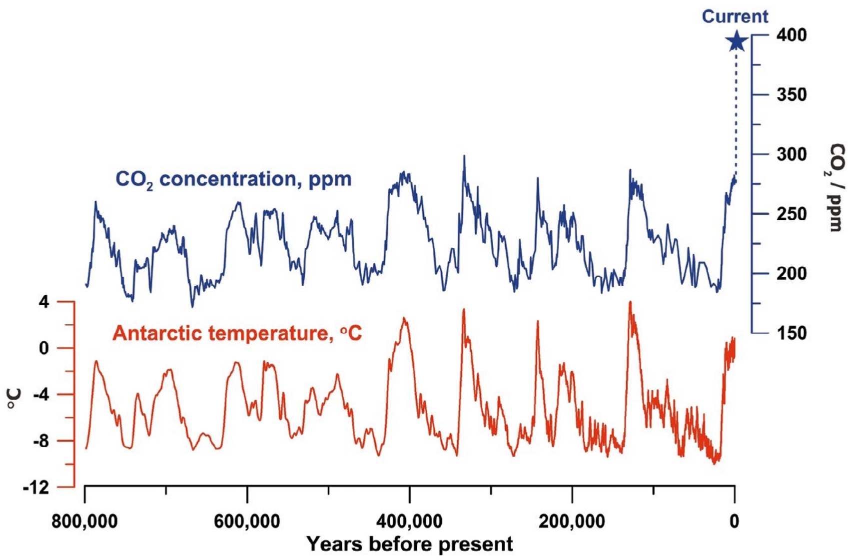
But human civilization has seen few of those changes. Over the ten thousand years or so in which our civilization emerged, the Earth's climate has been unusually stable. Global temperature and sea levels have hardly varied. We have taken advantage of this period of stability to grow crops, build cities, and develop a global economy.

Figure 1: **The last 60 million years.** Changes in global deep ocean temperature[1]



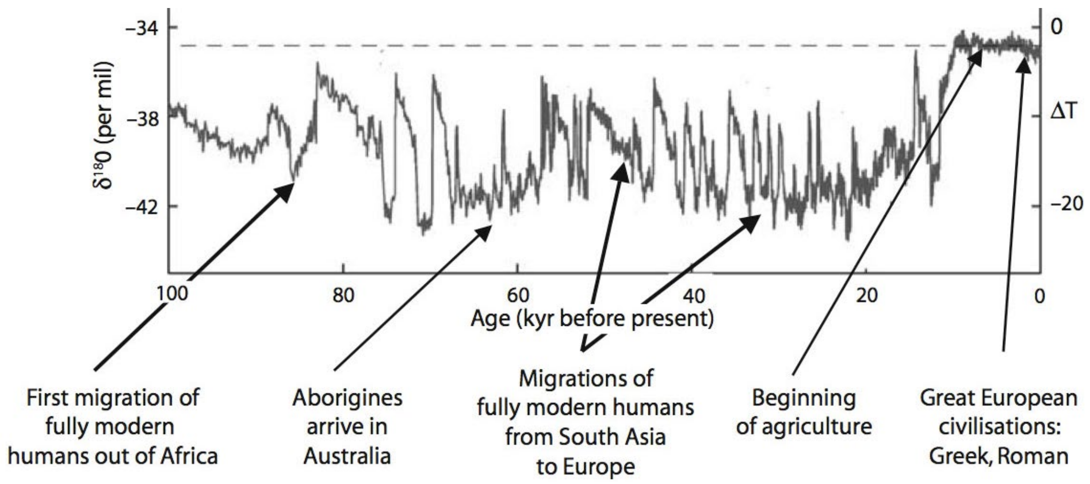
Global deep ocean temperature, estimated based on the oxygen isotope record in ocean sediments. Viewed on this timescale, the long-term trend has been one of cooling, since ocean and atmospheric temperatures peaked at more than 12°C above present levels around 50 million years ago.

Figure 2: **The last 800,000 years.** Changes in Antarctic air temperatures and atmospheric CO_2 concentrations[2]



Antarctic air temperatures and atmospheric CO_2 concentrations over the past 800,000 years, estimated using data from ice cores. Viewed on this timescale, the climate can be seen to have oscillated between ice ages (troughs) and relatively warm inter-glacial periods (peaks). The difference between the ice ages and the interglacials, in terms of global average near-surface air temperature, is around 4-5°C. The temperature differences shown on this graph are roughly twice as large because polar temperatures vary more than the global average. The blue star shows the current CO_2 concentration, using data from atmospheric measurements. As the record shows, the recent increase in atmospheric CO_2 concentration is unprecedented in the past 800,000 years.

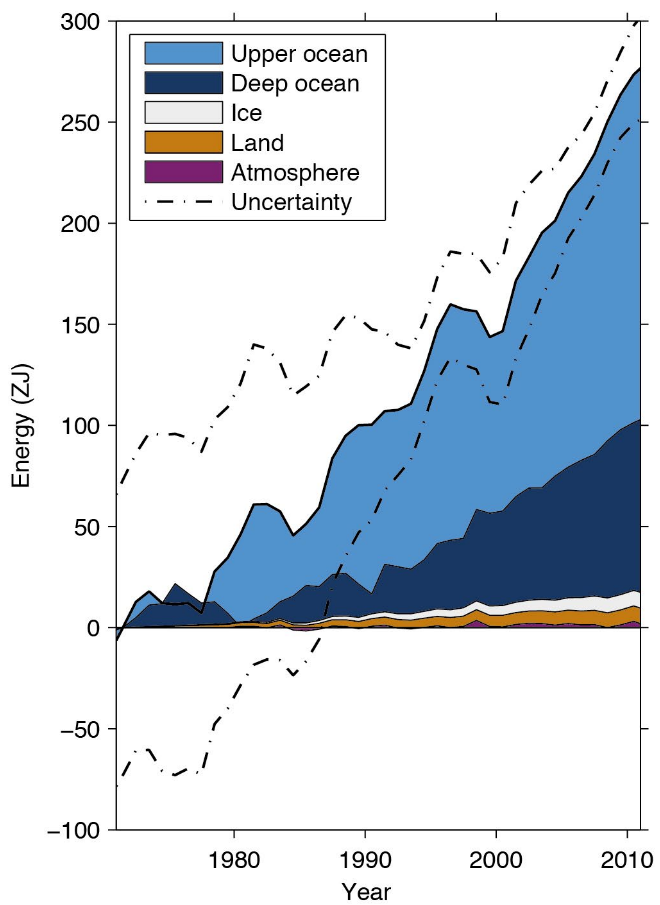
Figure 3: **The last 100,000 years** Temperature change, as measured in Greenland[3]



The last time large changes in climate took place, human civilization had not begun. Over the last 10,000 years, the period in which humans transitioned from hunter-gathers to an agricultural society, the Earth's climate experienced an unusually stable period. This graph shows local temperature change in Greenland. (As noted above, polar temperatures change more than the global average, and the increase in global average temperature change at the end of the last ice age, around 10,000 years ago, was about 5°C.)

That period of stability is now ending. The greenhouse gases emitted to the atmosphere by human activities are trapping heat, adding energy to the Earth's system. This flow of additional energy is substantial: it is roughly equivalent to adding the energy of four nuclear bombs of the size dropped on Hiroshima, every second.[4] As a result, not surprisingly, the Earth's climate is warming up.

Figure 4: **Energy added to the Earth system**[i, 5]



More than 90% of the energy added to the Earth system goes into warming the oceans. Only about 2% goes into warming the atmosphere, and the balance is taken up by the land and the melting ice. The total energy added continues to increase steeply over time.

i. Full IPCC caption: Plot of energy accumulation in ZJ (1 ZJ = 1021 J) within distinct components of the Earth's climate system relative to 1971 and from 1971 to 2010 unless otherwise indicated. See text for data sources. Ocean warming (heat content change) dominates, with the upper ocean (light blue, above 700 m) contributing more than the mid-depth and deep ocean (dark blue, below 700 m; including below 2000 m estimates starting from 1992). Ice melt (light grey; for glaciers and ice caps, Greenland and Antarctic ice sheet estimates starting from 1992, and Arctic sea ice estimate from 1979 to 2008); continental (land) warming (orange); and atmospheric warming (purple; estimate starting from 1979) make smaller contributions. Uncertainty in the ocean estimate also dominates the total uncertainty (dot-dashed lines about the error from all five components at 90% confidence intervals).

Small changes in global temperature correspond to large changes in the global climate. If the world were five degrees cooler than it is now, we would be in an ice age, last experienced some ten thousand years ago, before the dawn of human civilization. Five degrees warmer, and we would be in a climate of heat last experienced by this planet more than ten million years ago, long before the beginning of human existence.

That climate five degrees warmer, or more, is a very real possibility. It could occur within the lifetimes of children alive today. Decisions we take now will affect its likelihood, and will continue to influence the climate for thousands of years and hundreds of human generations into the future.

Why do we need a risk assessment?

Our starting point is that we have an interest in understanding what the consequences of our decisions might be. When the consequences could be so far-reaching in space and in time, we have an interest in understanding them as fully as possible.

A risk is something bad that might happen. A risk assessment asks the questions: 'What might happen?', 'How bad would that be?' and 'How likely is that?' The answers to these questions can inform decisions about how to respond.

Climate change fits the definition of a risk (more academically described as 'the effect of uncertainty on objectives',[6] or 'an uncertain, generally adverse consequence of an event or activity with respect to something that humans value'[7]), because it is likely to affect human interests in a negative way, and because many of its consequences are uncertain. We know that adding energy to the Earth system will warm it up, raising temperatures, melting ice, and raising sea levels. But we do not know how fast or how far the climate will warm, and we cannot predict accurately the multitude of associated changes that will take place. The answer to the question 'how bad could it be?' is far from obvious.

Limiting climate change will take some effort. Although many of the policies that would reduce greenhouse gas emissions could also be good for public health, quality of life, and economic growth,[8] they will not necessarily be easy to put in place. They will require the investment of both political and financial capital. Governments and societies will have to decide how much effort they are prepared to make, and how to prioritize this issue in relation to their other objectives. An assessment of the risks will be a necessary basis for judging what would be a proportionate response.

It is sometimes argued that a full assessment of the risks of climate change would be counterproductive, because the risks may be so large and the solutions so difficult that people will be overwhelmed with a feeling of helplessness, and will look the other way. In some cases, this may be true. The anthropologist Jared Diamond, in addressing the question: 'Why do some societies make disastrous decisions?', writes:

> *"…consider a narrow river valley below a high dam, such that if the dam burst, the resulting flood of water would drown people for a considerable distance downstream. When attitude pollsters ask people downstream of the dam how concerned they are about the dam's bursting, it's not surprising that fear of a dam burst is lowest far downstream, and increases among residents increasingly close to the dam. Surprisingly, though, after you get just a few miles below the dam, where fear of the dam's breaking is found to be highest, concern then falls off to zero as you approach closer to the dam! That is, the people living immediately under the dam, the ones most certain to be drowned in a dam burst, profess unconcern. That's because of psychological denial: the only way of preserving one's sanity while looking up every day at the dam is to deny the possibility that it could burst. Although psychological denial is a phenomenon well established in individual psychology, it seems likely to apply to group psychology as well.[9]"*

Our premise for writing this risk assessment is that we can all choose whether or not to look up at the dam. Governments can choose either to ignore it, or to send their best experts to inspect it closely. We have taken the view that it is better to be well informed than not. As the American nuclear strategist Albert Wohlstetter wrote during the Cold War, *"We must contemplate some extremely unpleasant possibilities, just because we want to avoid them."*[10]

This report does not pretend to give all the answers. Its purpose is to be illustrative: to present a new framework for a climate change risk assessment, and to put forward our best – in some cases rough – estimates of what the findings of such an assessment might be. We hope that these findings will be challenged, updated, and improved. It is less important that readers should agree with us, than that they should understand why we have asked the questions that we have.

We have ended with some thoughts on the question of risk management. A risk assessment is a way to better understand a problem, not a guide to solving it, and so this is a small part of our report. We provide a few individual perspectives on how our national and global responses to climate change could be made more effective, in proportion to the scale of the risk, simply because we would not wish to leave readers with the impression that the situation is hopeless. That, we believe, is far from the case.

Endnotes

1. Hansen, J.E. and Sato, M. (2012). Climate Sensitivity Estimated from Earth's Climate History. Available at http://www.columbia.edu/~jeh1/mailings/2012/20120508_ClimateSensitivity.pdf
2. Figure by Jeremy Shakun, data from Lüthi et al., 2008 and Jouzel et al., 2007. Source: Figure 3, (2014). Climate Change: Evidence and Causes. National Academy of Sciences, The Royal Society. https://nas-sites.org/americasclimatechoices/more-resources-on-climate-change/climate-change-evidence-and-causes/climate-change-evidence-and-causes-figure-gallery/
3. Figure 14.1 from Young, O.R. and Steffen, W. (2009). 'The Earth System: Sustaining Planetary Life-Support Systems'. From Folke, C., Kofinas, G. P. and Chapin, F.S. (eds.) (2009). Principles of Ecosystem Stewardship. Springer New York. pp 295-315. http://www.cs.toronto.edu/~sme/PMU199-climate-computing/pmu199-2012F/notes/Discovery_of_Global_Warming.html
4. Source: FigBox 3.1-1 from Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley and F. Wang (2013). 'Observations: Ocean'. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
5. Schellnhuber, H. J. (2013). 'Avoiding the unmanageable, managing the unavoidable'. From Chatham House event on 'Delivering Concrete Climate Change Action'. Available ay http://www.chathamhouse.org/sites/files/chathamhouse/home/chatham/public_html/sites/default/files/0900%20John%20Schellnhuber.pdf
6. International Organization for Standardization definition
7. International Risk Governance Council (2012). An Introduction to the IRGC Risk Governance Framework. Available at http://www.irgc.org/wp-content/uploads/2015/04/An_introduction_to_the_IRGC_Risk_Governance_Framework_final_v2012.pdf
8. See The New Climate Economy online report, available at: http://newclimateeconomy.report/
9. Diamond, J. (2011) 'Collapse – How Societies Choose to Fail or Survive'. Penguin Books, p436.
10. As quoted in 'The New Nuclear Age'. The Economist, 6 March 2015.

2 PRINCIPLES, SCOPE AND APPROACH OF THIS RISK ASSESSMENT

Including contributions from **Dr David Hare**, **Trevor Maynard**, **General Ronald E. Keys** & **Cherie Rosenblum**, and **Dr Claire Craig**

What is new about this assessment?

Many climate science reports and climate change risk assessments have been published by governments, research institutes and other agencies around the world. Most notably, the reports of the Intergovernmental Panel on Climate Change (IPCC), which summarize the findings of thousands of scientists, have made an enormous contribution to our collective knowledge. To a very great extent, our assessment relies on the findings of those earlier assessments.

While some new scientific and other studies have been undertaken to provide content for this report, our main aim has been to collate and present existing knowledge in a way that is consistent with the principles of risk assessment. In particular, we have aimed to put forward a risk assessment that will be relevant to governments' decision-making on how to respond to the problem of climate change as a whole, including through policy on emissions ('mitigation', in the climate policy jargon). This sets it apart from those risk assessments that are primarily intended to inform decision-making on the response to specific impacts of climate change (known as 'adaptation').

We have aimed to be holistic: to take into account the different factors and the different kinds of knowledge that are most relevant to an understanding of the risk. The assessment considers four main areas:

1. **The future pathway of global greenhouse gas emissions.** The future rate and extent of climate change, and all the risks that flow from it, depend significantly on the future pathway of global emissions. Since no government controls global emissions, from the point of view of any individual government (or person) this is a variable that depends mainly on the actions of other governments – as well as on non-governmental forces, such as technological progress, economic trends, investor sentiment, and popular will.

2. **The changes in the physical climate, and their direct risks to human interests.** Whatever emissions pathway is eventually followed, the risks will depend on how the physical climate responds: how much temperature rises in response to emissions; how changes in temperature influence changes in rainfall; how changes in temperature, rainfall and other factors lead to changes in crop yield, etc. The risks to human interests will also depend on how successfully we can adapt to these changes. The most significant risks may arise if thresholds are crossed beyond which certain kinds of adaptation are no longer possible.

3. **The systemic risks arising from interactions between changes in the physical climate and human systems.** In complex systems, small changes can sometimes lead to large divergences in future state. The risks of climate change to human interests will depend not only on the direct impacts of changes in the physical climate, but also on the response of complex human systems such as the global economy, food markets, and the system of international security.

4. **The value we choose to give to all of the changes that might take place.** If risk is defined as 'the effect of uncertainty on objectives', or as the chance of an adverse impact on something that we value, then a risk assessment cannot be complete without some subjective judgment being made about what one's objectives are, what it is that one values, and what value one places on avoiding the adverse impacts. Only once some value judgment has been made can the risk assessment be useful in informing decisions.

In each of these four areas, we have drawn on different expertise, and taken different approaches.

Our assessment of the future pathway of global greenhouse gas emissions is a political and a technological assessment. With regard to the short-term future, it looks in particular at the policies, plans and targets that governments are implementing or have announced. With regard to the long-term, it concentrates on describing the main technological challenges to reducing emissions, and considering their difficulty or the level of effort it might take to overcome them. By attempting to make some judgment about the relative likelihood of different emissions pathways, this assessment differs from others, such as those of the IPCC, which do not.

The section on changes in the physical climate and their direct risks to human interests is a scientific assessment. It attempts to be consistent with the principles of risk assessment by asking first what it is that we might wish to avoid, and then how likely that is to occur. Many climate change risk assessments apply this principle to consideration of the risk of extreme weather events, so as to use this information to inform decision-making on disaster risk reduction and climate change adaptation. We also apply it to a consideration of long-term changes, and the risk that even the averages of climatic variables eventually reach extreme values or exceed important thresholds, since this is relevant to decision-making on energy and emissions.

Our consideration of the systemic risks arising from interactions between changes in the physical climate and complex human systems is in large part a security risk assessment. Recognizing the depth of uncertainty about the future state of complex systems, it uses the futures tools of scenarios and wargaming to help us think about what might happen. It differs from much of the published literature on climate change and security by deliberately making explicit distinctions between security risks in the near-term with low degrees of climate change, and security risks in the long-term with high degrees of climate change.

Finally, our consideration of the value we choose to give to all of the changes that might take place is based on a recognition of the essential subjectivity of this question. Rather than attempt to quantify this value, we focus on making clear the limitations of a quantitative approach. We highlight the inescapable ethical questions that economics can inform, but not answer. Rather than put forward any valuation as being 'correct', we invite readers to make up their own minds.

The introductory sections at the beginning of each of the four parts of the risk assessment set out our approach in more detail.

Principles of risk assessment

While each stage of our risk assessment has drawn on different kinds of knowledge and applied different methodologies, we have tried to be consistent in our application of some basic principles. We identified these principles from literature on risk assessment, and from discussions with expert practitioners in risk assessment from the fields of finance and national security.[1]

The principles of risk assessment that we have applied are:

1. **Identify risks in relation to objectives.** As one guide to risk assessment states, 'Risk assessment begins and ends with specific objectives.'[2] As noted above, our risk assessment ends with the consideration of value, which we recognize as being essentially subjective. But we must also start with some objectives, otherwise we cannot identify risks to them. So we have assumed that that our common objectives are human prosperity and security, and it is risks to those objectives that we consider. It follows from this principle that in assessing risks, we ask first what might happen that could most affect our interests, and then how likely that would be to occur. (We do not ask first what is most likely to happen, and then how that would affect our interests.)

2. **Identify the biggest risks.** This follows logically from the first principle. The more a risk could affect our objectives, the more relevance it is likely to have for our decision-making. If risk is defined simply as the product of likelihood and impact, then the biggest risks may be those which are most likely to occur, or those which would have the greatest impact, or those which fall somewhere in between. Mathematically speaking, this will depend on the shape of the probability distribution function. In practice, the risks of most concern are usually those with the greatest impact, especially when there is potential for irreversible consequences (e.g. death).

3. **Consider the full range of probabilities.** This follows from the second principle, since the biggest risks could lie anywhere in the probability distribution. However, it is worth stating separately, because of the particular importance of not ignoring low probability, high impact risks. It is a matter of judgment how low a probability is worth considering. Insurance firms in Europe are regulated to guard against '1 in 200 year' risks to their solvency (i.e. risks that have a 0.5% probability of occurrence in a given year). It has been argued that if preserving a stable climate is as important as avoiding the insolvency of an insurance firm, then we should apply no less a cut-off point to our consideration of climate risks.[3] The UK Government's *National Risk Register of Civil Emergencies* gives serious consideration to risks with even lower probabilities: for example, the risk of major industrial accidents, which is assessed to have a likelihood of between 1 in 20,000 and 1 in 2,000.[4] When a probability cannot be meaningfully quantified, it is usual to consider a 'plausible worst case'. Again, the question of what is a relevant threshold of 'plausibility' is a matter of judgment.

4. **Use the best available information.** This may be quantitative or qualitative, the results of experiments or the exercise of expert judgment. Even where there is deep uncertainty, a best estimate – based on the best available information – is usually better than no estimate at all. Where there is no information, ignorance itself may be a data-point that is relevant to decision-making – as it would be to a man walking along a cliff-top in a heavy fog.

5. **Take a holistic view.** This means taking into account all relevant factors, as far as possible – including human behaviour, and the complex interactions between different parts of a system. While models can be useful for understanding complex systems, factors that fall outside the consideration of a model should not be ignored. When a system is impossible to model in a meaningful way, scenarios may be developed to imagine its possible future states.

6. **Be explicit about value judgments.** Subjective value judgments are inherent both in identifying what constitutes a risk (i.e. what it is that we might wish to avoid), and in deciding how much we care about it. These value judgments need to be clear and explicit, so that readers can easily apply different values if they choose. At the same time, once a risk has been identified, the assessment of its likelihood should be entirely objective, based on the best available information.

Finally, as recommended by the International Risk Governance Council,[5] we have maintained a clear separation between risk assessment – analyzing and understanding a risk – and risk management – deciding what to do about it.

Here we present some brief perspectives from the fields of finance, security and government science advice to further illustrate some of these principles and their relevance to understanding the risks of climate change.

An actuarial perspective

Dr David Hare, **Immediate past-President of the Institute and Faculty of Actuaries**

Climate change is primarily a risk management problem – one of the most important goals of climate change policy should be to limit the probability of a very bad outcome to an acceptably small value.

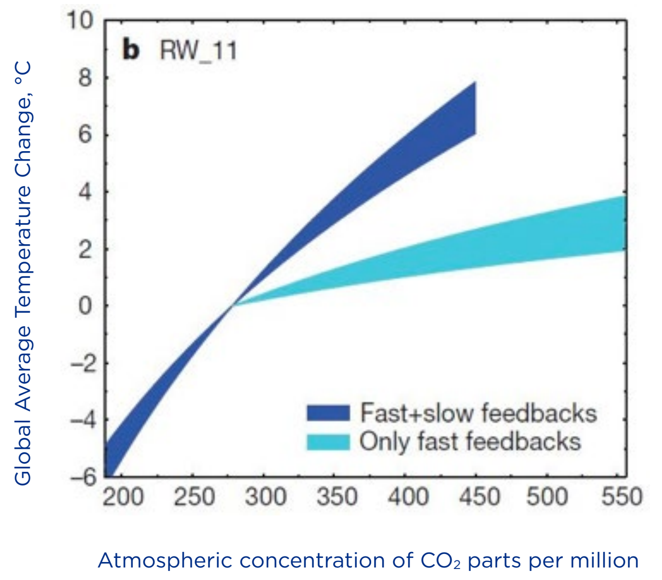
Risk assessment in the actuarial profession is based on understanding scenarios that could have the greatest impact, even if the probability is low – we are concerned with protecting against the 'risk of ruin'. To assess and manage the risk of ruin in the insurance industry actuaries rely on three important elements: models to determine sufficient capital to cover liabilities that could arise from a '1 in 200 year event'; scenario testing to manage risks and assess future risks; and, disclosure and transparency to assist market forces in imposing discipline on firms.

Modelling alone will not assess or manage risk effectively – all three aspects of risk assessment are required and are applicable in the case of climate change risk:

- Risk models are a representation of the world (albeit imperfect) and should reflect all appropriate quantitative and qualitative data. A factor that is important in determining risk should never be excluded from consideration simply because it cannot be quantified.
- Understanding risk drivers and contingent risks is critical in determining potential outcomes. For climate change, risk drivers include human emissions, climate feedbacks, and human vulnerability. Contingent risks include 'second order' risks, such as political instability arising as a result of climate change impacts on food and water security.
- Transparency and disclosure of risks are paramount so that markets and decision-makers can respond to risk appropriately.

One of the key risk drivers for climate change is the response of global temperatures to emissions. If only 'fast feedbacks' are taken into account, relatively low temperature increases will be calculated. But past climate change indicates that in the long term, 'slow feedbacks' can lead to much higher temperature increases (see Figure 5). A risk management approach should examine the risks that these 'slow feedbacks' are relevant to us and consider the scenarios of most concern. In actuarial work, it is the extreme cases that we consider to be the most important.

Figure 5: **Example of a non-modelled risk**; alternative estimates of temperature sensitivity to CO_2 (plotted areas include uncertainty of 1 standard deviation, the full range of possible outcomes is wider).[6]



Good decisions are often based on exploring difficult scenarios and then using this information to mitigate the risk. In the case of climate change, the question remains – are we focusing too much attention on a 2°C world, rather than the risk of a more extreme temperature rise of 4°C or more? These more extreme scenarios are possible by the end of the century and, due to the uncertainty about the nature and scale of impacts, there is no certainty that adaptation will be successful.

A reinsurance perspective

Trevor Maynard, **Head of Exposure Management and Reinsurance, Lloyds of London**

Risk assessments in reinsurance use a mixture of methods including horizon scanning, scenario tests and catastrophe modeling. The principles of risk assessment we apply include: (i) concentrate your effort on the largest risks, (ii) base analysis on the best available information, (iii) avoid the dangers of averaging, (iv) carry out continual reassessment of the risk; (v) cater for human factors and (vi) take account of uncertainty.

Human factors are critically important in assessing the risk of climate change. Just as our catastrophe models consider the uncertainty in natural hazards, so our climate policy must be based on risk assessments that consider the possibility that the negotiations fail, that some carbon capture technologies do not deliver, that policies may be reversed by future administrations, etc. When these are considered we will see that extreme outcomes are much more likely, and we may decide to strengthen our actions so as to avoid them.

Avoiding the dangers of averaging is important in identifying the largest risks. My friend Professor Lenny Smith has an excellent analogy to bring this point home. Imagine three policymakers who like river walking; none of whom can swim. They ask their scientific advisor whether the depth of water ever exceeds head height. The advisor asks three universities to develop models: the first notes that the water exceeds head height near to the west shore, the second believes this is not the case but water exceeds head height in the centre of the river and the third, being very fond of their model, believes the others are both wrong and the water only exceeds head height near the east shore. The advisor, noting the uncertainty in the modeling, believes the best approach is to average the three results. The outcome is regrettable! The fact is that each of the models predict certain death – but the precise location is not known. By averaging, this crucial information is lost.

In my view, much time is spent worrying about whether a particular climate model is correct regionally. We cannot predict exactly what temperatures will be in future at different locations, what the sea level rise will be; how much extreme rainfall or drought will change – but the majority of climate models predict dire outcomes somewhere – hence that overall prediction, that outcomes will be very serious indeed is very robust – even if the details are not.

The best available information can take many forms; sometimes, all we have to rely on is expert judgment. In these cases, it is essential for the expert to communicate without bias. It has always concerned me that our use of the word ‘conservative’ has the opposite meaning in insurance to its meaning in science. Scientists are ‘conservative’ if they constrain their worst fears, and wait for more evidence before communicating them; therefore, ‘conservative’ predictions tend to understate risk – they are less than best estimates. In insurance, ‘conservative’ reserves are higher than would be required by best estimates. In matters of risk assessment, I feel the insurance point of view is more appropriate.

A security perspective

General Ronald E. Keys, **USAF (ret.) Former Commander, U.S. Air Force Air Combat Command, Chairman CNA Military Advisory Board.** **Cherie Rosenblum**, **Executive Director, CNA Military Advisory Board.**

The military and security community is constantly dealing with decision-making under imperfect information and uncertainty. General Gordon Sullivan, former Chief of Staff of the U.S. Army, stated in the first CNA Military Advisory Board report *“We never have 100 percent certainty. We never have it. If you wait until you have 100 percent certainty, something bad is going to happen on the battlefield.”* There is inherent risk in decision making with incomplete information, but as General Sullivan says, the decision-maker cannot wait. General Sullivan’s comments get to the foundation of why risk assessment, risk management—and the ability to act under uncertainty—is so critical in dealing with the impacts of a changing climate.

Risk assessment has to pay attention to low probability, high impact risks. As Admiral Frank ‘Skip’ Bowman, United States Navy (Retired) has said: *“Even very low probability events with devastating consequences must be considered and mitigation/adaptation schemes developed and employed. We operate our nuclear submarine fleet in this fashion. Some may argue that this continuing process results in overdesign and overcautiousness. Maybe so, but our U.S. submarine safety record testifies to the wisdom of this approach. That’s where we should be with climate change knowns and unknowns.”*

In a second report on the national security risks of climate change, the CNA Military Advisory Board warned against a ‘failure of imagination’ with regard to situations of deep uncertainty:

> *“When it comes to thinking about how the world will respond to projected changes in the climate, we believe it is important to guard against a failure of imagination. For example, in the summer of 2001, it was, at least partly, stovepipes in the intelligence community and a failure of imagination by security analysts that made it possible for terrorists to use box cutters to hijack commercial planes and turn them into weapons targeting the World Trade Center and the Pentagon. Regarding these threats, the 9/11 Commission found “The most important failure was one of imagination. We do not believe leaders understood the gravity of the threat. The ... danger ... was not a major topic for policy debate among the public, the media, or in the Congress....” Failure to think about how climate change might impact globally interrelated systems could be stovepipe thinking, while failure to consider how climate change might impact all elements of U.S. national power and security is a failure of imagination.”*

One of the key purposes of risk assessment is to allow decision-makers to weigh choices for action under uncertainty. To give leaders a process to evaluate threats, probabilities, outcomes, and courses of action with incomplete information, in this case, divorced from political pain and personal preferences. If policy-makers, under the guise of ‘waiting for perfect information’, fail to set strong climate change mitigation and adaptation policies today, they are ignoring the risks to our economy and our national security for the future. Risk analysis is pretty simple really: ‘How bad can it be? Can I stand that? And if not, how do I move the fallout back to something I can live with, and when must I start?’ Two other points are critical: (i) how will I know my plan is working or not in time to change it? And (ii) if we are wrong, what’s the cost and how bad could that be? Not making any decision is actually letting fate decide. The military adage is, ‘Plan for the worst, hope for the best, and accept anything in between’ – and act.

The CNA Corporation’s Military Advisory Board (MAB) is a group of sixteen retired Generals and Admirals that studies global issues to assess their impact on national and global security.

A government science adviser’s perspective

Dr Claire Craig, **Director, UK Government Office for Science**

To understand systemic risks we must draw on evidence from all forms of science and scholarship.

> *“The infrastructure created by humans and the natural infrastructure of the planet are both vital for our survival and wellbeing. It is only possible for more than seven billion people to inhabit the Earth because of our ability to modify our environment. We achieved this by creating social and physical structures, and by discovering how to harness the fossil energy sources of the planet to power our modern world. But in spite of all our innovation and ingenuity we are still critically dependent on our natural infrastructure, on our interactions with animal and plant health, on weather, climate and all the other aspects of the physical and biological environment of the planet.[7]”*

The UK Government Office for Science provides science advice in situations that range from emergencies such as the Fukushima Daiichi nuclear incident or the recent Ebola outbreak, to the exploration of the very long term such as in the future of cities.

It is true in all cases that management of any risk (or opportunity) of significance to decision-makers requires evidence from both the physical and the human sciences. Usually, this is because assessment of the risk and its responses requires insights into the behaviour of complex systems in which human and physical behaviours are coupled. Also, because the aim is to change the future the evidence must facilitate action, and actionable evidence requires insights into human behaviour.

A practical example comes from the UK's National Risk Register.[8] There, the overviews of the consequences for each risk explicitly include both direct and indirect or systemic impacts. The potential consequences of pandemic flu, for example, include the direct medical impact of dealing with infections, together with indirect impacts causing social and economic disruption including potential threats to the continuity of essential services, lower production levels, and shortages and distribution difficulties.

During the recent Ebola emergency, the UK worked with US, French and other partners to manage risks at source and in the home nations. Getting this right required sophisticated epidemiological modelling. But decision-makers also drew on the behavioural and social sciences, including anthropology and history, to help understand human behaviours such as the significance of traditional burial customs. This enabled them to better assess and anticipate the risks, and to design and monitor interventions to bring the rates of infection down as rapidly as possible.

What is true about facing up to risk in the short term is also true about major long term risks. It is certainly true for our understanding of climate risk. We need to consider the role of climate change as risk multiplier and the interdependencies between different sources of risk.[9] GO-Science's Foresight programme has shown how intimately climate change interacts with social, technological and economic drivers to shape possible futures in the global food and farming system, in patterns of international migration and in flood risk.[10] These studies show that we need to get from considering the physics of climate change in isolation, to a better understanding of how intimately climate change interacts with social, technological and economic drivers.

Scope of the risk assessment, in space and in time

A risk assessment informs decision-making by providing information about the possible consequences of decisions. So it is logical that a risk assessment should have a scope in space and time that is wide enough to include the most significant consequences of the decisions it is aiming to inform.

As stated above, our risk assessment is intended primarily to inform governments' decision-making on emissions policy. The consequences of emissions – the risks of climate change – occur in every part of the world, and so it follows that our risk assessment should have a global scope. Since we have not attempted to be comprehensive, we have described a range of risks across the world that we think may be of particular interest to decision-makers in national governments, particularly those of countries with significant economic size and political influence.

The logical scope in time of a climate change risk assessment is perhaps not so obvious. Risk assessments often have a relatively short-term focus: the UK Government's *National Risk Register of Civil Emergencies* considers only the next five years, and its *National Security Risk Assessment* only the next twenty. The risks of climate change that could occur over such short time periods are irrelevant to decision-making on emissions: inertia in the climate system means nothing we do now to reduce emissions will have any significant effect for at least the next couple of decades.

Decisions relating to emissions have consequences beginning in the medium term, and lasting over a very long time period. Once a coal-fired power station is built, it is likely to keep operating for several decades (though not inevitably: it could be closed early, if that cost is accepted). Once carbon dioxide has been emitted to the atmosphere, a substantial fraction of it will still be there, changing the climate, ten thousand years later.[11] So it makes sense for a climate change risk assessment to consider the long term.

A long-term view is not unique to climate change: in assessing the risks arising from the storage of radioactive nuclear waste, governments have considered timeframes of thousands, hundreds of thousands, and even a million years.[12] But climate change has a particular characteristic that makes consideration of the long term even more important: the risks of climate change tend to increase over time. This is likely to be true at least for as long as emissions of greenhouse gases are above zero, their concentration in the atmosphere is increasing, and the global temperature is going up. This makes the risks of climate change quite different from the risks of natural hazards such as earthquakes, which tend to be roughly constant over time in a given location, or the risks from a radioactive waste deposit, which will gradually decrease over time (see Figure 6). For climate change, if we do not consider the long term, we will not be considering the biggest risks.

Figure 6: **A risk roughly constant over time:** major earthquakes[13]

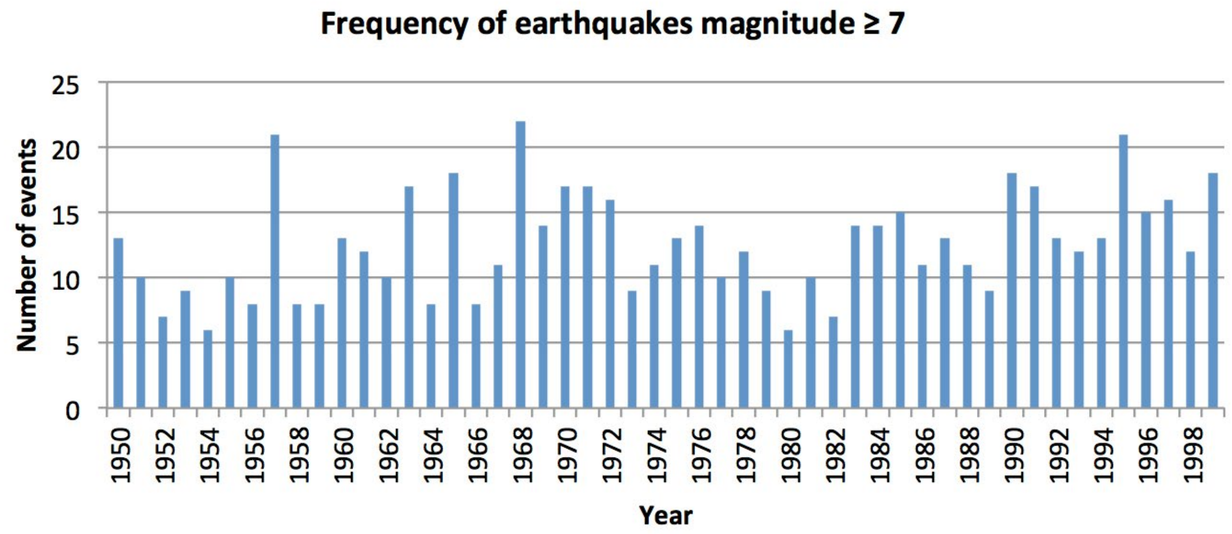


Figure 7: **A risk that decreases over time:** radioactivity from nuclear waste[14]

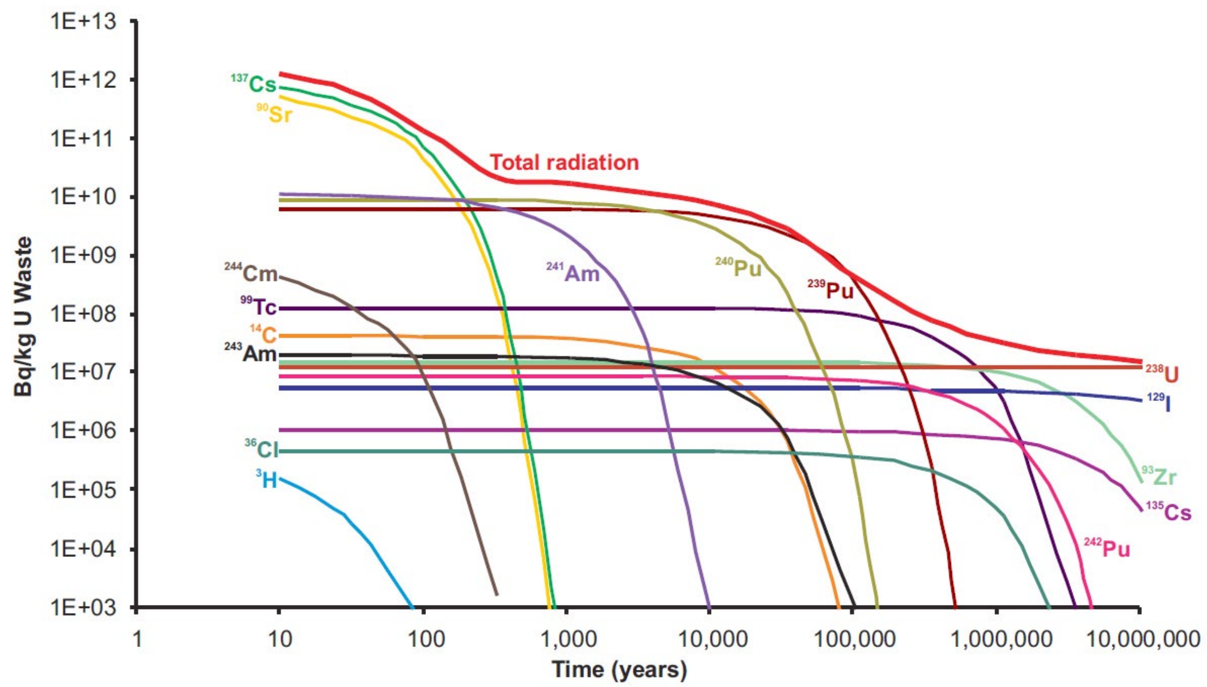
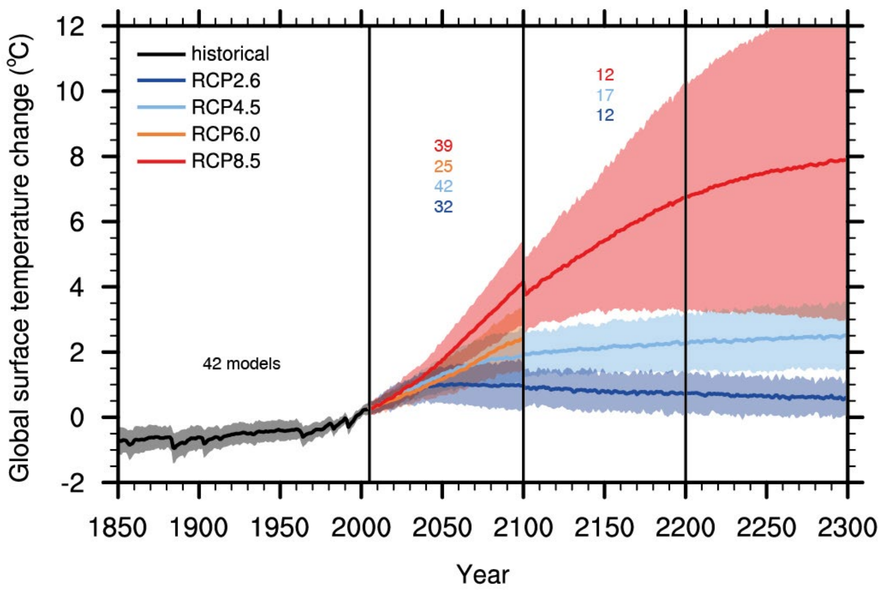


Figure 8: **A risk that increases over time:** climate change[i, 15]



For the purposes of this risk assessment, we have imposed no limit on the time period under consideration. However, in practice the time period for which a risk assessment can be meaningful depends on the quality of information available, and the degree of complexity of the risks. For very large, slow-moving components of the climate system such as continental ice-sheets, it is both possible and informative to consider what might happen over hundreds and even thousands of years. The direct risks of climate change – such as the impact on crop yields – are often assessed out to the year 2100; in some cases we have found it possible to look a little further. For the systemic risks, such as risks to global security, it is extremely difficult to consider as far ahead as the end of the century.

In general, we have aimed to look as far ahead as information or reasonable judgment will allow, and we leave it to readers to decide how much importance they attach to what could occur over different periods of time.

i. Full IPCC caption: Time series of global annual mean surface air temperature anomalies (relative to 1986–2005) from CMIP5 concentration-driven experiments. Projections are shown for each RCP for the multi-model mean (solid lines) and the 5 to 95% range (31.64 standard deviation) across the distribution of individual models (shading). Discontinuities at 2100 are due to different numbers of models performing the extension runs beyond the 21st century and have no physical meaning. Only one ensemble member is used from each model and numbers in the figure indicate the number of different models contributing to the different time periods. No ranges are given for the RCP6.0 projections beyond 2100 as only two models are available.

Endnotes

1. Sources used to identify these principles include:
(i) Federation of European Risk Management Associations (2013). A structured approach to enterprise risk management (ERM) and the requirements of ISO 31000. Retrieved from http://www.ferma.eu/app/uploads/2011/10/a-structured-approach-to-erm.pdf
(ii) International Risk Governance Council (2008). An introduction to the IRGC Risk Governance Framework. Retrieved from http://www.irgc.org/risk-governance/irgc-risk-governance-framework/
(iii) UK Cabinet Office (2012). National Risk Register of Civil Emergencies.
(iv) UK Government. Guidance: Risk assessment: how the risk of emergencies in the UK is assessed . Retrieved from https://www.gov.uk/risk-assessment-how-the-risk-of-emergencies-in-the-uk-is-assessed
(v) UK Government. Fact Sheet 2: National Security Risk Assessment.
(vi) PriceWaterhouseCoopers (2008). A practical guide to risk assessment.
(vii) UK Health and Safety Executive (2001). Reducing Risks, Protecting People: HSE's decision-making process. Retrieved from www.hse.gov.uk/risk/theory/r2p2.pdf
(viii) Committee of Sponsoring Organizations (2004). Enterprise Risk Management – Integrated Framework.
(ix) US Department of Justice (2005). Assessing and Managing the Terrorism Threat.
(x) Engineering Council (2011). Guidance on risk for the engineering profession .Retrieved from http://www.engc.org.uk/about-us/guidance-on-risk
2. PriceWaterhouseCoopers (2008). A practical guide to risk assessment. p.15
3. Oliver Bettis (2014). Risk Management and Climate Change: Risk of Ruin. Retrieved from http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2014/01/Oliver-Bettis-Risk-Management-and-Climate-Change-Risk-of-Ruin.pdf
4. Cabinet Office (2012). National Risk Register of Civil Emergencies. p.8
5. International Risk Governance Council (2008). An introduction to the IRGC Risk Governance Framework. p.8
6. PALEOSENS project members (20120). 'Making sense of paleoclimate sensitivity'. Nature 491, 683-691. doi:10.1038/nature11574. Also see Kirby, A. 'Earth "may be doubly sensitive" to CO_2'. Climate New Network. http://www.climatenewsnetwork.net/2013/12/earth-may-be-doubly-sensitive-to-co2/
7. Annual Report of the Government Chief Scientific Adviser 2014 (2014). Innovation: Managing Risk, Not Avoiding It. Available at https://www.gov.uk/government/publications/innovation-managing-risk-not-avoiding-it
8. UK Government (2015). National Risk Register of Civil Emergencies – 2015 Edition. Available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/419549/20150331_2015-NRR-WA_Final.pdf
9. Foresight Report on the "International Dimensions of Climate Change", July 2011; https://www.gov.uk/government/publications/international-dimensions-of-climate-change
10. Government Office for Science (2011). The Future of Food and Farming. Available at https://www.gov.uk/government/publications/future-of-food-and-farming; Government Office for Science (2011). Migration and Global Environmental Change: Future Challenges and Opportunities. Available at https://www.gov.uk/government/publications/migration-and-global-environmental-change-future-challenges-and-opportunities; Government Office for Science (2004). Future Flooding. Available at https://www.gov.uk/government/publications/future-flooding.
11. Inman, M. (2008) 'Carbon is Forever'. Nature Reports Climate Change. Retrieved from http://www.nature.com/climate/2008/0812/full/climate.2008.122.html
12. Blue Ribbon Commission on America's Nuclear Future (2012), Report to the Secretary of Energy. p.90, retrieved from http://energy.gov/sites/prod/files/2013/04/f0/brc_finalreport_jan2012.pdf Thanks to Bob Ward from the London School of Economics for pointing this out.
13. Data from the National Centres for Environmental Information.
14. Retrieved from http://blogs.egu.eu/network/geosphere/2015/02/02/geopoll-what-should-we-do-with-radioactive-waste/
15. Source: Figure 12.5, Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner (2013). 'Long-term Climate Change: Projections, Commitments and Irreversibility.' Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

RISK ASSESSMENT PART 1:

EMISSIONS

WHAT IS THE PROBABILITY OF FOLLOWING A HIGH EMISSIONS PATHWAY?

RISK ASSESSMENT PART 1:

EMISSIONS

WHAT IS THE PROBABILITY OF FOLLOWING A HIGH EMISSIONS PATHWAY?

Contributing authors to this section: **Professor Daniel Schrag**,[i] **Professor Qi Ye**,[ii] **Dr Arunabha Ghosh**,[iii] **Mr Anil Jain**,[iv] **Professor Zhou Dadi**,[v] **Professor Sir David King**,[vi] **Professor David MacKay**,[vii] **Dr Elmar Kriegler**.[viii]

In this part of our risk assessment, we attempt to comment on the relative likelihood of different future pathways of global emissions. This approach differs from climate change assessments in which emissions pathways are presented as 'equally plausible', with no comment on their probability. We begin by explaining why, for our purpose, this difference in presentation is necessary.

3 HISTORY AND PURPOSE OF THE IPCC SCENARIOS

In 1992, the Intergovernmental Panel on Climate Change (IPCC) developed a series of scenarios (IS92) to evaluate future greenhouse gas trajectories and future climate. The purpose of using scenarios was to allow the climate assessment to compare climate model results based on identical greenhouse gas emissions over time. There were six scenarios, covering a wide range of trajectories, from low emissions scenarios that had CO_2 emissions peaking by 2020 below 8 billion tons (Gt) of carbon per year, to high emissions scenarios that had emissions growing steadily through the century, reaching 35 Gt of carbon by 2100.

In 2000, in preparation for the third Assessment Report (TAR), the IPCC published a Special Report on Emissions Scenarios (SRES), which replaced the IS92 scenarios with 40 different scenarios, grouped into six 'families', each with common themes for the major factors controlling greenhouse gas emissions. For the SRES scenarios, each family had projections for population, economic growth, economic disparity between Annex I and non-Annex I countries, and energy technologies. These scenarios covered a slightly narrower range as the IS92 scenarios, although still including a low-emissions scenario that had emissions decreasing through most of the century, and several high-emissions scenarios that showed emissions continuing to grow through 2100.

For the climate science assessment ('Working Group I') of the Fifth Assessment Report, the IPCC switched to using a new set of scenarios – called 'Representative Concentration Pathways' (RCPs). RCPs moved away from explicitly describing the various social factors such as economic or population growth. Instead, the RCPs describe four emissions pathways that lead to four different levels of radiative forcing in 2100 (+2.6, +4.5, +6.0 and +8.5 W/m^2). The RCPs were the first IPCC scenarios to explicitly consider emissions past 2100. We know from a variety of modelling studies that peak warming depends primarily on global, cumulative emissions of CO_2, the most important greenhouse gas, a significant portion of which remains in the atmosphere for tens of thousands of years. Thus, extending the scenarios beyond 2100 is important

i. Director, Harvard University Center for the Environment
ii. Director, Brookings-Tsinghua Centre for Public Policy, Tsinghua University
iii. CEO, Council on Energy, Environment and Water
iv. Senior Energy Analyst, National Institute for Transforming India (NITI Aayog). Mr Jain's views are given in his personal capacity and do not necessarily represent the official position of NITI Aayog.
v. Former Director General, Energy Research Institute, National Development and Reform Commission of China
vi. UK Foreign Secretary's Special Representative for Climate Change
vii. Regius Professor of Engineering, University of Cambridge; former Chief Scientific Advisor to the UK Government Department of Energy and Climate Change
viii. Vice Chair of Sustainable Solutions, Potsdam Institute for Climate Impact Research

because it emphasizes that stabilizing radiative forcing requires that emissions must ultimately decrease to near zero. However, because the social factors are not specified, the RCPs can emerge from a diverse set of possible socio-economic trajectories, as slower growth in energy consumption due to reduced economic growth, for example, could compensate for a slower shift to non-fossil energy systems, or faster growth in global population.[1] The simplicity of the RCP scenarios is an advantage, but it also makes it somewhat difficult to understand the underlying drivers of the greenhouse gas emissions.

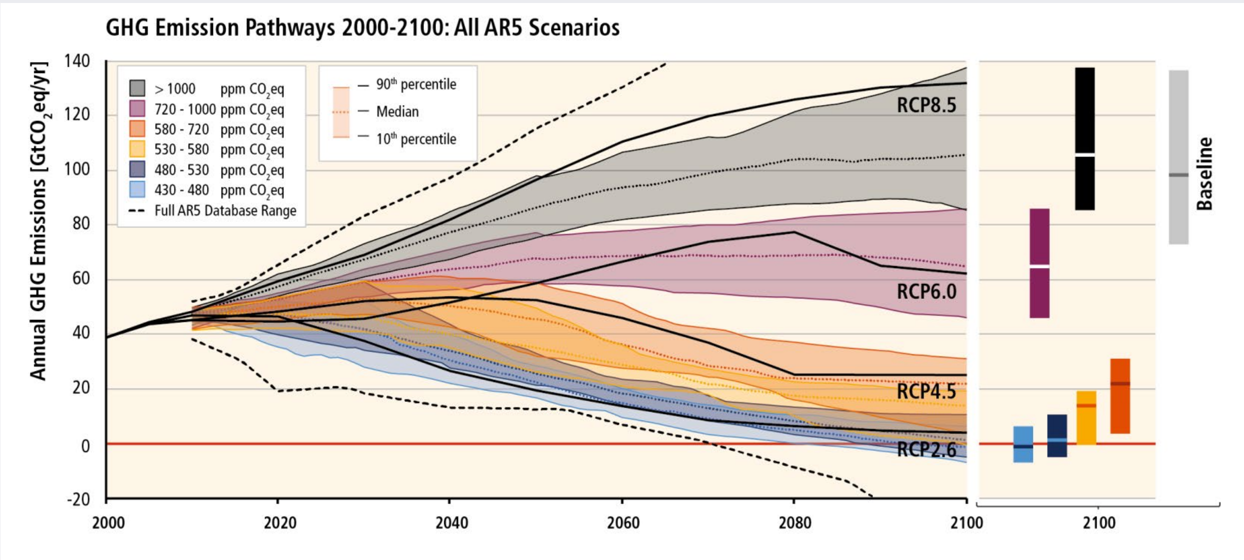
None of the three generations of IPCC scenarios were ever considered to be 'predictions' of the future, but simply different possible futures of greenhouse gas emissions. This allowed the main focus of the climate science assessment to be the carbon cycle and the climate system, without also needing to confront the huge range of factors that affect how global greenhouse gas emissions will change over time. One can easily understand why this decision to avoid any discussion of probability of the different scenarios was made, given the complexities of reaching consensus across all of the participating countries, and given the genuine uncertainties in all of the social factors. If the objective is simply assessment of climate science, then the approach of considering a range of different emissions trajectories, and then focusing on how the carbon cycle and climate system responds to each, is quite reasonable.

At the same time, a much larger range of scenarios, reviewed by the IPCC reports on mitigation ('Working Group III') has looked in depth at how social, political, economic, and technological factors could affect the future pathway of global emissions. This work helps illustrate what might be a plausible range for future emissions (see Box: 'Framing the plausible range'), and supports our understanding of the relative importance of the different variables.

Framing the plausible range

Models of the global system of energy, land use, population and economy provide a way to project future emissions on the basis of changes in socioeconomic trends and policy choices. In recent years, such models have been used to produce more than a thousand emissions scenarios. Taken together, these give us an idea of a plausible range for global emissions over the course of the century (see Figure 1).

Figure 1: **Emissions scenarios reviewed in the Fifth Assessment Report of Working Group 3 of the IPCC. Scenarios are grouped according to their CO_2 equivalent concentrations in the year 2100 (see colour legend).**[ix] Source: IPCC Fifth Assessment Report Working Group III Figure 6.7[2]



ix. Figure caption as used in source: | Emissions pathways for total CO2 and Kyoto gases for the various categories defined in Table 6.2. The bands indicate the 10th to 90th percentile of the scenarios included in the database. The grey bars to the right of the top panels indicate the 10th to 90th percentile for baseline scenarios (see Section 6.3.1). The bottom panels show for the combined categories 430–530ppm and 530–650ppm CO2eq the scenarios with and without net negative emissions larger than 20GtCO2eq/yr. Source: WG III AR5 Scenario Database

At the top end of the range are scenarios where no deliberate action is taken to reduce emissions, and fossil fuel (particularly coal) availability, economic growth and population growth are all assumed to be high. In these scenarios, emissions can more than triple by the end of the century. In all of the scenarios reviewed in the IPCC's Fifth Assessment Report in which no deliberate action is taken to reduce emissions, emissions continue to increase throughout the century, whatever assumptions are made about population growth, economic growth, energy intensity of the economy, and fossil fuel availability. Typically in these scenarios, emissions by the end of the century are more than double their level in 2010.

In scenarios that incorporate some of the emissions-reducing measures that have already been announced or implemented by various countries and regions, and extrapolate a similar level of effort into the longer term future, emissions tend to increase until around the middle of the century, and then slowly return to around present day levels by the end of the century.

'Climate stabilization scenarios' are those in which emissions are calculated backwards from the achievement of a target level of warming or of greenhouse gas concentrations. At the low end of the range are scenarios designed to be consistent with a good chance of limiting warming to 2°C. These scenarios typically reach near-zero emissions by the end of the century, and require net negative CO_2 emissions from the energy supply and land use sectors to compensate for remaining positive emissions of other greenhouse gases from land use and CO_2 emissions from transport.

4 TOWARDS A 'RISK' PERSPECTIVE ON EMISSIONS SCENARIOS

Our purpose here is to provide an assessment of risk that countries face from climate change. Emissions trajectories (and cumulative emissions) ultimately control how much climate change the world will experience, so they must be a central part of that assessment. But if risk is the product of probability and impact, then with no estimate of probability, there can be no estimate of risk. For this purpose, a neutral presentation of emissions scenarios is inadequate.

Providing governments with probabilistic assessments of different emissions scenarios therefore seems fundamental to helping them assess the risks of climate change, and make good decisions about risk management. If some scenarios in the group are much more likely than others, on the basis of information available today (even with the enormous uncertainties in factors such as economic growth or technological change), then it is critical for those judgments to be communicated to policy makers around the world. If those judgments are not communicated, then policymakers may either misinterpret the experts' selection of scenarios as representing such judgments, or they may base their decisions on their own estimates of the probabilities, whether these are explicitly stated or not.[3]

But placing probabilistic estimates on different emissions scenarios for the world is more easily said than done. Forecasting the future of global CO_2 emissions from fossil fuel consumption alone, leaving aside other greenhouse gases and emission due to land use, requires predictions of world economic growth and technological change over the next two centuries or more, as well as the possibility that climate policies will significantly influence these. There are so many uncertainties, with a high likelihood of technological, political and social surprises of many sorts that could fundamentally change the answer. The task seems Herculean.

As a starting point, we can look at how some probabilistic judgments are already present in the world of energy and emissions scenarios. The range of scenarios used and reviewed by the IPCC is not as wide as is physically possible: burning all the accessible fossil fuels in the ground could sustain high emissions for longer than the highest scenario pathway, and, in theory, an enormous effort to capture carbon and bury it underground could produce emissions lower than the lowest scenario pathway. The range has been constrained not as much by physics as by a judgment about what is plausible. Similar judgments were made in a scenario-based study[4] that took a carbon price of $1000/tonne of CO_2 to be the limit of 'economic feasibility', and in another that concluded that although models could compute climate pathways reaching 2 degrees by the end of the century where global emissions began to fall only after 2030, and then fell extremely rapidly, the difficulty of achieving these reductions 'make it seem unlikely that such pathways can be implemented in the real world'.[5] In all these cases, a judgment has been made largely on the basis of an understanding of politics, informed by knowledge of physical constraints and an assessment of technological difficulty. It is difficult to distinguish any difference in these examples between the concepts of 'infeasible', 'implausible', and 'very improbable'.

In this report, we attempt to make a judgment based on those same elements. After reviewing what is generally considered to be the plausible range for global emissions over the course of this century, we provide two different approaches to estimating the probability of different emissions scenarios within that range, and then use both approaches to reach a final conclusion. First, we examine the near-term trajectories of some of the major countries and regions of the world over the next few decades, based on our knowledge of those countries' policies, plans and economic circumstances. Second, we examine a series of technological innovations, some combination of which are required to ultimately displace fossil fuels from our energy mix and reduce CO_2 emissions to near zero. Consideration of the timescale over which those innovations will occur, as well as the necessary energy infrastructure that must be built, also places some constraints on the probability of different emissions scenarios coming to pass.

5 THE IMPLICATIONS OF CURRENT POLICIES AND PLANS FOR SHORT-TERM EMISSIONS

Over the past two years, some of the largest countries and regions have made progress in developing goals for stabilizing or lowering their greenhouse gas emissions. Some of this progress was made possible by falling prices for renewable energy technologies, particularly wind and solar photovoltaics. In addition, economic shifts away from energy-intensive industries are likely to play a major role in the coming years. In the following section, we review the likely trajectories for the U.S., the European Union, China and India, providing a brief discussion of the factors that will control their greenhouse gas emissions over the next few decades. This analysis does not allow for us to evaluate the timescale or probability of deeper emissions reductions required to ultimately stabilize greenhouse gas levels in the atmosphere, but can provide a qualitative sense of which of the IPCC emissions scenarios are more likely.

The United States

In the U.S., emissions have fallen more than 10% relative to 2005. Some of this decline comes from sustained high oil prices until the summer of 2014, which led to a reduction in vehicle miles travelled by passenger vehicles. The economic impact of the financial crisis of 2008 was also a factor in reducing the growth of energy demand. Finally, sustained low prices for natural gas driven by production from shale caused a shift away from coal consumption in the electricity sector, which has also been a major factor in reducing emissions. Moving forward, the Obama administration has taken steps to achieve much deeper reductions in emissions, proposing a target of 26% to 28% reduction in greenhouse gas emissions relative to 2005 by 2025. In order to achieve these reductions, two Federal policies have already been created by the Environmental Protection Agency (EPA), aimed at reducing emissions from transportation and from the electricity sector. There is also important policy activity at the state level, in particular an economy-wide cap-and-trade regime in California, and a cap-and-trade market specific to the electricity sector for several northeast states.

The first major Federal action on reducing greenhouse gas emissions was revisions to the Corporate Average Fuel Economy (CAFE) standards. These standards now require an average performance equivalent of 54.5 miles per US gallon (65.5 miles per imperial gallon) for passenger vehicles by 2025. In addition, in 2011, the Obama Administration finalized the first-ever fuel economy standards for heavy-duty trucks, buses, and vans, which applies to model years 2014-2018. In order to reduce emissions from the electricity sector, in April 2012 the EPA proposed a carbon pollution standard for new power plants, prohibiting building new coal-fired power plants that do not have emissions-reduction technologies (i.e. carbon capture and storage). More recently, the EPA proposed a new rule for existing power plants that specifies emissions reductions for each state based on the potential to shift from coal to natural gas, improve the efficiency of existing power plants, improve efficiency in electricity demand, and add renewable generation to the current energy mix. These EPA rules are likely to be challenged in the courts over the next several years. Their successful implementation will be critical to reaching the goal of 26% to 28% reduction in emissions relative to 2005 by 2025.

At the state level, California has passed new legislation to achieve a 40% reduction in emissions relative to 1990 by 2030. This is by far the most ambitious goal of any U.S. state, but it is too early to tell exactly how these levels of reduction will be achieved. Other states are also making progress. For example, the state of Iowa now has more than 30% of its electricity generation coming from wind. And the Regional Greenhouse Gas Initiative, an electricity sector cap-and-trade regime among several northeast states, is slowly having an impact on new investments in the electricity sector, after some initial years with a cap set much higher than actual emissions from the region.

The new efforts by the Obama administration represent an important shift in U.S. policy, and have renewed interest around the world in achieving more aggressive reductions in greenhouse gas emissions, but real progress still faces many challenges. First, the substantial drop in the price of oil will make it more difficult to expand on the reductions in emissions from the transportation sector that the U.S. experienced from 2005 until 2014. Second, challenges to the new EPA rules in the courts, as well as the possibility of a new American president elected in 2016 who may oppose such efforts, means that the U.S. targets for 2025 are not guaranteed.

The European Union

Europe's emissions have fallen by nearly 20% since 1990, largely as a result of energy and climate policies, supported by a decreasing share of energy intensive industry in the economy. At present, this leaves European per capita emissions above the world average, but still only about half those of the US, Canada and Australia. The largest emissions reductions initially came from the shift away from coal in the energy mix of Europe's largest economies: Germany and the UK both reduced their coal consumption dramatically after 1990 as they shifted to gas, and France continued to reduce its coal consumption as it increased its reliance on nuclear energy for electricity generation.

Climate policy has played an increasingly significant role, particularly in increasing the share of renewables in electricity generation through both direct subsidies and portfolio standards. Notably, Germany led the way with feed-in tariffs, initiated in 1989, to promote the installation of solar and wind capacity. In 2014, renewable energy provided 27% of Germany's electricity generation; solar delivered about 6% and wind 8%. Spain generated more than 20% of its power from wind in 2013, while it also made significant investments in solar photovoltaic and concentrated solar power. The UK and Denmark have led the world in the installation of offshore wind. Renewable energy subsidies have been complemented by carbon pricing: the European Union's Emissions Trading Scheme (ETS) applies to more than 11,000 power stations and industrial plants in 31 countries; during its first five years of operation it imposed a price in the range of €15–25 per tonne of CO_2. As the ETS price has fallen in recent years, countries such as the UK and Sweden have supplemented it with national carbon taxes of their own. At the same time, regulatory standards have been used to progressively decrease emissions from vehicles.

Given the progress already made, the EU looks likely to achieve its target of reducing emissions by 20% by 2020 compared to 1990. The EU's next target – a domestic reduction of at least 40% by 2030 – should also be achievable, but exceeding it would require overcoming some of the technical and policy challenges that are already preventing a faster pace of emissions reduction. The expansion of the EU to include eastern European countries has, on the one hand, slowed down the transition overall, but on the other hand it has incorporated these countries into the policy process.

The shift of Europe's major economies away from coal, while not yet complete, has already taken place to an extent that means it cannot simply be repeated. Further decarbonisation of the power supply will require a significant growth in low carbon generation. New nuclear power has been ruled out by some countries, such as Germany, and is included in the plans of others, such as the UK. So the prospects for renewable energy are critical. It is notable that the countries that have achieved the highest levels of renewable energy as a proportion of power generation are already experiencing some difficulties handling intermittency. Spain and Ireland have on occasion to cut off their wind generation when it exceeds manageable levels, but Germany and Denmark increase their electricity exports whenever solar and wind generation peak. It is recognized that raising the contribution of renewables to power generation from 20% to 40% will require significant advances in demand management, smart grids and energy storage. Continued reductions in cost can support this process, as can interventions to increase interconnectivity across the European continent. In parallel, Europe will need to begin to decarbonise its heating and transport – areas where progress to date has been uneven.

On the policy side, Europe will need to continue the process of reform of the ETS in a way that ensures the carbon price remains high enough to be effective. In recent years, the low price of around €5 per tonne of CO_2 – in combination with the fall in coal prices – has allowed coal to become more competitive than gas. This will need to be reversed if coal is to be phased out. Further progress may be made if ETS reform takes account of its interactions with renewable energy and efficiency policies. Under the cap and trade system of the ETS, progress on either renewable energy deployment or energy efficiency tends to make the carbon price fall, reducing the incentive to cut emissions in other sectors. For policies in these three areas to support each other, the ETS would need either to have a cap that can be lowered as needed to maintain an effective price, or to be replaced with something more similar to a fixed carbon tax. Similarly, policy on biomass will need to be reformed to ensure that it does not lead to increased emissions from deforestation and transport. The creation of the EU Energy Union this year gives some hope that these objectives will be achieved across the EU in coming years.

China

China's carbon emissions experienced rapid growth driven by the fast-growing economy for more than three decades. In 1990, energy related carbon emissions from China were 2.27 billion tons CO_2, accounting for a little more than a tenth of the world total, while U.S. emissions were more than 5 billion tons, close to a quarter of the world total. In 2014, China's carbon emissions increased to almost 9 billion tons, nearly four times their 1990 level, while the US added only 5%. In fact, China surpassed the US in 2008, becoming the largest carbon emitter in the world. In 1990, China's per-capita carbon emissions were less than half the world average; in 2007, China's per capita carbon emissions exceeded the world average and are now quickly approaching the average level of the EU's twenty-eight Member States.

In 2009, China set its 2020 carbon management target under the Copenhagen Accord, aiming to reduce its carbon intensity, measured as carbon emissions per unit of GDP, by 40% to 45% as compared to the 2005 level. By the end of 2014, China's carbon intensity was 33% lower than the 2005 level, well on track to deliver its Copenhagen pledge. Meanwhile, China's total carbon emissions continued to grow, from 5.1 billion tons in 2005 to nearly 9 billion tons in 2014.

Despite the continued increase in total carbon emissions, the growth rate of carbon emissions has been in a steady decrease since 2005, and was near zero in 2014. Several different government policies have played key roles in bringing down the carbon growth rate. First, energy efficiency in all major sectors has been improving. By the end of 2014, China's energy intensity had decreased by about 30% from the 2005 level. Coal fired power plants now use less than 290 grams of coal for generating one kWh of electricity. The best coal-fired power plants in China are now leading the world in energy efficiency, and the national average efficiency of all power plants is now rising to among the best in the world. The Top 1000 Enterprises Program, a nationwide program focused on the greatest energy consumers in China, saved more carbon emissions in five years than the European Union has saved under the Kyoto Protocol.

A second factor in slowing down the growth rate in emissions is the development of renewable energy. China is now leading the world in investing in renewable energy, contributing to a quarter of the world total. More than 30% of installed wind generation capacity is in China, adding roughly half of the world's new wind power development in 2014. The installed capacity of solar power generation in 2005 was 700 MW, and had grown to more than 28 GW by the end of 2014, a 40-fold increase in less than a decade. It is possible that China will overtake Germany to become the largest developer of solar power in the world by the end of 2015.

A third factor for reducing the growth in emissions has been a concern for air pollution, which has helped to set a cap for coal consumption in key regions, which will eventually extend to the whole country. As a result, coal consumption was down by 290 million tons in 2014 compared to the previous year, contributing to a stabilization of carbon emissions in China.

Fourth, some provincial and municipal governments have taken leadership to explore low-carbon development paths. From 2009 to 2012, 42 provinces or cities entered into a national pilot program for low-carbon development. These pilots seem to be making an impact on other subnational and local governments on choosing an alternative pathway for addressing economic growth and climate change.

Finally, China has made a deliberate decision to launch a nationwide carbon market in 2016 in order to price carbon emissions, based on a pilot program that covers seven provinces or cities. When completed, the Chinese carbon market will be the largest one in the world, more than twice the size of the cap-and-trade program in the E.U.

In the context of this progress, on November 12, 2014, China and the U.S. signed a bilateral agreement on climate change and clean energy cooperation. Under the joint agreement, *"China intends to achieve the peaking of CO_2 emissions around 2030 and to make best efforts to peak early, and intends to increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030."*[6] This is the first time that China has committed itself to a target for total carbon emissions. Assuming that these goals are achieved, China's carbon emissions will continue to increase by roughly one third to one half of the current level in the next 15 years, reaching per capita carbon emissions of approximately 10 tons, before they level off or decline.

Much of the progress in achieving a peaking of emissions will come from reductions in coal use in the industrial sector, outside of electricity generation. But perhaps the most important component of the joint China-U.S. agreement is the commitment to achieve 20% of non-fossil energy in the overall energy mix, as this will set the stage for reductions beyond 2030, as non-fossil energy begins to replace fossil capacity. Reaching this target will not be easy, as it requires 800 to 1000 gigawatts of new electricity generation capacity to be added, based on wind, water, solar and nuclear, requiring an investment of $1.8 trillion. But if these goals are achieved, it opens the possibility that economies of scale will bring down the cost of these non-fossil technologies, enabling them to become more widely used in the rest of the developing world, as other developing countries make energy choices in the middle of this century.

India

India faces a large developmental challenge of raising the standard of living of its citizens. As per capita consumption of energy is strongly correlated with quality of life, the above strategy will require an increase in per-capita and national energy consumption. Today, fossil fuels comprise nearly 90% of India's primary commercial energy, and this proportion is unlikely to fall in the near future. However, there are vast opportunities for raising the levels of technology in power generation, lighting and transportation among others, which could moderate the carbon intensity of the economy by reducing the energy demand. Similarly, India could leverage its strength in solar energy, as it is endowed with roughly 300 clear, sunny days per year, as well as a large wind-energy potential. Therefore, actions on both demand and supply sides, by enhancing energy efficiency and enhancing renewable energy, could moderate the carbon intensity of the economy in the coming decades.

Climate change impacts developing, tropical countries more than others, both due to their geographic location and their poor capacity to absorb adverse effects. The dependence of a large share of farmers in these countries on rain for their livelihood, high density of population, and weak economies further exacerbate their vulnerability to the impacts of climate change. Being conscious of the above, the Indian Government has strived to moderate emissions through its developmental agenda. A series of measures have been underway as a part of the eight missions under the National Action Plan on Climate Change in the areas of energy efficiency, solar energy, and forestry, among others. The erstwhile Planning Commission (now replaced by the NITI Aayog) had also constituted a Committee to suggest a strategy to moderate its carbon intensity under the Twelfth Five Year Plan (2012-17) and beyond, even while attempting inclusive growth. In more recent times, the Planning Commission has generated a scenarios based analytical tool – India Energy Security Scenarios 2047 – along the lines of the UK 2050 calculator, to help policy-makers develop a way forward in meeting India's energy challenges. This tool also aims at achieving energy security in terms of lowering import dependence for energy supplies, while ensuring reduction in carbon emissions.

Today, India is the third largest carbon emitter after China and the U.S., or fourth if one considers the European Union as one entity. However, at 1.7 tons per capita CO_2 emissions or 2.1 billion tons total in 2010, it is still far behind the others. It is also evident that the aggregate (and per capita) emissions of India are going to keep rising as the standard of living of Indians rises. The per capita emissions of India related to energy consumption in 2010 were 1.26 tons of CO_2, and could grow to between 3.3 tons and 5.1 tons by the year 2047, depending on the country's ability to adopt moderate carbon intense pathways.

India's annual per capita energy use was 614 kgoe (kilogram of oil equivalent) in 2011, while electricity use on similar parameters was 684 kWh. At this low energy use, a large section of the population is without access to modern sources of energy, or is served very poorly with large outages. The consumption pattern is further skewed towards essential life promoting activities like cooking and keeping warm, with negligible use in 'life quality' enhancing uses such as transport, lighting etc. As stated above, overall consumption of energy is bound to rise, but energy usage could be made efficient by adoption of technology, behavioural changes and better planning and infrastructural improvements. India's demand for building space and consequent demand for steel, transport, and energy for cooking and household electricity, are all likely to grow by at least a multiple of three between now and 2047 (the 100th year of India's independence). Adoption of efficient building codes, a shift to public transport, and adoption of electric vehicles and efficient devices, could all moderate India's emission intensity.

Similarly on the supply side, while coal is expected to remain the major source of energy for heavy industry and for electricity generation, the share of renewables and gas, and electrification of the energy sector hold large promises. Both grid-connected and decentralized renewable energy sources have the potential to contribute to meeting the electricity and cooking energy needs of the poor (while as a co-benefit, encouraging rural entrepreneurship).[7] In the transportation sector, a combination of demand and supply side interventions in this area (reduced demand for transport by better urban planning and use of electric vehicles and public transport) could moderate energy consumption. The share of electricity in primary energy supply, as well as contribution from renewables, could rise from the present 16% to 22%, and from 4% to 29%, respectively, to achieve a lower carbon intensity by 2047.

Two initiatives are particularly worth highlighting. The first relates to the National Mission on Energy Efficiency. India has already launched the innovative Perform, Achieve and Trade scheme, mandating energy efficiency targets for plants and factories in eight industrial sectors, failing which they would need to purchase additional energy savings certificates from over-performers (2015 will be the first year of trading). Efficiency will also be a major driver for residential appliances via the Super-Efficient Equipment Program, which was launched in 2013. Efficiency considerations will also impact the adoption of alternative chemicals and technologies for air conditioning and refrigeration in residential and commercial buildings. The government has also developed plans for demand-side management in municipalities to decrease their energy consumption.

The second policy initiative is the Indian government's goals for renewable energy. In a total installed capacity of more than 35 gigawatts of renewable energy (excluding large hydropower), wind power accounts for nearly 23 gigawatts. The National Solar Mission was launched in 2010 and more than 4 gigawatts have been deployed. But more recently, the government has announced plans to install 175 gigawatts of renewables-based electricity-generating capacity by 2022, including 100 gigawatts of solar power. Meeting the solar target alone will require a growth rate equivalent to doubling India's installed solar capacity every 18 months. It will also require a clear understanding of the three factors that drive energy demand in India (access, security, and efficiency); new federal and state policies and incentives; innovative financing for capital investments estimated at $100 billion or more; and additional funding for manufacturing, training, and job creation. Project developers will have to grapple with the cost and availability of land, grid connections, and backup power.[8]

Overall, there is enormous potential for India to reduce the energy intensity of its economy and the emissions intensity of its energy sector, as energy consumption increases over the next three decades. In particular, the decreasing costs of solar photovoltaics may be particularly helpful for India to limit the expansion of coal consumption, given its high solar potential. At the same time, it is important to acknowledge that India's GDP had been growing annually at a near 9% growth rate in the past, with a slowing down in recent years. India aims at growing above 7% annually in the 12th Five Year Plan period (2012-17) and a long term compound annual growth rate of 7% in the coming decades, too. The power sector is registering a near 10% generation capacity growth annually, with both fossil fuel and renewable energy based capacities being a part of this growth. India cannot afford to postpone its development for the sake of carbon reduction goals, and thus overall emissions from India are likely to rise substantially in the coming decades. India can partially temper this growth in emissions with adoption of efficiency in use of energy, and promote low carbon strategies even when locking in investments in related infrastructure. A co-benefits approach towards moderate carbon strategy will also be helpful in curbing energy imports, by replacing imported energy by local resources such as solar and wind power.[9]

A Global Perspective on Emissions over the Next Three Decades

What do these different perspectives from these four regions mean for the likelihood of different emissions scenarios? Current progress in the European Union and in the United States in reducing emissions is encouraging, but the rate of change is not compatible with low emissions scenarios. Similarly, the announcement that China's emissions will peak by 2030 is very important for avoiding the high emissions scenarios, but still not sufficient for achieving the low emissions scenarios. Perhaps the most important news is the growth of renewable energy installations around the world, and the concomitant reduction of renewable energy prices. If India and other developing countries (e.g. those in sub-Saharan Africa) are able to expand their use of renewables more rapidly than expected, then the high emissions scenarios are unlikely to occur. But it remains uncertain whether renewables will be able to continue their trajectory as higher levels of penetration are achieved, when countries face the challenge of intermittency of supply and the difficult technical challenge of energy storage.

The low emissions scenarios that have a high probability of limiting warming to less than 2°C will not be possible unless the EU achieves its goal of an 80% reduction by mid century, the U.S. and China both accelerate their progress, dramatically reducing their coal consumption in the next two decades, and India displaces its anticipated increase in coal consumption with an expansion of solar and other renewables. Other countries and regions must follow suit, with non-fossil technologies ultimately becoming disruptive for supporting economic development goals.

6 TECHNOLOGICAL CHALLENGES THAT WILL DETERMINE FUTURE GLOBAL EMISSIONS

Another approach to placing constraints on the likelihood of different global emissions trajectories is to evaluate different emissions scenarios through the rate of technological change and energy infrastructure investment. Quantitative modelling of low-carbon energy systems for different countries allows one to identify a series of technological innovations or infrastructure investments that must be made to enable reducing emissions to near-zero levels. In the following section, we ask a series of questions that relate to energy innovation and low-carbon energy systems. For any individual country, there are an infinite number of possible combinations of different technologies and approaches, and these are likely to vary across different countries and regions. Thus, not every one of the questions about technological innovations and investments discussed below must be answered in the affirmative to achieve near-zero emissions for the world. However, the modelling makes it clear that many of these innovations will ultimately be required, although the exact contribution from each one remains uncertain.

One important aspect of this approach is to evaluate a nation's energy system by sector. For example, energy for the transportation sector around the world is supplied almost entirely by petroleum. Replacing the petroleum with non-greenhouse gas emitting alternatives requires not only a technology for passenger vehicles (e.g. electric vehicles with batteries), but also a technology for replacing diesel fuel for freight transport, for which batteries are unlikely to be sufficient, and also a technology to replace jet fuel. Rather than specifying particular technologies in the following discussion, we chose instead to discuss very broad categories of technological solutions, allowing for the potential for technological surprises. At the same time, the quantitative modelling of emissions scenarios, both for the world and for individual countries, makes it clear that we can distinguish between the low and high emissions scenarios in terms of the timescales over which energy innovation must occur, and also the timescales of energy infrastructure investment.

1. **Can high penetration wind and solar be managed at large scale, using storage, demand management, backup, and other approaches? Will the cost of renewables decline sufficiently to drive the world's electricity systems to become dominated by renewable energy?**

   Over the last decade, there has been enormous progress in reducing the costs of wind and solar power. Onshore wind, in good locations, is now directly competitive with fossil sources of electricity (i.e. coal and natural gas). Around the world, we have seen the growth of wind as a percentage in overall electricity generation for countries such as Ireland (19%), Aruba (20%), and Denmark (28%), as well as regions within countries, such as Iowa (30%). Offshore wind has been deployed in countries like Denmark and the UK, although it remains a much more expensive option relative to onshore wind installations. Progress in reducing the cost of solar photovoltaics has been particularly dramatic, starting with Germany's aggressive policies of feed-in tariffs, leading to about 6% of their generating capacity supplied by solar power in 2014, and then followed by policies around the world that are driving large-scale installations in China, the U.S. (particularly California), and southern Europe. Coupled with the rapid expansion in installation have come advances in manufacturing around the world, particularly in China, that have driven reductions in prices. Costs for large-scale solar photovoltaic installations in many countries are now below $2 per watt, encouraging many countries, such as India, to revisit their investment decisions around electricity generating capacity.

The expansion of renewable electricity in countries and regions around the world has forced a more intense effort to develop strategies to manage the intermittency of wind and solar energy. Many approaches have been proposed, but only recently has the extent of renewable penetration in countries and regions mentioned above created market conditions that allow companies to make money by deploying energy storage and demand management strategies. The next two decades will be critical in determining whether countries can surpass canonical limits to intermittent resources of around 20% to 30%, and achieve much high levels of renewable penetration, when combined with energy storage, better transmission systems, and demand-management strategies that can shift the load to times when renewable resources are available. There are many theoretical studies that suggest such strategies are possible, but the details of their implementation, as well as the additional costs, remain uncertain. It is also possible that there will be renewed interest in concentrated solar power, and other renewable technologies that include some storage capacity as an integral component. For some regions with abundant natural gas resources, such as the United States, expansion of renewables will likely be facilitated by using natural gas turbines as backup supply. This will not be effective in many regions of the world, such as India. Moreover, using fossil systems as backup does not allow for the deep reductions in carbon emissions required in future years.

2. Will nuclear power become a serious option for the power sector in terms of cost, safety, and proliferation risk?

For some regions of the world, such as the United Kingdom, nuclear power is a critical component of plans to achieve low-carbon goals, as their renewable resources are limited. Even in countries with substantial renewable resources, uncertainty about the costs of storage or demand management, and thus the potential for deep penetration of renewables, nuclear power may be an attractive option for zero-carbon baseload power because it is highly reliable.

The challenge in the next few decades is to bring down the cost of nuclear power while increasing the safety and minimizing the risk of proliferation of nuclear weapons, including the risks of nuclear terrorism, as well as developing better strategies for disposal of nuclear waste. There are many proposals for new generations of nuclear power plants, including small modular reactors that would bring down costs through efficiencies of scale in manufacturing, more uniform designs of larger reactors that would bring down costs by streamlining the engineering and construction, and new reactor types, such as thorium reactors.

Current deployment efforts are being led by China, which has 24 nuclear power reactors under construction, and hopes to increase its nuclear capacity more than threefold to around 60 GW by 2020-2021, and then to some 150 GW by 2030.[19] Other countries, such as Germany and Japan, have moved away from nuclear power following the tsunami and nuclear accident in Fukushima. But even for countries with a commitment to nuclear power, the timescale of technological innovation in nuclear power is inherently slow, due to the relatively large scale of capital investments and the risks associated with experimentation of nuclear design and construction. For many countries that have had substantial nuclear power programs, such as the U.S., it looks like high costs and concerns about safety will cause a reduction in nuclear power over the next three decades as nuclear power plants from the 1970s are retired.

3. Can we eliminate the use of petroleum from the passenger vehicle sector (without biofuel that will be needed for jet fuel and diesel fuel)?

Use of petroleum in the transport sector is currently one of the largest sources of energy-related greenhouse gas emissions. Current global petroleum consumption (including natural gas liquids) is roughly 90 million barrels per day, and continues to expand despite reductions in the U.S. and the E.U. Reaching any of the low-carbon emissions scenarios and stabilizing CO_2 at only a modest increase relative to today will require a massive, global transition over the next few decades to the use of non-fossil technologies for vehicle transportation.

Current technologies for electric cars are making enormous progress, with several automobile manufacturers currently producing full electric vehicles for both the luxury (e.g. Tesla, BMW) and entry levels (Chevrolet, Nissan). At the same time, the cost of these vehicles remains expensive; current prices

are roughly double the cost of equivalent vehicles with internal combustion engines, although progress in reducing costs of batteries is expected in the coming years. Another area of innovation is in smaller electric vehicles, such as scooters and motorcycles, particularly in China and Southeast Asia. Although the progress in battery-powered electric cars is encouraging, some automobile manufacturers are investing in hydrogen fuel-cell vehicles as an alternative pathway to non-fossil transportation. Fuel cell vehicles would require a massive infrastructure investment for transport and distribution of hydrogen, which is currently made at large scale from natural gas, but could be produced in the future from renewable energy. Thus, a transition to battery-powered electric vehicles appears to be the most likely technology that can prove disruptive to internal combustion engines for passenger vehicles, but it remains possible that fuel cells will also be competitive.

The major challenge that this sector poses for achieving low emissions scenarios is the pace and scale of the necessary changes. In 2014, there were more than a billion vehicles in the world, nearly all of them with internal combustion engines. In order to reach the low emissions targets, non-fossil technologies would have to become disruptive, dominating sales around the world by mid century, or perhaps even earlier. Even after electric or fuel cell cars become competitive with internal combustion engine cars, it will likely take several decades before the technology becomes dominant in the actual vehicles on the roads around the world. Such a large shift in manufacturing and technology is possible, but the pace and scale is daunting without major efforts to bring costs down in the immediate future.

4. Can biomass or alternative technologies be used to displace diesel and jet fuel at a reasonable cost? How can impacts of biomass through land use be managed?

Replacing petroleum currently used for jet fuel and for diesel fuel for freight transport may be the most difficult technological hurdle to reach a non-fossil economy in the future. Current aviation technologies require hydrocarbon fuels because of the technical requirement for fuel with very high energy density and very low mass. Some freight transport could be transferred to trains powered with electricity, but it is difficult to imagine replacing all truck transport with trains. Whatever freight transport will be done with trucking will be very difficult to electrify, given the power-to-weight challenges of battery technologies in the foreseeable future. A likely alternative to petroleum-derived diesel and jet fuels is biofuel, produced through a variety of biochemical and thermochemical processes, including Fischer-Tropsch synthesis that is used to produce fuels from coal in South Africa. The biomass feedstock requirements of replacing diesel and jet fuel with biofuel are massive, even with enormous efficiency gains in aviation and trucking. For example, using current Fischer-Tropsch technologies to produce 10 million barrels of fuel per day – equivalent to roughly 11% of current petroleum demand – using biomass as a feedstock would require more than 125 million hectares of cropland, even assuming very high biomass yields of 20 dry tons per hectare. It is not clear whether cultivation of biomass crops for energy use at such a scale can be accomplished in the context of growing food demand around the world, nor is it clear that 10 million barrels of jet and diesel fuels per day will be sufficient.

Some work has been done to look at recycling of CO_2 from biofuel and fossil fuel combustion into fuels, first through reduction to carbon monoxide, and then through Fischer-Tropsch synthesis, using hydrogen produced from renewable sources. In theory, this is possible, but the chemical reduction of CO_2 into carbon monoxide is very energy intensive and remains a challenge to economic competitiveness. Overall, it is clear that there is no technology currently available that appears to be competitive with petroleum, even at much higher prices and with a very high price on carbon. Thus, relatively little effort has been dedicated to this problem, and it seems unlikely to emerge as a major priority for several decades. An appropriate technological replacement for petroleum will eventually emerge as oil supplies dwindle, but waiting until most of the oil reserves are extracted is simply incompatible with low-emissions scenarios.

5. Is carbon storage feasible at very large scale (i.e., tens of billions of tonnes per year)?

One approach to reducing CO_2 emissions involves CO_2 capture from emissions sources and then storage in geological repositories, often referred to as carbon capture and storage (CCS). CCS appears particularly attractive in reaching a low-carbon economy for several reasons. First, CCS might allow the world to transition to a low-carbon economy without discarding capital investments that have been made in electricity infrastructure. Currently, there are more than 2,000 power plants that emit at least 1 million tons of CO_2 a year. Together these power plants released more than 10 billion tons of CO_2, or roughly one-third of global emissions. To the extent that some of these plants can be retrofitted with capture technology and that appropriate storage locations can be identified, CCS would allow the world to continue to use some of these facilities for many decades but dramatically reduce their environmental impact.

Even aside from the use in existing fossil fuel facilities, such as large coal-fired power plants, CCS is likely to be a critical part of a low-carbon economy in the industrial sector for stationary sources of emissions, such as cement plants, that are difficult to eliminate. One particularly important application of CCS may be for the biofuels sector, if biofuels become an important source of non-fossil liquid fuel for freight transport and air transport. Whatever the specific technology used to convert biomass to fuels, whether through fermentation or through thermochemistry, a biofuel refinery will create a large, concentrated stream of CO_2 that represents a relatively low-cost source of emissions reduction. Such use of CCS can be viewed as 'air capture' of CO_2 as the life cycle emissions from such a facility would be negative.

Currently, there are a small number of demonstrations of carbon storage in geological repositories around the world. The most successful is the Sleipner Field in the North Sea, operated by StatOil, the Norwegian Oil Company, and injecting 1 million tons of CO_2 per year since 1996. Based on this experience, it seems very likely that carbon storage in saline formations, whether onshore or offshore, is likely to be effective in permanently storing CO_2, but it remains unknown whether the geologic reservoirs can handle the enormous volumes of CO_2 required if CCS ever became a dominant technology, for example in large biofuel refineries around the world. Estimates of capacity are extremely large, but some studies have questioned those estimates based on limits to injectivity, potential for induced seismicity, and leakage potential. Until more commercial-scale demonstration projects are operating in different geological settings around the world, it will be impossible to guarantee that CCS will be feasible at the scale required to play a major role in a low-carbon world.

6. Will technologies and planning that allow large increases in energy efficiency be deployed at large scale?

There are enormous potential gains in energy efficiency across all sectors of our energy system. Buildings have been a particular emphasis of many studies; new building materials and new building designs can reduce energy use in buildings by 70% or more relative to current levels, even in countries that have experienced relatively high energy prices and are already quite efficient. Similar arguments have been made for industrial facilities, and also transportation systems, focusing on the potential for use of lighter materials (e.g. carbon fibre) and more efficient motors and control systems, as well as improvements in urban planning and more efficient systems such as light rail.

Energy efficiency plays a critical role in determining whether the world will follow a low or high-carbon emissions scenario, primarily by reducing the total amount of industrial capacity required. For example, if passenger vehicles are powered with electricity, but are lighter and use much less energy than current vehicles, then less electricity generation will have to be constructed. Similarly, if biofuels become a critical source of non-fossil liquid fuels for aviation, then more efficient airplanes with lighter materials will require fewer biofuel refineries and less land area required for growing biofuel feedstocks.

The critical question is whether these large improvements in energy efficiency that seem to be theoretically possible will actually be implemented across entire countries and regions. Some have argued that many energy efficiency investments will ultimately save money, and that there are market failures that prevent such investments from occurring. On the other hand, progress in energy efficiency has been slower than expected, leading some economists to question whether the analyses of costs and savings from energy efficiency are correct. If the world is going to manage to limit emissions and follow one of the lower-emissions scenarios, then it will be critical to achieve as many gains in energy efficiency as possible, at all scales from appliances and vehicles to factories and large-scale transportation systems.

7. How fast can large-scale energy infrastructure be built?

A transition to a low-carbon or zero-carbon economy at a global scale requires massive new investments in infrastructure to replace existing systems based on fossil fuels. One large area for new infrastructure construction will be for production of liquid fuels, whatever the technology. An even larger need will be in the electricity sector, as electrification of transportation, industrial energy demand, and heating for buildings will dramatically increase overall demand for electricity. If much of this electricity is generated using wind or solar systems, then the new capacity requirements will be even larger due to the relatively low capacity factors for solar and wind (20% to 30%) relative to fossil fuel based generating systems. Thus, one of the key factors that may limit our ability to lower emissions and achieve a low-carbon emissions scenario is the rate at which we can build new infrastructure.

In the U.S., for example, the current rate of installation of new generating capacity is roughly 10 GW per year. At this rate, one would need more than 100 years to rebuild the existing grid, much less the grid required by a new energy system based largely on renewable sources that would be several times larger. Over the last decade, China has been building new generating capacity at roughly 100 GW per year, but that was with overall economic growth rates of more than 10%. Can countries build new infrastructure quickly enough to lower global emissions, even if their economy is growing more slowly overall? The required level of industrial activity in terms of materials (e.g. cement, steel, etc.) is daunting, but not impossible to imagine. In terms of a risk analysis, however, it seems that such a high level of industrial infrastructure investment is unlikely to occur without extraordinary political will.

8. Will breakthrough technologies such as capture of carbon dioxide from air become feasible?

In this discussion of future energy technologies, it is important to point out the possibility that an unanticipated technological breakthrough could change our thinking about existing options and future technological choices. One example of such a breakthrough would be the development of capture of CO_2 from air at a low cost, aside from the use of biomass combined with carbon capture and storage (discussed above). Current estimates of cost for air capture are highly variable, with several small companies focused on building demonstration plants. It seems unlikely that this technology will allow for a less expensive route to decarbonisation than the replacement of fossil sources of energy, but if air capture were economically feasible, then it would add another option. In particular, air capture of CO_2 might be most important in creating non-fossil liquid fuels without the need for massive land area for energy crops.

9. How can the use of low-priced fossil resources, such as coal and oil sands, be limited at a global scale, even if there are large economic incentives for using such resources?

A final question is whether it will be possible to limit the extraction and consumption of those fossil fuel resources that are abundant and therefore are likely to remain extremely inexpensive throughout the next century and beyond. Chief among these resources is the world's coal reserves, which currently represent almost 70% of the carbon in fossil fuel proved reserves. The total coal resource (i.e., what could be extracted, not necessarily based on the current prices) is larger still, with vast undiscovered and undeveloped coal deposits across Russia and in Alaska. Some unconventional oil resources can also be added to this carbon reservoir, such as oil sands and shale oil.

A critical question for the future is whether these fossil resources will be used to create liquid fuel when petroleum reserves begin to dwindle sometime over the next century. Ideally, this would be avoided by new, non-fossil technologies becoming disruptive, making it uneconomical to use coal or unconventional oil. But if this does not happen, will it be possible to leave these fossil resources in the ground, even when their extraction and conversion to liquid fuels or to synthetic gas could be highly profitable? This may depend on whether global concern around climate change is raised to such a high level that it becomes politically, socially or morally impossible to use these fossil resources, just as certain practices such as child labour have become socially and politically unacceptable in most countries.

From the carbon cycle perspective, it is clear that the use of coal and unconventional oil in place of conventional petroleum would be disastrous. If coal-to-liquids or shale oil becomes a dominant part of the world energy system, this would reverse most of the progress made in emissions reductions over the past two decades, and would ensure that even the middle emissions scenarios are impossible to achieve.

Summary of Technological Perspective on Probability of Different Emissions Scenarios

The previous survey gives only a brief overview of the critical technological issues. Indeed, each of the questions above could constitute a major report by itself. The purpose of this discussion is not to provide a complete analysis of each of these components of the global energy system, but simply to identify the major innovations in energy technology that must be accomplished if the world is to follow a low emissions pathway.

Not every one of these questions must be answered in the affirmative to reduce global CO_2 emissions sufficiently quickly to follow a low emissions trajectory. For example, it is possible to imagine a non-fossil energy system that does not use nuclear power (although it does make the challenge more difficult). But there is no question that limiting emissions to levels that are more likely to keep global temperature change below 2°C requires a positive response to nearly all of the questions. And given the current state of technology development, we do not know any of the answers. Another problem is timescale. Finding technological solutions that will allow us to answer affirmatively these questions with confidence needs to happen quickly, as a delay will result in more fossil carbon release to the atmosphere.

For the purpose of placing a probability judgement on different emissions scenarios, the scale of the technological challenges would support a conclusion that the family of low emissions scenarios seem very unlikely. Changing this conclusion would require substantial progress on innovation in energy technology over the next decade or two to allow positive answers to most of these key questions.

7 CONCLUSIONS

Based on an analysis of current policies and plans for major countries and regions, it is very likely that the world will continue to follow a medium to high emissions pathway for the next few decades. If goals for reducing emissions in the EU and the U.S. and stabilizing emissions in China are achieved, then the highest emissions scenarios are less likely to occur, especially if India is able to displace a part of its anticipated construction of new coal-fired power plants with renewable energy capacity. But this will only keep emissions on a moderate trajectory, still far in excess of what is required to limit the impacts of climate change below a harmful level.

The technological challenges to achieving the low emissions scenarios are substantial, and are not being adequately addressed with current policies. An enhanced effort is needed to accelerate innovation in energy technology. Because much of this innovation occurs through deployment of large-scale energy systems, a global commitment is needed. Current trends in the costs of renewable energy, particularly solar photovoltaic systems, are very promising, but still far short of what is required to achieve emissions goals even for the next few decades.

The climate response to anthropogenic emissions depends on cumulative emissions of CO_2. This means that partial reduction in emissions is not sufficient, as sustained lower emissions from fossil fuel combustion will continue to drive higher levels of atmospheric CO_2, and will lead to higher levels of climate risk. Accelerating the use of fossil fuels, including the use of coal for liquid fuel, the extraction of methane hydrates, and the development of oil shale, could reverse the current trend towards emissions reductions, and push emissions even higher than some of the high emissions scenarios. In this case, climate change itself may be the eventual limiting factor on emissions through a reduction in economic growth and energy demand.

Endnotes

1. This property is exploited in the parallel development of climate and socio-economic scenarios in the new scenario process (Special Issue: A Framework for the Development of New Socio-economic Scenarios for Climate Change Research, Climatic Change 122(3), 2014). Currently, the RCPs are augmented by Shared-Socio-Economic Pathways (SSPs) and associated emissions scenarios (https://secure.iiasa.ac.at/web-apps/ene/SspDb).
2. Clarke L., K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J.-C. Hourcade, V. Krey, E. Kriegler, A. Löschel, D. McCollum, S. Paltsev, S. Rose, P.R. Shukla, M. Tavoni, B.C.C. van der Zwaan, and D.P. van Vuuren, 2014: Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p.432
3. Schneider, S.H. (2002). 'Can We Estimate the Likelihood of Climatic Changes at 2100?'Climatic Change, 52, 441–451. http://stephenschneider.stanford.edu/Publications/PDF_Papers/SHSClCh2100ed.pdf
4. Rogelj et al. (2013). '2020 emissions levels required to limit warming to below 2°C', Nature Climate Change 3, 405-412. doi:10.1038/nclimate1758.
5. Potsdam Institute for Climate Impact Research (2013). 'Roadmaps towards sustainable energy futures and climate protection: a synthesis of results from the RoSE project'. p23 http://www.rose-project.org/Content/Public/RoSE_REPORT_310513_ES.pdf
6. The White House Office of the Press Secretary (2014). U.S.–China Joint Announcement on Climate Change. Available at https://www.whitehouse.gov/the-press-office/2014/11/11/us-china-joint-announcement-climate-change
7. Arunabha Ghosh (2015) "The big push for renewable energy in India: What will drive it?" Bulletin of the Atomic Scientists, in print.
8. Arunabha Ghosh and Karthik Ganesan (2015) Rethink India's energy strategy. Nature 521(7551): 156-157. Available at: http://www.nature.com/news/policy-rethink- india-s-energy-strategy-1.17508.
9. World Nuclear Association (2015). Nuclear Power in China. http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China--Nuclear-Power/

RISK ASSESSMENT PART 2:

DIRECT RISKS

CLOSEUP OF THE ICE ISLAND FROM PETERMANN GLACIER

NASA Earth Observatory image by Jesse Allen and Robert Simmon, using data from NASA/GSFC/METI/ERSDAC/JAROS, and U.S./JapanASTER Science Team. Caption by Michon Scott

RISK ASSESSMENT PART 2:
DIRECT RISKS

8 INTRODUCTION: A LONG-TERM RISK ASSESSMENT APPROACH TO CLIMATE SCIENCE

Climate risks may be thought of as falling into two categories: the risks of extreme weather events, and the risks due to long-term changes in average conditions. An assessment of climate science will approach these two kinds of risk differently, depending on the nature of the decisions it aims to inform.

An assessment that aims to inform policy on disaster risk reduction will naturally focus on the risk of extreme weather events. These low probability, high impact events are a form of 'worst case' occurrence in any given climate. Since extreme weather events already pose a danger in the present, and can be forecast a few days or a season in advance, it may be reasonable for such a risk assessment to have a relatively short-term focus. An assessment that aims to inform planning for adapting to climate change is also likely to be concerned with extreme events, and with any changes in their frequency or intensity that occur over time, as well as with changes in average conditions. For some planning purposes, the 'worst case' may be important; for others, it may be the 'most likely' case that is most relevant to decision-making. The timescale for such an assessment may not need to go far beyond the planning horizons in the economic sectors concerned.

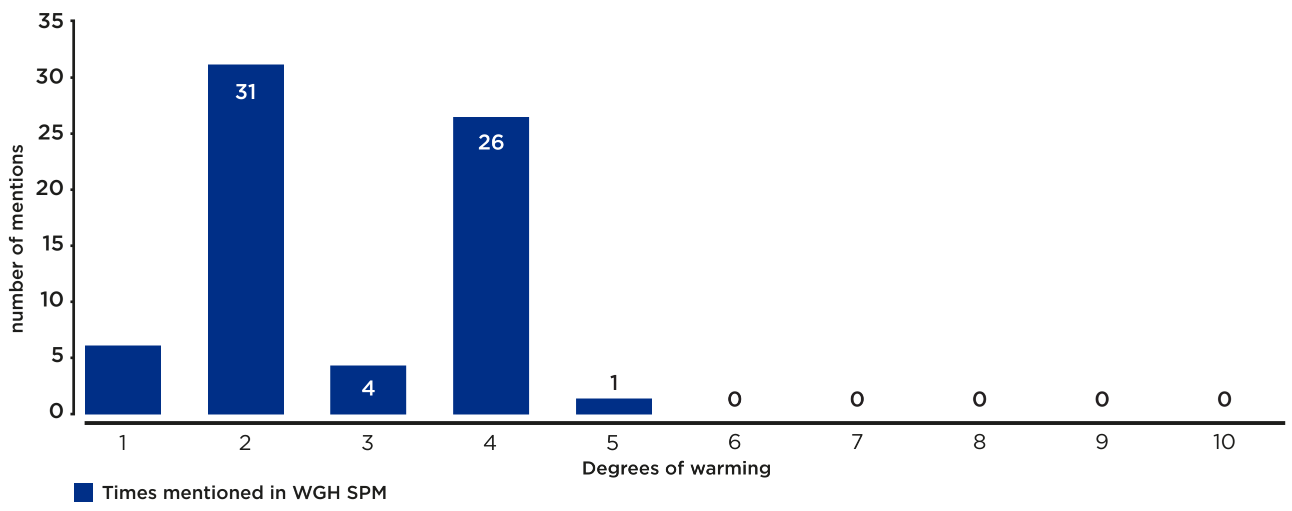
A risk assessment that aims to inform our response to climate change as a whole must consider the whole of the timescale that is affected by our current decisions on energy and emissions. It has to consider 'worst case' outcomes not only in terms of individual events, but also in terms of long-term changes: the risk that average conditions may themselves reach extreme values. That is our aim, in this section of our report.

Knowing the least about what matters most

If we take global mean temperature increase to be a simple proxy for the extent of climate change, then the risks with the largest impacts are likely to occur at the highest degrees of temperature increase. In the Chapter 9, we see that on a very high emissions pathway, temperature increases of more than 10°C over the next few centuries cannot be ruled out. The risks at the top end of that range are likely to be those that are most relevant to our assessment.

However, it appears that most of our scientific knowledge relates to the risks associated with much lower degrees of temperature increase. Figure 1 shows the number of times each degree of temperature increase is mentioned in the Summary for Policymakers of the IPCC's report on Impacts, Adaptation and Vulnerability.[1] While there are many mentions of impacts at 2°C and 4°C, there is only one mention of 5°C, and no mention of anything higher.

Figure 1: **Number of times different degrees of warming are mentioned in WGII SPM**



The detailed chapters of the same report suggest that the impacts corresponding to high degrees of temperature increase are not only relatively unknown, but also relatively unstudied. This is illustrated by the following quotes:

- **Crops:** "Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4ºC or more."[2]
- **Ecosystems:** "There are few field-scale experiments on ecosystems at the highest CO_2 concentrations projected by RCP8.5 for late in the century, and none of these include the effects of other potential confounding factors."[3]
- **Health:** "Most attempts to quantify health burdens associated with future climate change consider modest increases in global temperature, typically less than 2ºC."[4]
- **Poverty:** "Although there is high agreement about the heterogeneity of future impacts on poverty, few studies consider more diverse climate change scenarios, or the potential of 4ºC and beyond."[5]
- **Human security:** "Much of the current literature on human security and climate change is informed by contemporary relationships and observation and hence is limited in analyzing the human security implications of rapid or severe climate change."[6]
- **Economics:** "Losses accelerate with greater warming, but few quantitative estimates have been completed for additional warming around 3ºC or above."[7]

A simple conclusion is that we need to know more about the impacts associated with higher degrees of temperature increase. But in many cases this is difficult. For example, it may be close to impossible to say anything about the changes that could take place in complex dynamic systems, such as ecosystems or atmospheric circulation patterns, as a result of very large changes very far into the future.

Starting by deciding what we wish to avoid

Rather than attempt to predict the unpredictable, a more manageable approach is to start from our first principle of risk assessment: assess risks in relation to objectives. Or, put another way: focus on what it is that we wish to avoid. In accordance with this principle, risk assessments usually first identify an impact (or severity of impact) that one would hope to avoid, and then assess its probability.[i] If a risk is changing over

i. See, for example, the UK National Risk Register of Civil Emergencies.

time, a corresponding approach would be to assess that probability as a function of time. Conceptually, this is the opposite of an approach that asks first what is most likely to happen, and then how that might affect our interests.

For each area of climate science that we consider in this section, we start by asking *"What is it that we wish to avoid?"*, and then ask *"How likely is that, and how does that likelihood change over time?"*

Identifying the biggest risks

Risk assessments, and risk management measures, often focus especially on thresholds at which impacts become non-linear or irreversible, or beyond which no further severity of impact is possible. For example, regulations for the structural integrity of buildings in earthquakes, the capital reserve requirements for insurance firms, and the health and safety standards for people at work, are particularly concerned with avoiding the non-linear impacts of building collapse, insurance firm insolvency, and worker death, respectively.[8,9,10]

Where possible, we have identified what it is that we wish to avoid in terms of thresholds or discontinuities in severity of impact. Where there are no obvious such thresholds, we have attempted to ensure we identify the biggest risks by simply asking *"What is the worst that could happen?"*

Using the best available information

Depending on the question we are trying to answer, the best available information may be the laws of physics, the output of a model, or an expert's judgment. For the purpose of risk assessment, we may need to use all of these – but we need to keep in mind their different levels of reliability.

When a risk assessment is informed by science, as it is here, we also need to bear in mind how cultural preferences may affect the way expert judgment is presented. In our chapter on principles of risk assessment, the reinsurance executive Trevor Maynard said it concerned him that the meaning of a 'conservative' estimate appeared to have the opposite meaning in science from its meaning in insurance. Here the scientist Dr Jay Gulledge explains what might be at the root of this difference, and why it matters for our risk assessment.

ATTITUDES TO ERROR IN SCIENCE AND RISK ASSESSMENT

Dr Jay Gulledge, Director of the Environmental Sciences Division, Oak Ridge National Laboratory.

Type I error aversion

Scientists who strive to provide useful information about climate change and decision-makers who seek such information, *"are linked by a thin thread of climate information that is relevant to their respective endeavors, but they are separated by different needs, priorities, processes and cultures."*[11] One element that often divides these two communities is the ways in which they characterize and treat uncertainty about future outcomes.

Scientists are conservative about drawing incorrect conclusions—so much so that they would rather draw no conclusion than an incorrect one. Consequently, they have developed standard practices and cultural norms to protect the scientific knowledge pool from being contaminated by falsehoods. For example, scientists typically apply statistical tests that estimate the probability that a predicted outcome may have happened purely by chance rather than because of a hypothesized cause. If the probability of the random outcome is greater than five percent, standard practice is to reject the hypothesis. Ironically, this rigor often results in the rejection of a correct hypothesis because there was only a small chance—potentially less than 6 percent—that the hypothesis was indeed a random outcome.[12]

Such scenarios involve two types of uncertainty, or 'error' in statistical terminology. First is the possibility that the hypothesized cause is accepted, but is actually wrong. This condition is commonly called a 'false-positive;' statisticians call it a 'type I error.' Conversely, there is the possibility that the hypothesis is rejected, but is actually correct. This situation presents a false-negative, or 'type II error.' Scientists

CLIMATE CHANGE: A RISK ASSESSMENT 49
RISK ASSESSMENT PART 2: DIRECT RISKS

are relatively tolerant of false-negatives: in most scientific fields it is not standard practice to estimate the probability of committing a type II error.

In contrast, professional risk managers are often more concerned about type II errors which could result in their disregarding a risk with potentially severe consequences.[13] For example, even though the probability of any particular house burning down in a given year is very low, the mortgage lender requires the homeowner to carry casualty insurance to protect the lender's investment. The point is that even a very low probability of an outcome may represent a large risk if the outcome would be very severe. Consequently, when scientists tolerate type II errors, their work may lack rigour from the standpoint of the decision-makers they seek to inform.

Downward bias under uncertainty

Consistent with their aversion to type I error and tolerance of type II error, climate scientists have often erred toward underestimating risk when faced with deep uncertainty.[14] A stark illustration of this phenomenon occurred when the IPCC's 'Reasons for Concern' (RFC), first published in 2001,[15] were updated in 2009.[16] The RFCs are categories of climate change impacts that IPCC authors deemed of potential interest to decision-makers and include risks to unique and threatened ecosystems, extreme weather events, distribution of impacts geographically and across income classes, aggregate economic impacts, and sudden dramatic changes in the regulation of the global climate (e.g., a sudden collapse of a large ice sheet leading to abrupt sea level rise). The RFC assessment evaluated the sensitivity of each RFC category to global temperature increases between 0 and 5 degrees Celsius.

As governments emphasized climate change research during the 2000s, much more evidence became available for assessing these risks. After considering the new evidence, the update estimated greater sensitivity to warming than the original assessment for all five categories of RFC.[17] This outcome suggests that scientists tend to underestimate risk in the face of incomplete information.

Communication breakdown

There may also be a dangerous interaction between climate scientists' cultural aversion to type I error and a documented tendency of the public to discount low-probability, high impact outcomes. For example, the IPCC defines 'likely' as 66-90% probability, and 'unlikely' as 10-33% probability. When college students were asked what they thought the term 'unlikely' meant for the probability of a land-falling hurricane, the most common response was 1-10% (i.e. lower than the probability range assigned to the term by the IPCC).[18] If the scientific community tends to underestimate the severity of impacts under uncertainty, and the public tends to adjust probability of a severe event downward, the net effect may be a serious under-appreciation of the potential severity of climate change impacts among the public and decision-makers.

Conclusion of the U.S. National Academy of Sciences

For the reasons described above, among others, the U.S. National Academy of Sciences has stated that *"Scientific priorities and practices need to change so that the scientific community can provide better support to decision-makers in managing emerging climate risks."*[19]

Scientists who seek to inform decision-making on climate change need to adopt a more risk-sensitive analytical approach. In some cases, this adjustment will require more tolerance of type I error and less tolerance of type II error.

The cultures of science and risk assessment described by Dr Gulledge are not impossible to reconcile. One might expect them to meet in the middle, resulting in an equal aversion to either kind of error. There are many fields in which the use of science to support risk assessment has become highly developed – including the forecasting of extreme weather events.[ii]

For the purposes of this risk assessment, we have tried to make sure relevant information is not omitted simply because the uncertainty is high. At the same time, we have aimed to make the uncertainties, and the expert judgments, as clearly visible as possible. To do this, we have adapted an old rule of intelligence assessment[iii] and asked scientists to tell us: i) what they know; ii) what they do not know; and iii) what they think.

ii. For example, the UK Met Office's National Severe Weather Warning Service uses a matrix of the probability of an event happening versus the impact if it does, and on occasion warns of very low probability events that might have huge impacts if they occurred.

Illustrative examples

In the pages that follow, we apply this approach to assessing risks associated with global temperature increase, human heat stress, crop production, water stress, flooding, drought, coastal cities and sea level rise, and large-scale disruption of the climate system. This is a small subset of the risks of climate change, which leaves out some important issues entirely (such as ocean acidification), and gives relatively brief summaries of others.

The purpose of this section is not to provide a comprehensive survey of the scientific literature. Indeed, each of these chapters reflects the perspectives of its individual authors. The purpose is simply to identify some of the biggest risks, and to illustrate a way in which they may be communicated effectively to policy-makers.

Endnotes

1. Source: Global Challenges Foundation, analysis of content of IPCC AR5 WG2 SPM http://globalchallenges.org/wp-content/uploads/Briefing-on-IPCC-AR5-WGII-and-WGIII.pdf
2. See p.506. IPCC (2014). 'Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects.' Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.
3. IPCC (2014), p.276.
4. IPCC (2014), p.735.
5. IPCC (2014), p.816.
6. IPCC (2014), p.779.
7. p.19 of IPCC (2014). 'Summary for policymakers'. Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32
8. GFDRR, The World Bank. Knowledge Note 1-2: Building Performance. p.4. Retrieved from http://wbi.worldbank.org/wbi/Data/wbi/wbicms/files/drupal-acquia/wbi/drm_kn1-2.pdf
9. Bettis, O. (2014). Risk Management and Climate Change: Risk of Ruin. Accessible at http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2014/01/Oliver-Bettis-Risk-Management-and-Climate-Change-Risk-of-Ruin.pdf.
10. Health and Safety Executive (2001). Reducing Risks, Protecting People: HSE's decision-making process. p.46
11. Rogers, W and J. Gulledge (2010). Lost in Translation: Closing the Gap Between Climate Science and National Security Policy. Center for a New American Security, Washington, D.C.
12. Mabey, N., J. Gulledge, B. Finel and K. Silverthorne (2011). Degrees of Risk: Defining a Risk Management Framework for Climate Security. E3G, London, UK and Washington, DC (p. 61).
13. Schneider, S.H. and Mastrandrea, M.D., (2009). 'Risk, uncertainty, and assessing dangerous climate change'. In: Climate Change Science and Policy, Schneider, S.H., Rosencranz, A., Mastrandrea, M.D., Kuntz-Duriseti, K. (Eds.), Island Press.
14. Engelhaupt, E. (2007). 'Models underestimate global warming impacts.' Environmental Science & Technology, 41, 4488-4489.
15. Smith, J.B. et al. (2001). 'Vulnerability to climate change and reasons for concern: a synthesis.' In J.J. McCarthy et al., eds. Climate change 2001: impacts, adaptation and vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.
16. Smith, J.B., et al. (2009). 'Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) 'reasons for concern''. Proceedings of the National Academy of Sciences of the United States of America, 106, 4133–4137.
17. Mabey, N., J. Gulledge, B. Finel and K. Silverthorne (2011). Degrees of Risk: Defining a Risk Management Framework for Climate Security. E3G, London, UK and Washington, DC (pp. 65-68).
18. Patt, A.G. and D.P. Schrag (2003)/ 'Using specific language to describe risk and probability.' Climatic Change 61: 17–30.
19. National Research Council (2009). Panel on Strategies and Methods for Climate-Related Decision Support. National Academies Press, Washington, D.C.

iii. Attributed among others to the former US Secretary of State and military General, Colin Powell, who is said to have said: "Look, I have got a rule. As an intelligence officer, your responsibility is to tell me what you know. Tell me what you don't know. Then you're allowed to tell me what you think. But you always keep those three separated."

9 GLOBAL TEMPERATURE INCREASE

Professor Jason Lowe, Head of Mitigation Advice, and **Dr Dan Bernie**, Senior Scientist, UK Met Office Hadley Centre

What global temperature increases might we wish to avoid?

Two degrees: The United Nations framework convention on climate change aims to avoid potentially dangerous climate change and has adopted a long-term goal of keeping global average warming below 2°C above pre-industrial levels.[1] The choice of appropriate level is a subjective policy choice informed by estimates of future climate impacts and relative difficulty of adaptation, and the judgment that there is a sufficiently high chance of being able to limit warming to this level.

Four degrees: The recent IPCC report concluded that *"global climate change risks are high to very high with global mean temperature increase of 4°C or more above preindustrial levels in all reasons for concern, and include severe and widespread impacts on unique and threatened systems, substantial species extinction, large risks to global and regional food security, and the combination of high temperature and humidity compromising normal human activities, including growing food or working outdoors in some areas for parts of the year".*[2]

Seven degrees: There has been much less research focusing on the impacts at higher temperatures but limited studies suggest the possibility of even greater impacts, with a rise in temperature of around 7°C potentially giving rise to extreme heat events in excess of human physiological tolerance in some regions.[3]

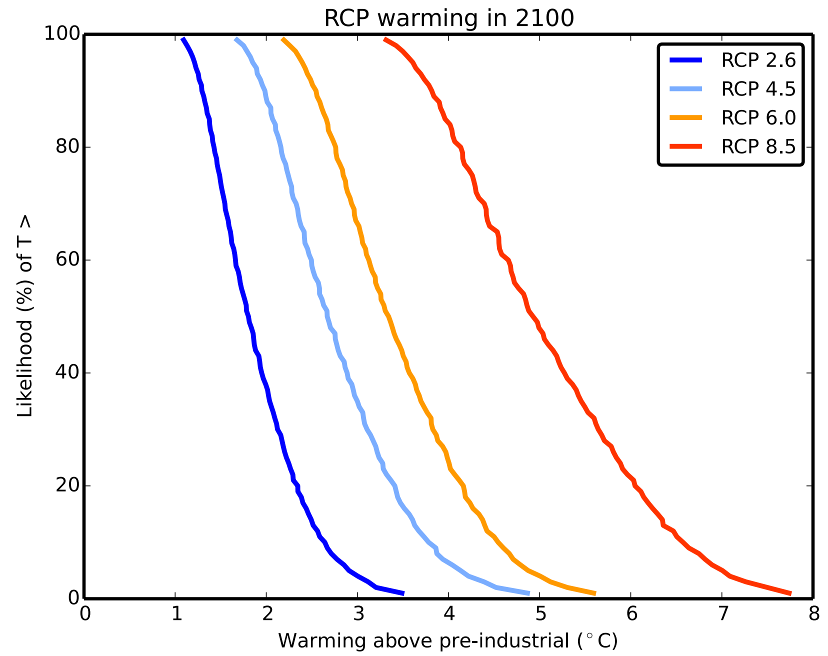
It is important to note that, whilst global average warming is convenient to use as a simple metric, many specific risks depend on local warming and heat extremes (as discussed in the next two sections). Land warms faster than the oceans, so warming in most land areas will exceed the global average, in some places by a significant amount. In addition, there will be changes in extremes, such as the hottest day of the year.

How likely are we to exceed the temperature thresholds we've identified?

The climate response for any future emissions or concentrations scenario must be expressed as a range, frequency distribution or probability distribution because of uncertainty in the relationship between changes in atmospheric greenhouse gas emissions and concentrations and the climate response. The IPCC fifth assessment estimated a likely range of warming by 2081-2100 relative to a near present day period to be in the range of 0.3°C to 4.8°C (equivalent to 0.9°C to 5.4°C relative to pre-industrial) for the range of concentration scenarios considered.[4]

This set of IPCC simulations does not sample all of the known uncertainties in the climate systems, and the experimental set-up over-constrains the spread in atmospheric concentration of greenhouse gases for a given emission pathway. Like the real climate, the climate model used in the AVOID2 programme takes emissions as its input and includes the dependence on CO_2 and the uncertainty in carbon cycle-climate feedback[5] – the way in which the amount of carbon absorbed and emitted by soil vegetation and the ocean may change in response to climate change, and in turn accelerate climate change. It shows the probability of exceeding a range of different warming levels in 2100 relative to pre-industrial level when this additional factor is included in the climate simulations. Even the lowest emissions scenario (RCP2.6) has a more than a 33% chance of exceeding 2°C. The probability of warming beyond 4°C is significant in the middle two pathways, and in the highest emissions pathway, RCP8.5, is somewhere in the region of 90% (Figure 2) in these simulations. In the highest pathway, there is also a small probability of exceeding 7°C.

Figure 2: **Estimate of warming at 2100 from a simple climate model based on emissions from the RCP pathways.** The RCP2.6 pathway represents a world with very rapid emission reductions. RCP8.5 represents a world with a continued focus on fossil fuels and significant increases in greenhouse gas use.

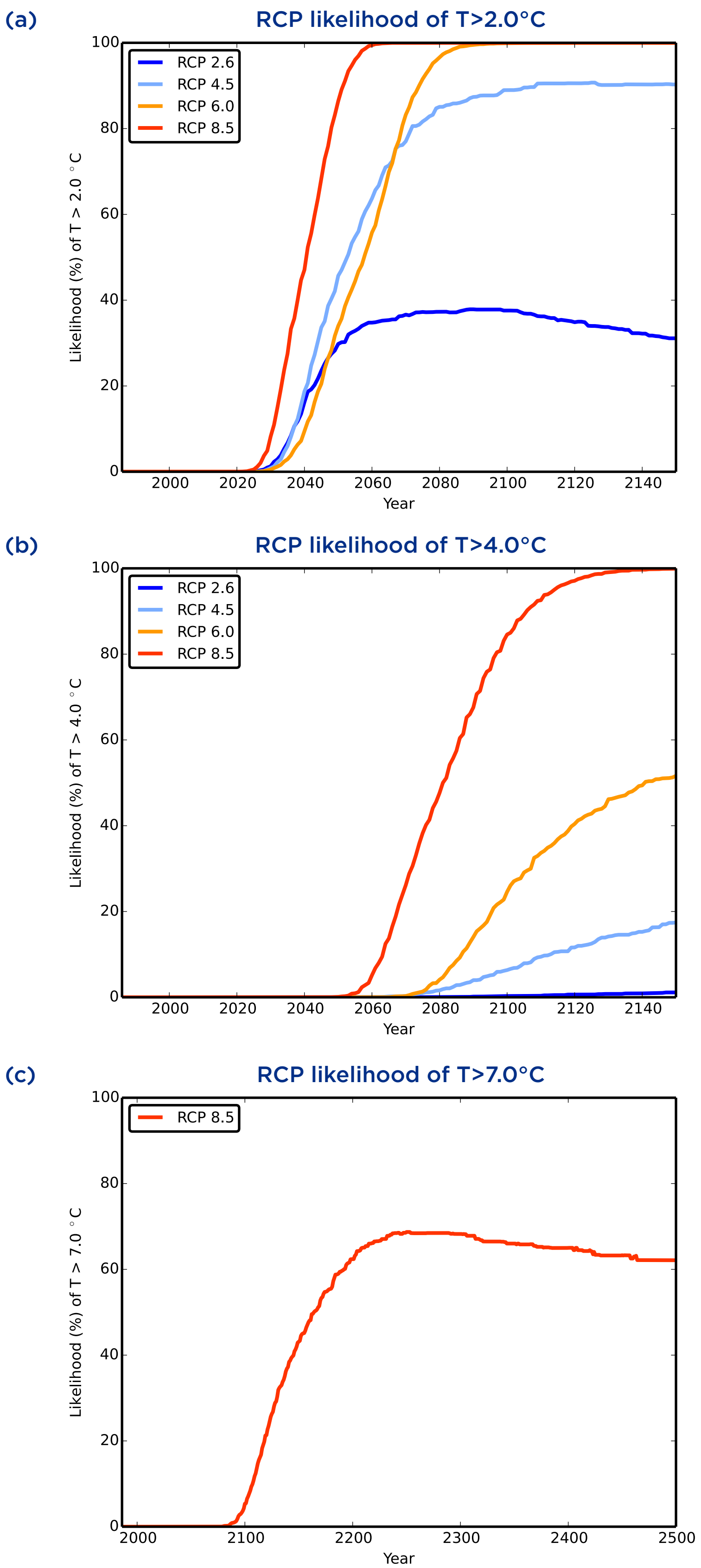


It is important to recognize how these probabilities change over time, and to look beyond 2100, especially for the higher emission scenarios, because in some cases impacts and the probability of major climate system disruption will still be increasing. Figure 3 shows the probability of exceeding 2°C, 4°C and 7°C respectively as a function of time, for the four emissions pathways.

- The probability of exceeding 2°C can be seen to exceed 50% within the first half of the century for the highest emissions pathway, and to exceed 80% late in the century for all except the lowest emissions pathway.
- The probability of exceeding 4°C by 2150 appears to be somewhere in the region of 100%, 50%, and 20%, for the highest and middle two post-2100 continuation pathways respectively, while remaining at only a few percent for the lowest pathway.
- On the highest emissions pathway (the RCP8.5 extension scenario, where beyond 2100 emissions are held constant for 50 years, and then sharply reduced), the probability of exceeding 7°C appears to exceed 50% during the 22nd century, before peaking at around 65% in the following century.

Alternative model set-ups may show small differences in these probabilities, but the conclusions will be qualitatively the same.

Figure 3: **Probability of exceeding: (a) 2°C; (b) 4°C; and (c) 7°C** based on the projected warming to 2500 from a simple climate model set up to cover the range of climate sensitivity from the more complex general circulation models, and sampling uncertainty in climate-carbon cycle feedback.

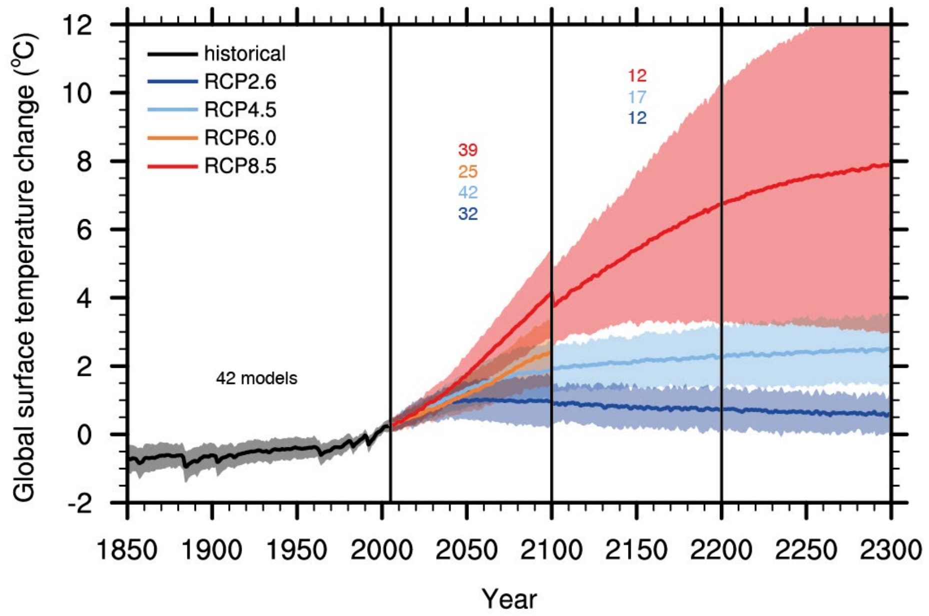


Could the planet warm even further in the next century and beyond?

As shown above, for the highest emission pathway considered in Working Group I of the IPCC Fifth Assessment there is a sizeable possibility of more than 7°C warming above pre-industrial levels in the period after 2100.

It is difficult, if not impossible, to provide a robust estimate of the maximum possible warming. First, it is unclear how to define an absolute upper emissions scenario. For instance, it might include known reserves of fossil fuels, or perhaps projected increases in reserves, which are very uncertain. It may or may not include economic constraints on extracting and using the fossil fuels. For this study we do not look beyond RCP8.5 and its time-extension. The transient evolution of the IPCC model simulations is shown in Figure 4 below. By 2300 a small subset of the climate models reach global average temperature increases in excess of 10°C above pre-industrial levels.

Figure 4: **Time series of global annual mean surface air temperature anomalies** (relative to 1986–2005) from IPCC 5th assessment climate models. (Add 0.6°C to these numbers to compare to a pre-industrial baseline[i, 6]). Projections are shown for each RCP for the multi-model mean (solid lines) and the 5% to 95% range across the distribution of individual models (shading).

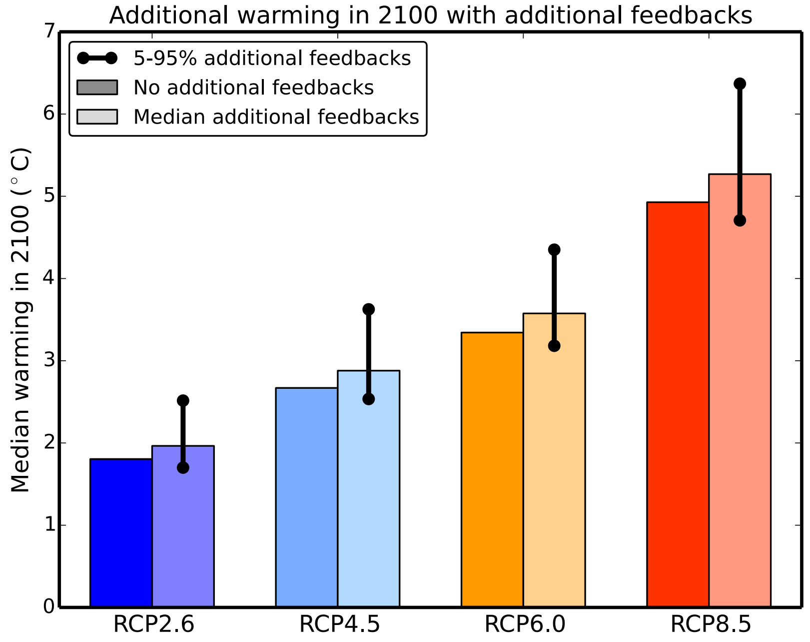


A second reason that we cannot easily estimate the maximum warming is due to the remaining uncertainty in the climate system response. The upper values of our estimates of climate sensitivity are not well bounded. Additionally, there are a range of missing processes that might change the level of warming by, for instance, contributing additional greenhouse gases. Using the published studies from the IPCC 5th assessment of the possible extra forcing provided by known earth system feedbacks as an extra component in a simple climate model we estimated this could add around a further degree of warming on to our median estimate of warming in RCP8.5 by 2100 (Figure 5).[7] Put another way, this could bring forward the time at which the probability of exceeding 4°C on RCP8.5 reaches 50%, by a handful of years in the central estimate, or by more than a decade in the more extreme but unlikely case.

i. Full IPCC caption: Time series of global annual mean surface air temperature anomalies (relative to 1986–2005) from CMIP5 concentration-driven experiments. Projections are shown for each RCP for the multi-model mean (solid lines) and the 5 to 95% range (±1.64 standard deviation) across the distribution of individual models (shading). Discontinuities at 2100 are due to different numbers of models performing the extension runs beyond the 21st century and have no physical meaning. Only one ensemble member is used from each model and numbers in the figure indicate the number of different models contributing to the different time periods. No ranges are given for the RCP6.0 projections beyond 2100 as only two models are available.

If climate sensitivity turns out to be at the higher end of our estimated range the effect of other earth system processes that could amplify warming may become greater, but additional modelling is needed to quantify reliably how much. However, we do know that some of these amplifying factors may take a significant time to be fully realized and so could become larger beyond 2100.

Figure 5: **Estimate of added warming from earth system processes** considered in the IPCC assessment but not typically included in climate change estimates.



Increases in warming such as we project for the RCP8.5 emissions scenarios are unprecedented in the observational record, and even (using proxy measurements) to around 1000AD.[8] Looking over a longer period the IPCC Fifth Assessment Report concludes that during the mid-Pliocene (3.3 to 3.0 million years ago), temperatures were 1.9 to 3.6°C above pre-industrial levels. During the early Eocene (52 to 48 million years before present) global mean temperature were 9 to 14°C higher then pre-industrial levels, for an atmospheric CO_2 concentration of around 1000ppm, which is slightly higher than the 2100 concentration expected in RCP8.5.[9] When considering these distant historical periods it is important to keep in mind both uncertainty in the records and whether the past period really represents a suitable analogue to the anthropocene.

What do we know, what do we not know and what do we think?

Climate projections of the future need to be placed in the context of our understanding of the climate system. We have a clear and longstanding knowledge of the basic physics that tell us increases in atmospheric greenhouse gases are expected to warm the planet.[10] We know that the planet has warmed over recent decades and that this warming is unusual compared to the expected natural variations.[11] This can be explained by the extra energy accumulated in the climate system.

We now have a range of estimates of how sensitive the climate system is to changes in radiative forcing, but we do not know a single precise value. We also understand many of the processes that determine this sensitivity. Whilst there is evidence that complex climate models can simulate skillfully many aspects of past and present climate, expert judgement in the IPCC assessment considers that the 5th to 95th percentile range of 21st century warming by the current generation of complex climate models is too narrow for the range of future greenhouse gas concentration increases.[12]

The fraction of greenhouse gas emissions that remain in the atmosphere for a significant time after production or release can be constrained to a likely range but a single value is not known. We are aware of feedbacks between changes in climate and the carbon cycle, and between the climate and atmospheric chemistry. All of the above have been factored into our quantitative view of the future by one means or another, but again precise values are unknown.

We know that in the distant past there have been large-scale disruptions to the climate system, similar to what we would consider today as tipping points. We think that the chances of these events occurring in the future are more likely at greater levels of warming but we do not know the precise conditions needed to trigger these events (see chapter 17).

We know that there are a range of earth system processes, and that the majority of those considered in the IPCC assessment, such as thawing permafrost, might accelerate warming and climate disruption across the planet. But, while we are starting to make estimates of these effects, they are rarely included in current climate models or climate risk assessments (see Figure 6 as an exception). Additionally there are processes, such as the potential release of methane from hydrate stores in and under ocean sediments, that could contribute significant extra warming.[13] We know that these stores are very large, and have contributed significantly to warming over long time periods in the distant past. Our best estimate is that they will only have a very small effect over the next century or so, but we have very limited understanding of what might happen in the longer-term future.

Production of this chapter was supported by the AVOID2 programme (funded by the UK Government and Natural Environment Research Council)' with 'Production of this chapter was supported by the AVOID 2 programme (DECC) under contract reference 1104872. and the EU HELIX programme (funded by European Union Seventh Framework Programme FP7/2007-2013 under grant agreement no 603864)

Endnotes

1. United Nations (1992). United Nations Framework Convention on Climate Change. Available at http://unfccc.int/resource/docs/convkp/conveng.pdf
2. IPCC (2014). 'Summary for policymakers'. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.
3. Sherwood, S.C. and Huber, M. (2010). 'An adaptability limit to climate change due to heat stress'. PNAS 107
4. Table SPM.2 in IPCC (2013). 'Summary for Policymakers'. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
5. Lowe, J., Huntingford, C., Raper, S.C.B., Jones, C.D., Liddicoat, C.D. and Gohar, L.K. (2009). 'How difficult is it to recover from dangerous levels of global warming?'. Environmental Research Letters 4 doi:10.1088/1748-9326/4/1/014012
6. Figure 12.5, Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner (2013). 'Long-term Climate Change: Projections, Commitments and Irreversibility.' Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
7. Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFries, J. Galloway, M. Heimann, C. Jones, C. Le Quéré, R.B. Myneni, S. Piao and P. Thornton (2013). 'Carbon and Other Biogeochemical Cycles'. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 465–570, doi:10.1017/CBO9781107415324.015.
8. Masson-Delmotte, V., M. Schulz, A. Abe-Ouchi, J. Beer, A. Ganopolski, J.F. González Rouco, E. Jansen, K. Lambeck, J. Luterbacher, T. Naish, T. Osborn, B. Otto-Bliesner, T. Quinn, R. Ramesh, M. Rojas, X. Shao and A. Timmermann (2013). 'Information from Paleoclimate Archives'. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 383–464, doi:10.1017/CBO9781107415324.013.
9. Masson-Delmotte, V. et al (2013).
10. e.g. Houghton, J. (2009) Global Warming: The Complete Briefing. Cambridge University Press, Cambridge.
11. Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari and X. Zhang (2013). 'Detection and Attribution of Climate Change: from Global to Regional'. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 867–952, doi:10.1017/CBO9781107415324.022..
12. Table SPM.2 in IPCC (2013). 'Summary for Policymakers'.
13. Masson-Delmotte, V. et al (2013).

10 THE RISK OF HEAT STRESS TO PEOPLE

Dr. Tord Kjellstrom, **Professor Alistair Woodward**, **Dr. Laila Gohar**, **Professor Jason Lowe**, **Dr. Bruno Lemke**, **Lauren Lines**, **Dr. David Briggs**, **Dr. Chris Freyberg**, **Dr. Matthias Otto**, **Dr. Olivia Hyatt**[i]

What global temperature increases might we wish to avoid?

The human body has behavioural and physical mechanisms that work to maintain its core temperature at about 37°C. If the body's internal temperature rises above this level, then body systems and vital physiological functions are compromised, and in severe cases, death can result. The climatic conditions relevant to such heat stress may be measured in terms of the Wet Bulb Globe Temperature (WBGT), which takes account of temperature, humidity, wind speed, and solar radiation.[1] We calculate WBGT for in-shade (no solar heat addition) or indoor (no air conditioning) conditions from climate data using methods described by Lemke and Kjellstrom.[2] We have considered heat stress thresholds relevant to four human interests: survival, sleep, work and sport.

Survival

The threshold for survivability is defined as climatic conditions so extreme that if a person is exposed to them (i.e. not protected by air-conditioning), core body temperature rises to potentially fatal levels while sleeping or carrying out low energy daily tasks.

For day-time heat we set the threshold for survivability according to the WBGT that causes core body temperature to rise to 42°C, for an average individual at rest,[ii] in the shade, for four hours. We estimate this occurs when the daily maximum WBGT is ≥ 40°C. We have set the threshold at the situation when 10% of the days in the hottest month are projected to exceed this threshold ('the three hottest days in the hottest month'), since at this point exceeding it at least once becomes almost certain.

For night-time heat we define the threshold for survivability as conditions which prevent a reduction in core body temperature overnight, so that the heat exposure of the following day adds directly onto the high heat exposure of the previous day.[3] We estimate this occurs in most people when the average minimum WBGT is ≥36°C. (We use the same 'three night' assumption as used above for days).

Sleep

Our threshold for 'sleepability' is defined in terms of conditions that permit some reduction in core body temperature, but not to the full extent necessary for normal sleep:[4] specifically, when the core body temperature remains above 37°C during eight hours of rest, at night. We estimate this applies for most people when the average minimum WBGT is ≥ 30°C. (Again, we use the same 'three night' assumption.)

It is important to note that individual susceptibility to heat varies widely. Relevant factors include age, gender, health status, and past exposures to heat.[5] In relation to the survival and sleep thresholds described above, we have sought to identify a plausible mid-range temperature, i.e. one at which roughly 50% of the population cannot stay in heat balance.

Work

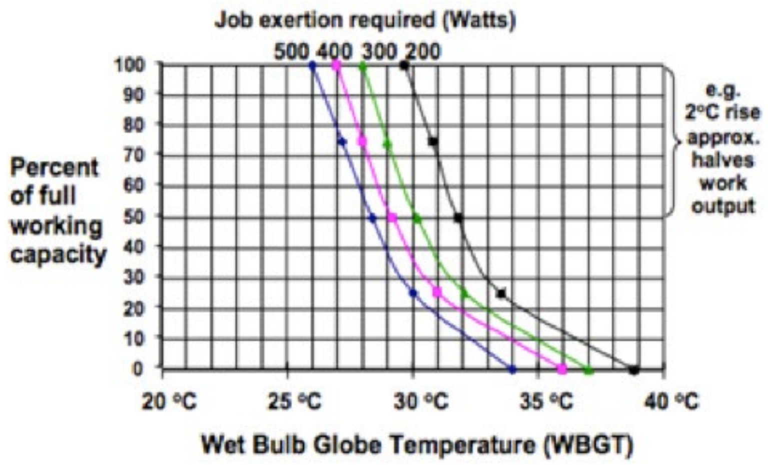
As human muscle activities create important intra-body heat production, working people are at particular risk as climate change increases ambient heat levels.[6] We have defined the limits to work according to time-based threshold limit values published by the United States Occupational Safety and Health Administration[7] and the 'no work at all' ceiling recommended by the US National Institute of Occupational Safety and Health.[8] On the basis of these guidelines, which are summarized in Figure 1, we conclude that when WBGT reaches 36°C it is not safe for medium/heavy labour,[iii] even with rest breaks. We define 'too hot to work' as conditions in which the average daily maximum WBGT is 36°C or more for a month.

i. Dr. Tord Kjellstrom, Department of Public Health and Clinical Medicine, Umeå University; Professor Alistair Woodward, University of Auckland; Dr Laila Gohar, Met Office Hadley Centre; Professor Jason Lowe, UK Met Office Hadley Centre; Dr. Bruno Lemke, Nelson Marlborough Institute of Technology; Dr. David Briggs, Imperial College, London; Dr. Chris Freyburg, Massey University; Dr. Matthias Otto, Nelson Marlborough Institute of Technology; Olivia Hyatt, Health and Environment International Trust.

ii. Emitting heat at a rate of 120W

iii. Equivalent roughly to working at a rate of 400W

Figure 1: **The relationship between heat and work** - a function of ideal human physiology and a pointer to fundamental temperature thresholds.[9]



Based on ISO Standard for Heat Stress in the Workplace (1989)

Wet Bulb Globe Temperature – a measure of heat stress that is sensitive to air temperature, radiant temperature, humidity and wind velocity

Sport

The limit in this case is based on a guidance note from sports medicine experts in the USA.[10] This states that competitive outdoor sports activities should cease when WBGT reaches 28°C. We define the threshold for 'sportability' as a situation in which all daylight hours in the three hottest months exceed 28°C WBGT. Given what is known about the 24 hour distribution of temperatures and humidity, we infer that the threshold conditions are met when the average WBGT is ≥ 28°C, for three months. We note that this level includes a substantial 'safety margin' to protect the most sensitive individuals.

How close are we to these thresholds in the current climate?

Heat stress already causes many deaths and a great deal of illness each year, especially in low income tropical countries.[11] However, even in the hottest parts of the world, temperatures in populated areas seldom if ever approach the thresholds of survivability described above.

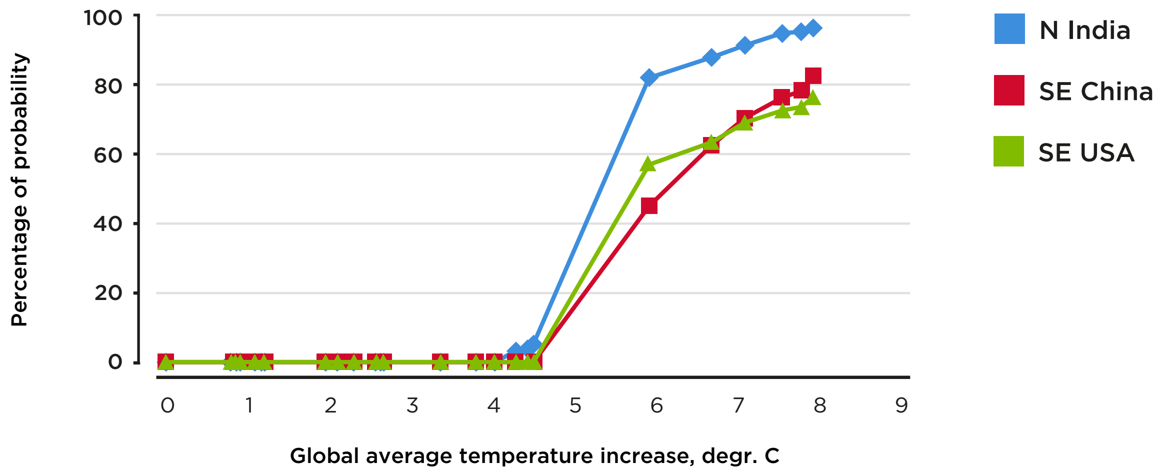
The OSHA threshold limit values are frequently exceeded for short periods, in hot countries, but not for the extended periods described by our threshold.[12] Similarly the 28°C WBGT sportability limit is crossed every year in many places, for short periods. (For instance, games at the Australian Open Tennis championship in January 2014 were cancelled when ambient (dry bulb) temperatures exceeded 40°C.[13] However, these high temperatures are seldom sustained, at present.

Estimates of the likelihood of exceeding these thresholds as a function of global average temperature increase, for selected locations

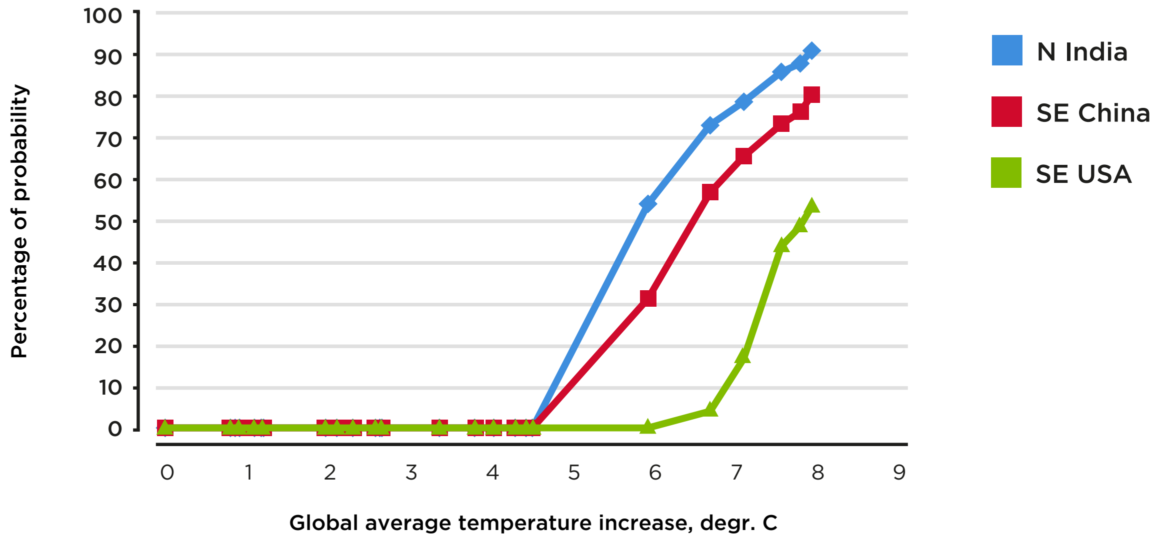
Figure 2 shows how the probability of crossing these thresholds could increase in three regions: North India, Southeast China, and Southeast USA, as global temperatures rise. On these graphs, 'probability' represents the proportion of each region's population estimated to be in areas where climatic conditions cross the relevant threshold. The relationship between global temperature increase and local climatic conditions has been estimated using climate models, and the spatial distribution of population has been estimated based on UN projections. There are some rough approximations in this calculation, but it serves to provide an illustration of the risk. A full description of the methods is located in the Annex.

Figure 2:

Survivability (day): Probability (%) that a person in a region is exposed to heat that causes core body temperature to rise to 42°C, for an average individual at rest in the shade for 4 hours. Defined as WBGTmax ≥ 40°C, for 10% of the days in the hottest calendar month of the year. Temperature increase is relative to present day.[iv]

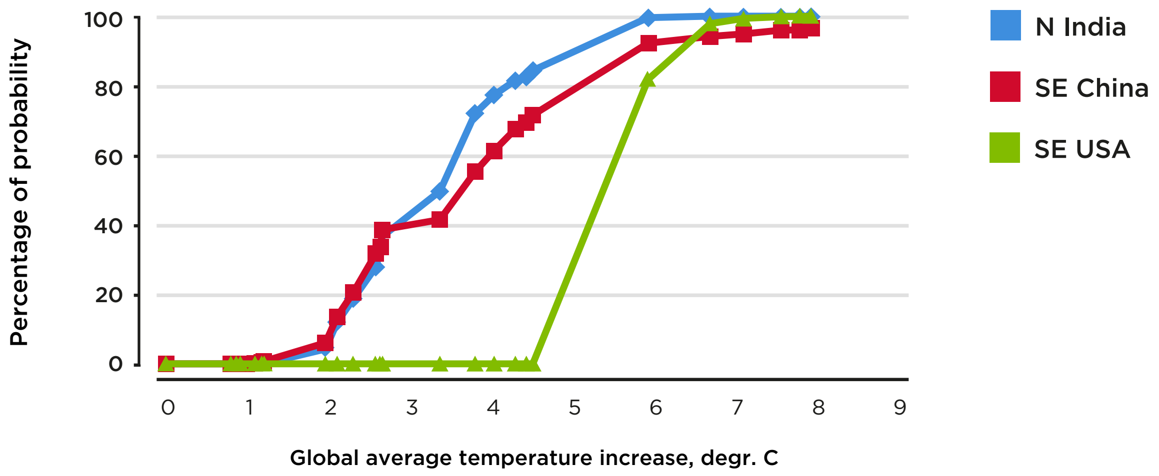


Survivability (night): Probability (%) that a person in a region encounters conditions that prevent any fall in core body temperature at night. Defined as WBGTmin ≥ 36°C, for 10% of the nights in the hottest calendar month of the year. Temperature increase is relative to present day.

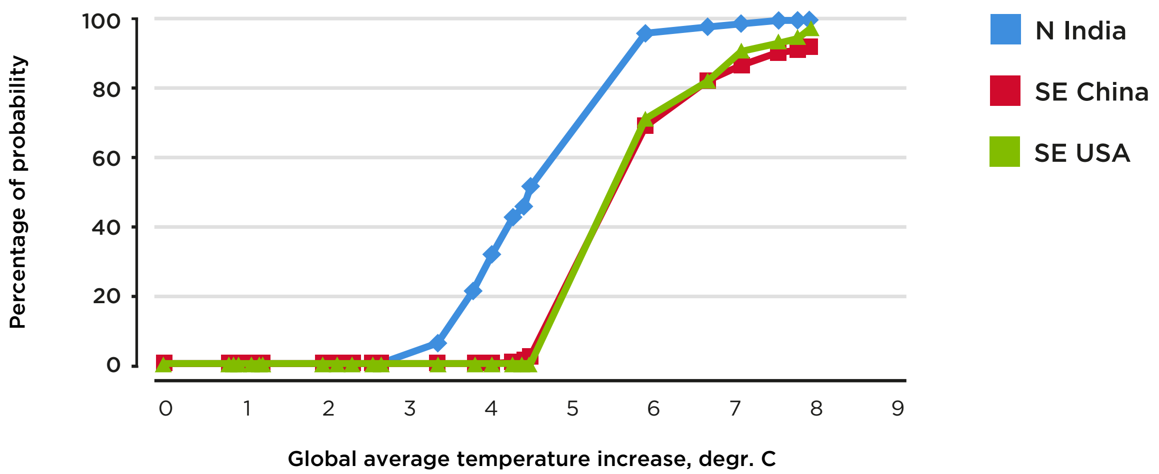


iv. Global average temperature increase is shown here as relative to a 'present day' baseline, as defined by the 30-year average centred on 1995 (i.e. from 1980 to 2009). This is about 0.6 degrees C higher than the 'pre-industrial' baseline used in the temperature increase chapter, and referred to generally throughout this report.

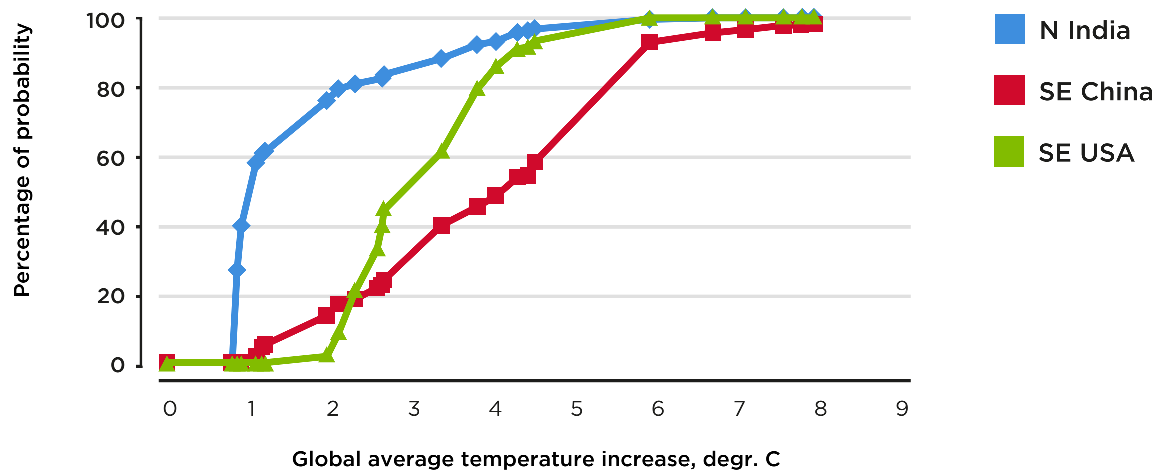
Sleepability: Probability (%) that a person in a region encounters heat that prevents core body temperature from falling down to normal (37°C) during eight hours of rest at night. Defined as WBGTmin ≥ 30°C, for three nights in a month. Temperature increase is relative to present day.



Workability: Probability (%) that a person in a region cannot work at 400W. Defined as average daily WBGTmax ≥ 36°C for a month. Temperature increase is relative to present day.



Sportability: Probability (%) that a person in a region encounters conditions in which daylight hours in the hottest three months of the year exceed 28°C WBGT. Defined as daily WBGTmean ≥ 28°C during three months. Temperature increase is relative to present day.



The projections shown here suggest the first limit to be crossed will be that related to sport. Using the definition of dangerous heat that is applied today in many countries, there is about a 40% chance that individuals in northern India will not be able to participate in competitive outdoor activities in summertime when global average temperatures have risen on average by one degree compared to the present. With four degrees of warming this probability will have risen to around 80-90% in northern India and southeastern USA, and there is a 50:50 chance the population of southeastern China will be affected similarly.

According to these estimates, the limits on work, as defined above, will emerge before the world warms by four degrees on average compared to the present. At this point, in northern India there is a probability of about 30% that temperatures will be so high that moderate/heavy outdoor work cannot be carried out in the hottest month. The probability of exceeding the threshold is close to 80-100% in all regions when the global average temperature rises by 7-8°C.

Heat so severe that it is not possible to reduce core body temperature while sleeping, as defined above, will be encountered once the global average temperature increases by more than 5°C. In northern India and southeastern China the probability of being exposed to heat that makes healthy sleep impossible rises rapidly when global warming exceeds 6°C. At +8°C global warming we estimate a probability of 50-90% in the study regions that individuals will encounter conditions so hostile that normal sleep becomes impossible.

The daytime survivability threshold that we have defined is not crossed until global warming exceeds 4°C. But if warming continues, we estimate that populations in all study regions will be at risk: the probability of encountering conditions that cannot be tolerated, even in the shade and at rest, at +6°C global warming range from about 50% (southeastern China) to 80% (northern India).

We can understand how these risks vary over time by comparing these results with the findings of the previous chapter. For example, it is notable that the probability of passing several of our heat stress thresholds rises steeply when global temperature increases by around 4°C compared to the present (around 4.8°C relative to pre-industrial). As the previous chapter showed, on the highest emissions pathway such an increase becomes more likely than not by the end of this century.

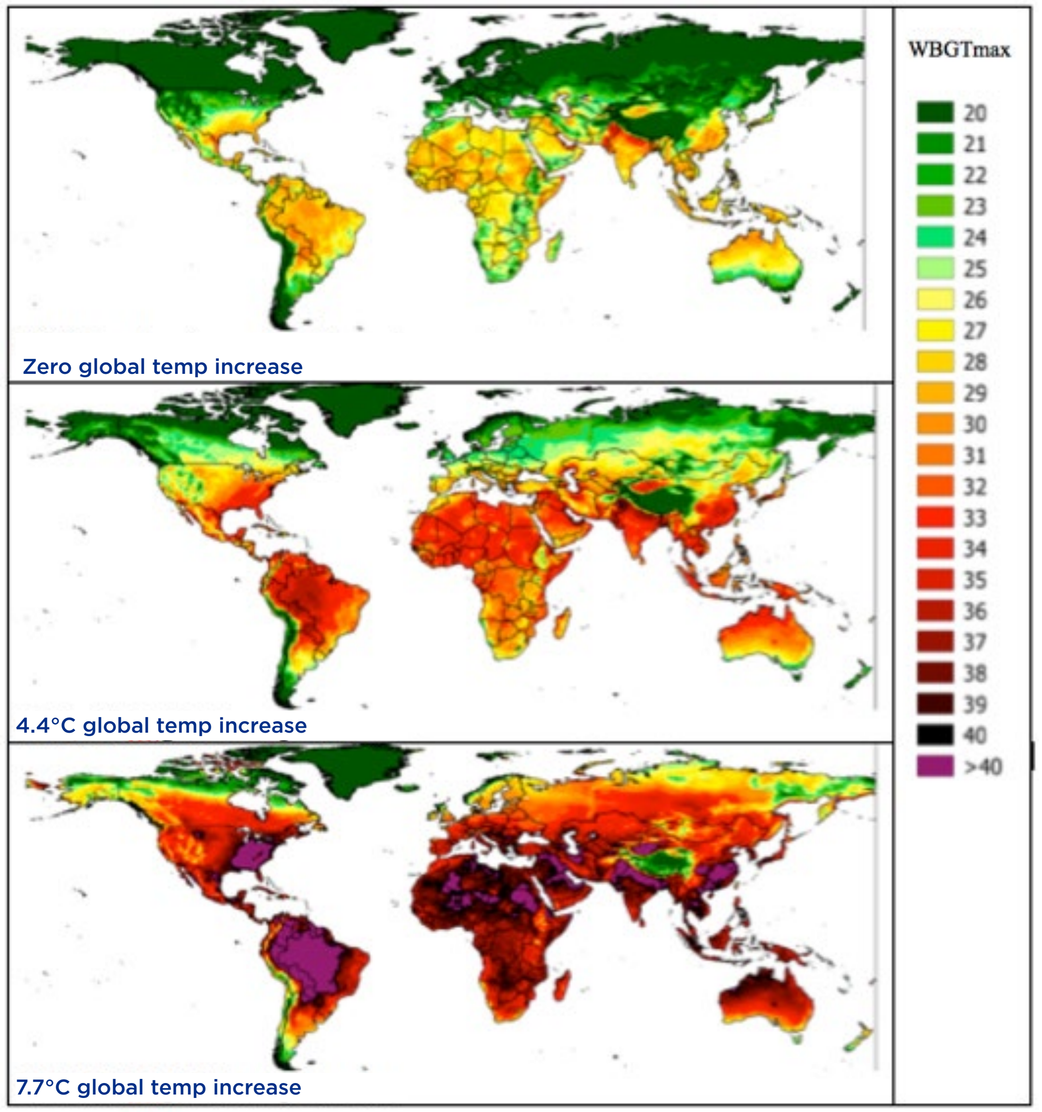
What is a plausible worst case for heat stress due to climate change this century and beyond?

An even more extreme threshold than any we have used here has been defined on thermodynamic grounds: when wet bulb temperature exceeds skin temperature, since it is impossible at this point for the body to shed heat. This would occur when wet bulb temperature exceeds 35°C.[v, 14] In practical terms, the limit for survival will be reached at lower ambient temperatures, due to the necessity in all populations for some moderate - light activity.

Sherwood & Huber (2010) suggested that these conditions would first be experienced in small areas when global average temperature rose 7°C above the current level, and that large populated areas of the globe would experience these conditions once global warming reached 10-11°C on average above the current level. Elsewhere in this report we conclude there is a 'sizable possibility' (probability about 60%) that global average temperatures will rise by more than 7°C above pre-industrial in the 22nd century, under the high emissions scenario RCP8.5. It is difficult to estimate the risks of warming greater than this. However, by 2300 a small subset of the IPCC climate models reach global average temperature increases in excess of 10°C above pre-industrial levels.

To provide more information on the projections used here, Figure 3 shows three maps that display average daily peak WBGT during the hottest month of the year, at three different points of global temperature increase.[15] The Annex also includes estimates of the proportion of work hours lost due to heat stress, at different levels of physical activity, in relation to global average temperature increase.

Figure 3:



v. E.g. temperature is 35 degrees C with 100% humidity, or other equivalent combinations

What do we know, what do we not know, and what do we think?

What we know: The response of the human body to heat is well-understood, and the limits that extreme temperatures impose on functioning and well-being are clearly demarcated. We also understand the many factors that influence vulnerability to heat stress. Surveys in many parts of the world find that heat is already a significant constraint on work and sport. Globally temperatures are rising, and it is expected, with high confidence, that episodes of extreme heat will occur more frequently in the future.[16]

What we do not know: There are many uncertainties in these climate model estimates particularly with regard to regional variations. Temperatures are projected with greater confidence than humidity and rainfall. An even greater uncertainty concerns social adaptation: undoubtedly it will occur, but the speed of change, its inclusiveness or otherwise, and the costs and acceptability of responses such as 24/7 air-conditioning and totally indoor lifestyles are uncertain.

What we think: It is important to recognize that the probabilities shown here understate the risks that apply in many locations. This results from the wide variations in temperatures due to local meteorological and other environmental factors (the urban heat island effect, for instance, may increase night-time temperatures by as much as 10°C). How much people are exposed to outdoor conditions will also vary greatly. Those without access to artificial cooling, and people who must work outdoors, unprotected, to maintain their livelihoods will obviously be more severely affected than those who can live and work away from the heat. The effect of being in afternoon sunlight, rather than in the shade, adds an extra 3-4°C on to WBGT. The old, the young and those with chronic poor health are especially vulnerable to heat-related illness.

When it is too hot to sleep comfortably, the stressful effects of exposure to high temperatures during the day are likely to be magnified. Similarly, we would expect productivity at work to be reduced significantly by persistent high night-time temperatures. For these and other reasons we suggest that beyond a certain point, the heat stress implications of rising global temperatures could threaten the habitability of low-income regions in which people rely on local agriculture for their livelihoods. Throughout the hottest parts of the world, heat will threaten the viability of industries and activities whose environments cannot be artificially cooled. This may include some utilities, construction, and emergency response services such as ambulance crews and fire-fighters.

Production of this chapter was supported by the AVOID 2 programme (DECC) under contract reference 1104872. Elements of the production of this chapter were supported by the EU HELIX programme (funded by European Union Seventh Framework Programme FP7/2007-2013 under grant agreement no 603864)

Endnotes

1. Parsons K. (2014). Human Thermal Environments. The Effects of Hot, Moderate and Cold Environments on Human Health, Comfort and Performance. Third Edition. Boca Raton, CRC Press.
2. Lemke B, Kjellstrom T (2012). 'Calculating workplace WBGT from meteorological data'. Industrial Health, 50, 267-278.
3. Krauchi K. (2007). 'The human sleep-wake cycle reconsidered from a thermoregulatory point of view.' Physiology & Behavior 90, 236-245
4. Krauchi K. (2007).
5. Parsons (2014).
6. Kjellstrom T, Holmer I, Lemke B (2009). 'Workplace heat stress, health and productivity - an increasing challenge for low and middle-income countries during climate change'. Global Health Action 2: Special Volume, pp. 46-51.
7. OSHA (1999). Section III Chapter 4: Heat Stress. OSHA Technical Manual.Occupational Safety and Health Administration [Internet]; [Accessed on 27 Apr 2015]. Washington DC. Available at: http://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_4.html.
8. NIOSH (1986). Criteria for a Recommended Standard. Occupational Exposure to Hot Environments. DHHS (NIOSH) Publication No.86-113. Department of Health and Human Services April 1986.
9. Heat at work safety guidelines based on ISO (1989). Hot environments - Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature). ISO Standard 7243. Geneva: International Standards Organization and NIOSH (1986) recommendations, and adapted from graph in Kjellstrom, T, Kovats S, Lloyd SJ, Holt T, Tol RSJ (2009). 'The direct impact of climate change on regional labour productivity.' Int Archives of Environmental & Occupational Health 64, 217-227)

10. Binkley H, Beckett J, Casa DJ, Kleiner DM, Plummer PE (2002). 'National Athletic Trainers' Association Position Statement: Exertional Heat Illnesses'. J Athletic Training 2002; 37(3): 329-343; American College of Sports Medicine (2007). 'Exertional Heat Illness During Training and Competition'. Medicine & Science in Sports & Exercise 39(3): 556-572
11. Hyatt OM, Lemke B, Kjellstrom T. (2010). 'Regional maps of occupational heat exposure: past, present and potential future.' Global Health Action 3: 1-11; Kjellstrom T, Lemke B, Otto M (2013). 'Mapping occupational heat exposure and effects in South-East Asia: Ongoing time trends 1980-2009 and future estimates to 2050'. Indust Health 51: 56-67.
12. Crowe J, Wesseling C, Solano BR, Umana M, Ramirez AR, Kjellstrom T, Morales D, Nilsson M. (2013). 'Heat exposure in sugarcane harvesters in Costa Rica'. Am J Industrial Medicine 56: 1157-1164; Sheffield PE, Herrera JGR, Lemke B, Kjellstrom T, Romero L. (2013). 'Current and future heat stress in Nicaraguan work places under a changing climate'. Industrial Health 51: 123-127
13. See http://www.bbc.com/news/world-asia-25743438)
14. Sherwood S, Huber M. (2010). 'An adaptability limit to climate change due to heat stress.' PNAS 107: 9552-4
15. Generated using the HadGEM climate model, with the RCP8.5 emissions pathway.
16. IPCC (2014). 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, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

11 THE RISKS OF CLIMATE CHANGE FOR CROP PRODUCTION

Professor John R. Porter,[i] **Dr Manuel Montesino**[ii] and **Dr Mikhail Semenov.**[iii]

For this assessment of climate change risks to crop production, we draw heavily on the chapter 'Food Security and Food Production Systems'[1] of the IPCC's Fifth Assessment Report. We add to this some discussion of important thresholds.

What do we wish to avoid, and how likely is it?

In terms of the risk of climate change to the production of individual crops, one thing we wish to avoid is crop failure. This may be defined as: *"Reduction in crop yield to a level that there is no marketable surplus or the nutritional needs of the community cannot be met."*[2] Since this level is not easily defined, this chapter considers two cases:

i. Plausible worst case reductions in average yield.

ii. The possibility of near-complete loss of yield in a given year.

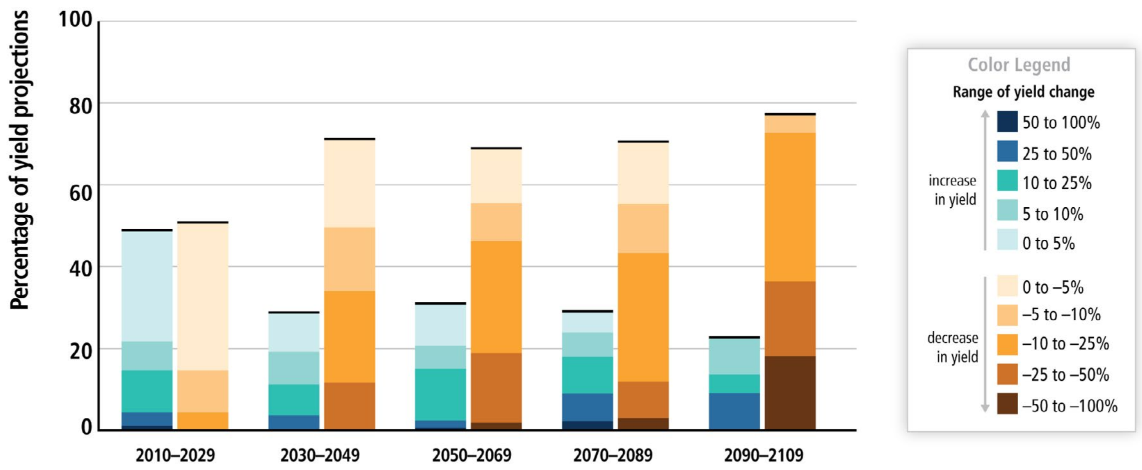
In terms of the risk of climate change to global crop production, what we wish to avoid is the failure of production to keep pace with growing demand.

THE RISK TO INDIVIDUAL CROPS: RISK OF CROP FAILURE

Plausible worst case reductions in average yield

As climate change progresses over time, its effect on crop yields is projected to become increasingly negative. The magnitude of this effect is highly uncertain. This progression, and its uncertainty, are illustrated by figure 1.

Figure 1: **Summary of projected changes in crop yields due to climate change over the 21st century.**[iv] From IPCC AR5 WG2 Summary for Policymakers.[3]

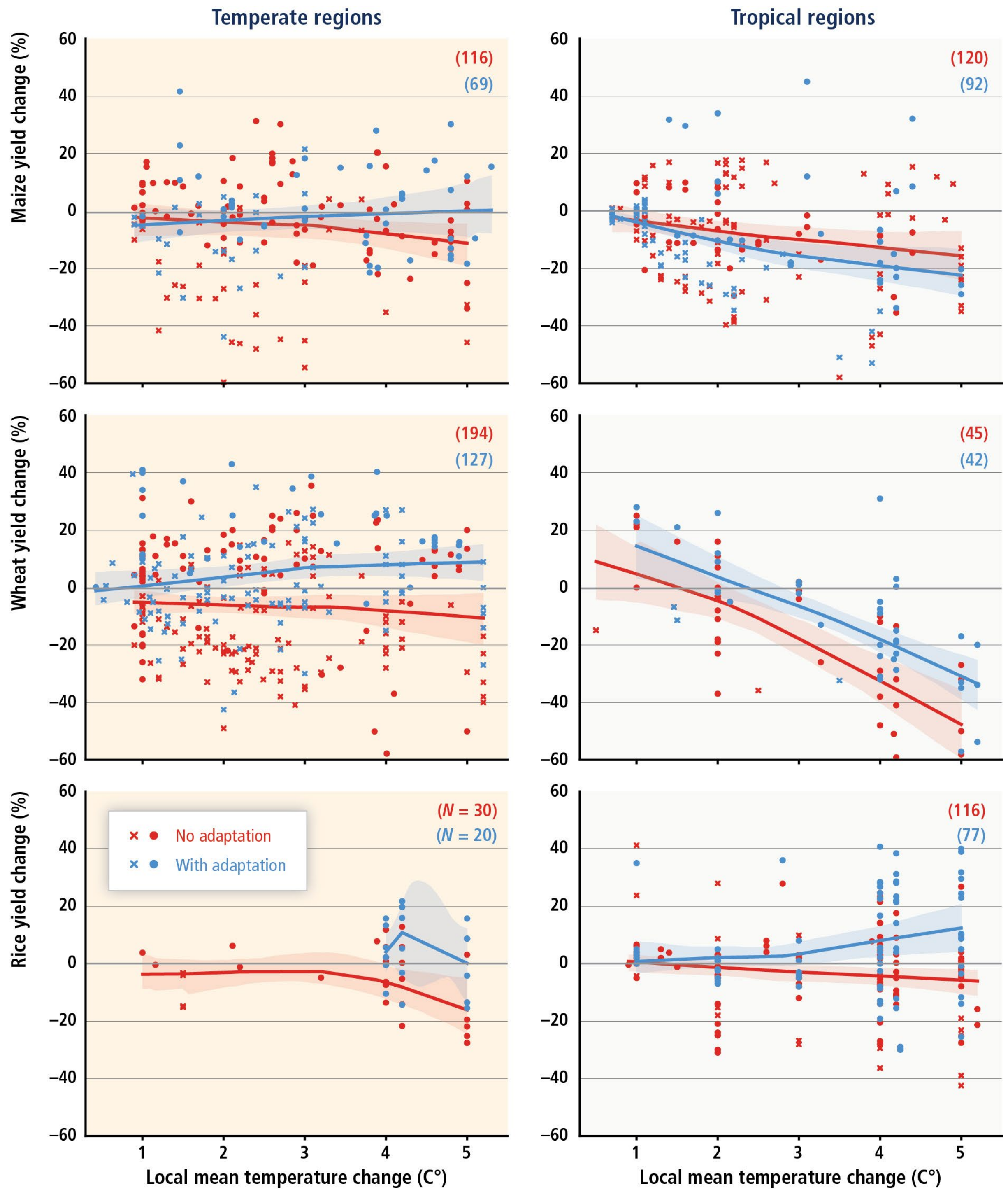


i. Professor John R. Porter is Professor of Climate and Food Security at the University of Copenhagen.
ii. Dr Manuel Montesino is a member of the University of Copenhagen.
iii. Dr Mikhail Semenov is a member of Rothamstead Research.
iv. The figure includes projections for different emission scenarios, for tropical and temperate regions, and for adaptation and no-adaptation cases combined. Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more. For five timeframes in the near term and long term, data (n=1090) are plotted in the 20-year period on the horizontal axis that includes the midpoint of each future projection period. Changes in crop yields are relative to late-20th-century levels. Data for each timeframe sum to 100%.

Figure 1 shows an aggregation of projections for change in the yield of different crops, in different regions, at different degrees of climate change, and under different assumptions including with regard to whether adaptive measures have been taken. From this high-level overview, some initial 'worst case' information may be inferred: by 2030-2049, the lowest tenth of projections give yield decreases of 25% - 50%. By 2090-2109, the lowest fifth of projections give yield decreases of 50% - 100%.

There are, however, dangers in averaging. When the data for different studies are disaggregated, as in figure 2, the wide range of possible outcomes is more clearly visible.

Figure 2: **Percentage simulated yield change as a function of local temperature change for the three major crops and for temperate and tropical regions.**[v, 4] From IPCC AR5.[5]



From the underlying data, we can see how wide is the range of projections for a given crop, in a given region, for a given temperature increase. For example, of two studies considering the impact on wheat production in Pakistan with a temperature change of 3°C, one estimates a 23% increase, and the other a 24% reduction. Similarly one study estimates the impact of a 3°C change on rice production in China to be anywhere between a reduction of 40% and an increase of 0.2%.[6] The low end of these ranges gives a rough idea of a plausible worst case.

What can we say about the likelihood of the low end projections versus that of the high end projections? There are many uncertain factors (discussed below), and the projections are not probabilistic. To a first approximation, we may assume that the worst case and the best case are equally likely, but that the overall trend is clearly for a reduction in crop yields for increases in local temperatures. (This has to be seen in the context of an increasing human population, as discussed below).

While the data in the IPCC figures show a wide range of impacts on crop production for a certain range of temperature increases, it is notable that the range of temperature increases considered is relatively narrow. As can be seen from Figure 2, all the projections relate to local temperature increases of 1-5°C, and most of them are at the lower end of this scale. Since land temperatures increase more than the global average, most of these results may be considered to fall into a range of global mean temperature increase of roughly 1-3°C. As noted in the IPCC AR5 WG2 Summary for Policymakers, 'relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more'.

Chapter 9 observes that in the worst case, global mean temperature could increase by more than 7°C this century, and more than 10°C over the next few centuries. The impact of climate change on crop production for the upper half of this range is relatively unstudied. In this sense, our knowledge of worst case scenarios for climate change impacts on crop production is severely lacking.

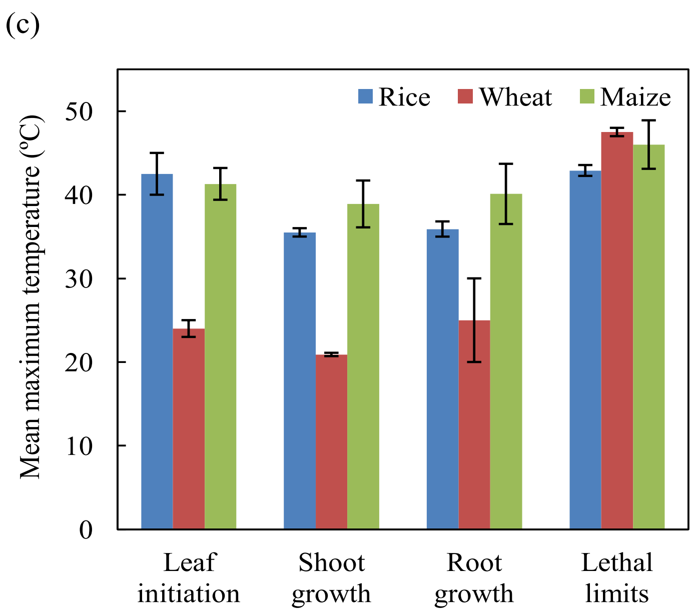
This lack of information is particularly important given that the relationship between temperature increase and impact on crop yield is not expected to be linear. The World Bank's 'Turn Down the Heat' report on the impacts of climate change at 4°C stated: *"Recent research also indicates that there may be larger negative effects at higher and more extreme temperatures… In particular, there is an emerging risk of nonlinear effects on crop yields because of the damaging effect of temperature extremes. Field experiments have shown that crops are highly sensitive to temperatures above certain thresholds. This effect is expected to be highly relevant in a 4°C world. Most current crop models do not account for this effect, leading to recent calls for an 'overhaul' of current crop-climate models."*[7]

Near-complete loss of yield in a given year

The decline in crop yields shown above mainly considers the shortening of the growing season caused by raised average temperatures. A shorter time-period in the field translates into less time to settle, grow and produce dry matter. At the same time, it has long been known that crops can also be severely damaged by short and extreme heat events. Temperatures exceeding critical thresholds, especially during sensitive periods, may cause drastic drops of yield.[8] Temperatures equal to or higher than 30-34°C at the time of flowering may inhibit pollen production and grain setting giving unstable yields from year-to-year. Figure 3 shows a range of thresholds for wheat, maize and rice, including the lethal limits – in the range of 45–47°C – beyond which the plant dies. While some crop models incorporate this non-linear response to high temperatures,[9] the majority do not.

v. Percentage simulated yield change as a function of local temperature change for the three major crops and for temperate and tropical regions. Dots indicate where a known change in atmospheric CO2 was used in the study; remaining data are indicated by x. Note that differences in yield value between these symbols do not measure the CO2 fertilization effect, as changes in other factors such as precipitation may be different between studies. Non-parametric regressions (LOESS, span = 1 and degree = 1) of subsets of these data were made 500 times. These bootstrap samples are indicated by shaded bands at the 95% confidence interval. Regressions are separated according to the presence (blue) or absence (red) of simple agronomic adaptation (Table 7-2). In the case of tropical maize, the central regression for absence of adaptation is slightly higher than that with adaptation. This is due to asymmetry in the data—not all studies compare adaptated and non-adapted crops. Figure 7-8 presents a pairwise adaptation comparison. Note that four of the 1048 data points across all six panels are outside the yield change range shown. These were omitted for clarity. Some of the studies have associated temporal baselines, with center points typically between 1970 and 2005. Note that local warming in cropping regions generally exceeds global mean warming (Figure 21-4).

Figure 3: **Rice, wheat and maize** - Mean maximum temperature for leaf initiation, shoot growth, root growth and lethality.[10]



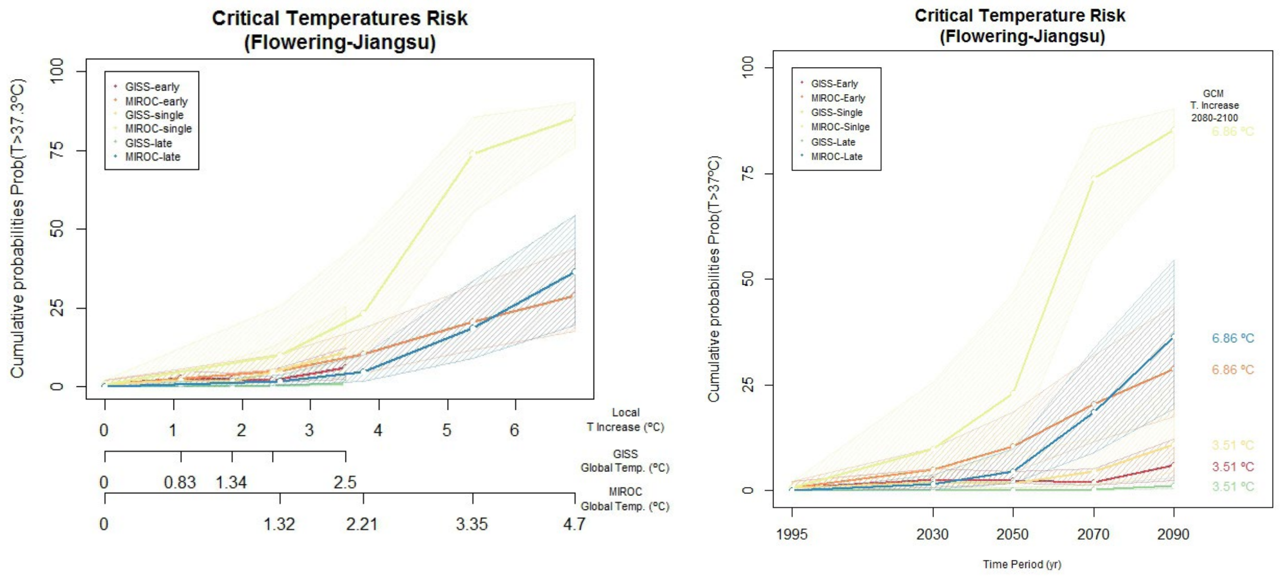
A new study undertaken for this risk assessment by Dr Manuel Montesino, Dr Mikhail Semenov and Professor Dr John R Porter investigated how the likelihood of crossing the threshold temperature for flowering could increase over time. The study looked at the highest emissions scenario (RCP8.5) to identify maximum probability boundaries for three major crops in three growing areas: wheat in the Punjab, India, rice in Jiangsu, China, and maize in Illinois, USA.[vi] The study considered several varieties and managements[vii] for each crop.

The results supported earlier findings that crop failure due to high temperature stress at flowering is an important issue to consider, especially for maize and rice. For the crop-location combinations examined, the largest risk was for rice in Jiangsu. The probability of exceeding the threshold temperature at least once for flowering during the time when the crop would be at that stage of the growth cycle increased from close to zero in the present day, to above 25% for two varieties (early and late rice) and 80% for another (single rice), for a global temperature increase of 4.7°C (local temperature increase of 7°C), reached by the high sensitivity model in 2090 (see Figure 4). This result could also be interpreted as a decrease in the return time from 1 in 100 years at present, to around 1 in 8, or 1 in 1.25 years (depending on variety) by the end of the century.

vi. The precise locations used were: Punjab (31.01ºN, 75.4ºE); Jiangsu (32.9ºN,119.16ºW); Illinois (39.7ºN,-89.5ºW), USA

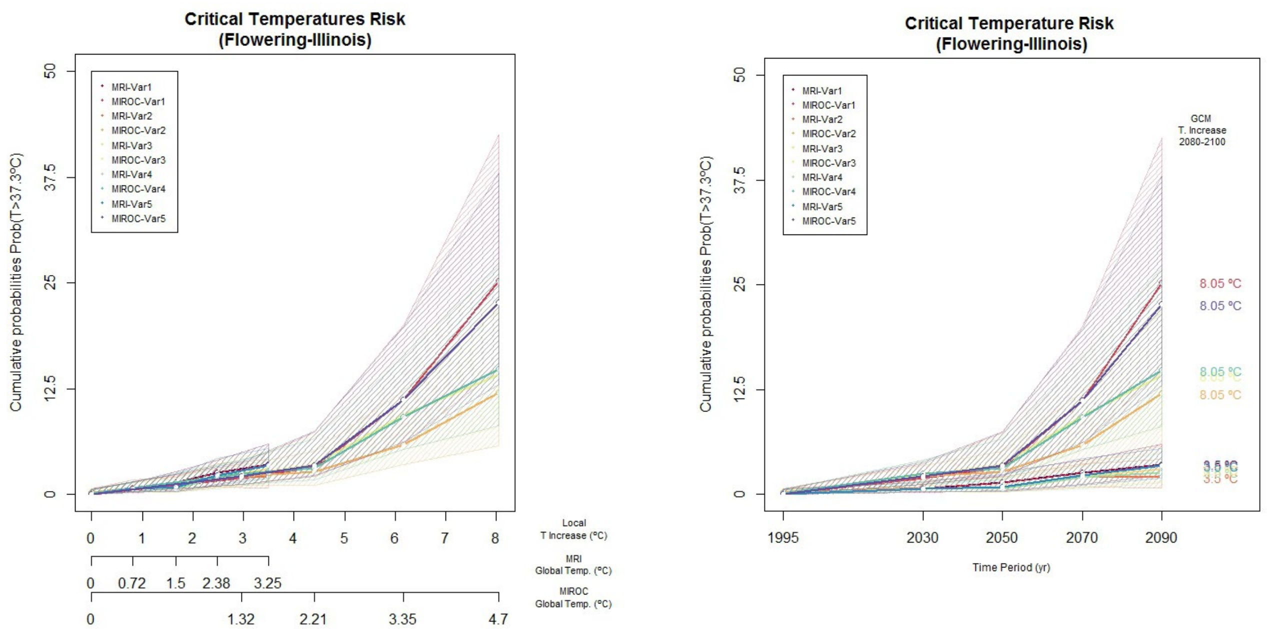
vii. 'Management' in this context refers mainly to planting and sowing dates. In some cases planting/sowing dates were assumed equal for different cultivars and for some others, when data was available, each cultivar implied a particular planting/sowing date.

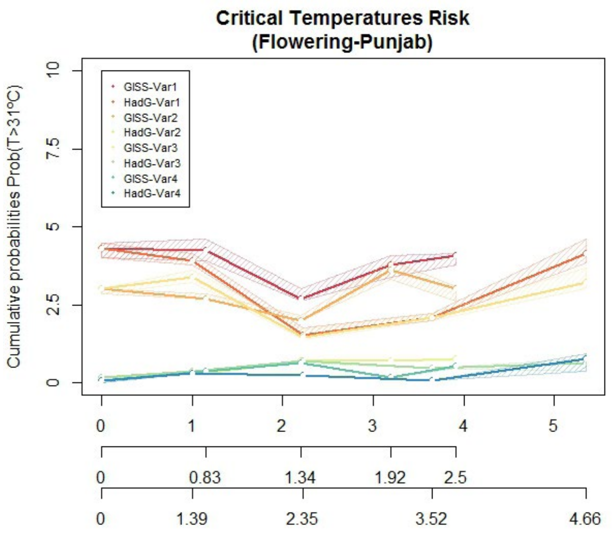
Figure 4: **Probability of exceeding threshold temperature for flowering for rice in Jiangsu, as a function of (a) temperature increase, and (b) time.** Results are shown for two climate models (GISS and MIROC) and for three varieties of rice.

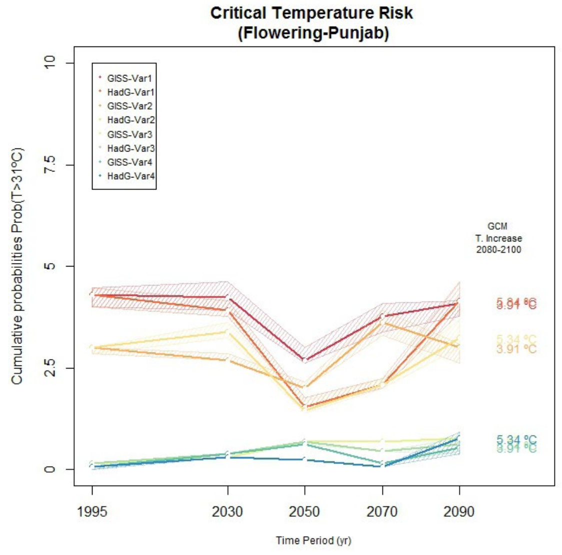


For maize in Illinois, the return time for exceeding the threshold temperature for flowering reduced from around 1 in 100 now to 1 in 50 (probability of 1-3%) for a global temperature increase of 2-3°C, and 1 in 6 (probability between 6-40%) for 4.7°C (with local temperature increase of 8°C). For wheat in the Punjab there was a less significant risk of acute effects, since it remained possible for flowering to take place early enough in the year to avoid the hottest temperatures.

Figures 5 and 6: **Probability of exceeding threshold temperature for flowering for maize in Illinois (5), and wheat in Punjab (6) as a function of (a) temperature increase, and (b) time.** Results are shown for two climate models (MRI and MIROC for maize, and GISS and HadG for wheat) and for several varieties of each crop.







A caveat of the study is that the results presented here do not compute the effect of climate change on crops. Results refer only to the probability of the temperatures exceeding thresholds. We know that temperatures above flowering thresholds will have an acute effect on yield, but we have not quantified that effect. This would require experimental and further modelling studies, but the balance of probability is that the risk to yield from short-term intense periods of high temperatures at sensitive stages of crop development can give dramatic decreases in crop yields for two of the three major global crops.

Risk to production of individual crops: what we know, what we do not know, and what we think

What we know:
Research on crop physiology over the past 30-40 years has enabled us to understand, quantify and thus to some extent predict the effects of environmental factors such as temperature, CO_2 level and water and nutrient supply on the major crops.[11] This understanding has been derived from hundreds of experiments in laboratories, growth chambers and fields.

What we do not know:
A main source of uncertainty in crop responses to climate change is how combinations of growth and development controlling factors affect yield. This is particularly the case with non-major but important crops such as millet, sorghum, and vegetables. Combinations of effects such as changes in CO_2 level, temperature, and nutrition etc. have been studied less commonly than single factors. A second major uncertainty is the effects of biotic stresses from diseases, pests and weeds. Taking these factors into account could mean the real range of uncertainty is even wider than the range of projections given by crop models.

What we think:
Most of the factors not taken into account in the models – and the projections – are likely on balance to have a negative effect. Invasive weeds are expected to spread further and become more competitive as a result of climate change; studies suggest a tendency for the risk of insect damage to plants to increase; and more frequent intense precipitation, flooding and drought would all be expected to further reduce average yields.[12]

RISK TO GLOBAL CROP PRODUCTION: RISK OF FAILING TO KEEP UP WITH DEMAND

The world already has several hundred million undernourished people, but not because there is not enough food. Food security depends not only on production, but also on the availability and affordability of food to people, on the systems of storage, transport and trade, and on patterns of consumption and nutrition. Climate change is likely to affect all the components of food security, and food security will be affected by non-climate factors too. As the IPCC stated, *"The overall impact of climate change on food security is considerably more complex and potentially greater than projected impacts on agricultural productivity alone."*[13] This more complex risk is considered in Part III of our risk assessment: Systemic Risks.

Here we focus on the narrower question of whether global crop production will be able to keep up with growing demand. Global demand for crops is projected to grow by around 60 – 100% between 2005 and 2050, due to population and economic growth.[14] The FAO estimates that meeting this demand will require crop production to grow by about 14% per decade.[15] Rapid growth in agricultural output has been achieved in the past, through combinations of better crop varieties and management, in almost equal proportion. There is scope for further growth, notably from the intensification of agriculture within developing countries mainly by improvements in infrastructure and crop management, especially fertilizer use and more effective irrigation. The question is whether such high rates of growth can be achieved, and high levels of output maintained, under any degree of climate change.

Ultimately, this must depend largely on our capability for what is known as adaptation. Understanding whether there are limits to adaptation, constraints on it, or thresholds beyond which it becomes significantly more difficult, is therefore a critical question for a risk assessment.

The main adaptive responses to reduce the risk of climate change to crop production are:

i. growing the crop at a different time of year;

ii. increasing the crop's tolerance for extreme conditions;

iii. growing the crop in a different place (migration of production zones);

iv. growing a different crop altogether.

All of these responses may be subject to some limitations or constraints. For example:

i. The timing of crop development – i.e. the window for growth - depends on day-length ('photoperiod') as well as temperature. There are limits to what can be achieved by shifting the time and place of planting, since a favourable shift with respect to temperature could correspond to an unfavourable shift with respect to photoperiod.

ii. Crops' tolerance for high temperatures may be raised either by breeding or by genetic modification, but the extent to which this is possible is ultimately subject to biophysical limits. The evidence is that there is little genetic variation either between varieties within a crop or between crops themselves in these sensitivities.[16]

iii. There is a finite supply of unused land, and not all of it is suitable for the crops we might wish to grow. For example, the potential for wheat production in Russia to be shifted northwards is limited by the poor nutritional quality of soils in that region. (Those soils also contain large amounts of carbon; their tillage could release huge amounts of CO_2 and methane into the atmosphere, further exacerbating warming).

iv. Over-reliance on a few major crops means alternatives are currently under-utilized and under-researched.

What do we know, what do we not know, and what do we think?

We know that food security, the balance between the demand for and the supply of food, is a matter of more than just crop production. It is essential to look at where in the food chain increases can be achieved, efficiencies gained and losses reduced (these issues are discussed further in Part III). At the same time, we know that crop production is vitally important.

We know that climate change poses a risk to crop production, as described above, and that there are potential constraints on our ability to adapt. We do not know enough about where and when those constraints might be encountered.

What we think may be summarized by the IPCC's headline conclusion that: *"Global temperature increases of ~4°C or more above late 20th century levels, combined with increasing food demand, would pose large risks to food security globally and regionally"*[17] and its more detailed statement that: *'The existence of critical climatic thresholds and evidence of non-linear responses of staple crop yields to temperature and rainfall thus suggest that there may be a threshold of global warming beyond which current agricultural practices can no longer support large human civilizations, and the impacts on malnourishment and under-nutrition… will become much more severe. However, current models to estimate the human health consequences of climate-impaired food yields at higher global temperatures generally incorporate neither critical thresholds nor nonlinear response functions, reflecting uncertainties about exposure-response relations, future extreme events, the scale and feasibility of adaptation, and climatic thresholds for other influences such as infestations and plant diseases. Extrapolation from current models nevertheless suggests that the global risk to food security becomes very severe under an increase of 4°C to 6°C or higher in global mean temperature (medium evidence, high agreement)."*

Endnotes

1. Porter, J.R., L. Xie, A.J. Challinor, K. Cochrane, S.M. Howden, M.M. Iqbal, D.B. Lobell, and M.I. Travasso (2014). 'Food security and food production systems', Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485-533.
2. As defined by businessdictionary.com
3. Figure SMP.7, p.18 from IPCC (2014). 'Summary for policymakers'. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.
4. Data are taken from a review of literature: Rosenzweig and Parry, 1994; Karim et al., 1996; El-Shaher et al., 1997; Kapetanaki and Rosenzweig, 1997;Lal et al., 1998; Moya et al., 1998;Winters et al., 1998; Yates and Strzepek, 1998;Alexandrov, 1999; Kaiser, 1999; Reyenga et al., 1999;Alexandrov and Hoogenboom, 2000; Southworth et al., 2000; Tubiello et al., 2000; DeJong et al., 2001; Izaurralde et al., 2001;Aggarwal and Mall, 2002;Abou-Hadid, 2006;Alexandrov et al., 2002; Corobov, 2002; Chipanshi et al., 2003; Easterling et al., 2003; Jones and Thornton, 2003;Luo et al., 2003; Matthews and Wassmann, 2003; Droogers, 2004; Howden and Jones, 2004; Butt et al., 2005; Erda et al., 2005; Ewert et al., 2005; Gbetibouo and Hassan, 2005; Izaurralde et al., 2005; Porter and Semenov, 2005; Sands and Edmonds, 2005; Thomson et al., 2005; Xiao et al., 2005; Zhang and Liu, 2005; Zhao et al., 2005;Abraha and Savage, 2006; Brassard and Singh, 2007, 2008; Krishnan et al., 2007;Lobell and Ortiz-Monasterio, 2007; Xiong et al., 2007; Tingem et al., 2008;Walker and Schulze, 2008; El Maayar et al., 2009; Schlenker and Roberts, 2009; Thornton et al., 2009a, 2010, 2011; Tingem and Rivington, 2009; Byjesh et al., 2010; Chhetri et al., 2010;Liu et al., 2010; Piao et al., 2010; Tan et al., 2010; Tao and Zhang, 2010, 2011a,b;Arndt et al., 2011; Deryng et al., 2011; Iqbal et al., 2011;Lal, 2011;Li et al., 2011; Rowhanji et al., 2011; Shuang-He et al., 2011; Osborne et al., 2013.
5. Figure 7-4, p. 498 from Porter et al (2014).
6. See Box 7-1, pp. 509-512 in IPCC (2014). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.

7. World Bank (2012). Turn down the heat : why a 4°C warmer world must be avoided. Washington DC : World Bank. p46. http://documents.worldbank.org/curated/en/2012/11/17097815/turn-down-heat-4°c-warmer-world-must-avoided
8. Negative impacts of high temperature stress at the time of flowering on the yield of grain crops have been documented in plant experiments with wheat (FERRIS, RACHEL, et al. "Effect of high temperature stress at anthesis on grain yield and biomass of field-grown crops of wheat." Annals of Botany 82.5 (1998): 631-639); rice (Jagadish, S. V. K., P. Q. Craufurd, and T. R. Wheeler. "High temperature stress and spikelet fertility in rice (Oryza sativa L.)." Journal of experimental botany 58.7 (2007): 1627-1635) and peanut (Prasad, Pagadala V. Vara, et al. "Effects of short episodes of heat stress on flower production and fruit- set of groundnut (Arachis hypogaea L.)." Journal of Experimental Botany 51.345 (2000): 777-784).
9. Challinor, A. J., et al. "Simulation of the impact of high temperature stress on annual crop yields." Agricultural and Forest Meteorology 135.1 (2005): 180-189
10. Sanchez, B., Rasmussen, A. and Porter, J. (2014) 'Temperatures and the growth and development of maize and rice: a review'. Global Change Biology 20, 408–417, doi: 10.1111/gcb.12389
11. Hay, R.K.M. and Porter, J. R. (2006). The Physiology of Crop Yield. Blackwells Scientific Publications).
12. Porter et al (2014).
13. Porter et al (2014), p502
14. World Bank (2012), p44
15. Porter et al (2014), p506
16. See Sanchez et al (2014) and Porter JR and Gawith M (1999). 'Temperatures and the growth and development of wheat: a review.' European Journal of Agronomy, 10, 23–36.
17. IPCC (2014). 'Summary for Policymakers'.

12 THE RISK OF WATER STRESS

Professor Nigel Arnell, Director of the Walker Institute for Climate System Research.

Water resources are under stress in many regions due to increasing demands and, in places, falling quality. Climate change has the potential to change the risks of water stress.[1] The focus in this section is on strategic definitions of water stress, which are based on generalized indicators of the amount of water that is available and the demands on that resource. Operational definitions, on the other hand, are typically based on the reliability of the supply of appropriate quality water and are strongly determined by local conditions.

What do we want to avoid?

The most widely used sets of indicators of high-level water resources stress are based on the ratio of total resources to population ('resources per capita') and the proportion of resources that are withdrawn for human use.[2] The first is simpler but does not reflect stresses introduced by high per-capita water use, for example where there is significant irrigation for agriculture; on the other hand, data on current and future water withdrawals can be highly uncertain.

There are three widely used thresholds for defining levels of water stress on the basis of per capita availability. Basins or countries with average annual resources between 1000 and 1700 m^3 per capita per year are typically classed as having 'moderate water shortage', and if resources are below 1000 m^3 per capita per year then the region is classed as having 'chronic water shortage'. If resources are below 500 m^3 per capita per year then the shortage is 'extreme'.[3] The thresholds are essentially arbitrary, although derive ultimately from an assessment of exposure to water resources stress in Africa.[4]

In 2010, almost 3.6 billion people, out of a global population of around 6.9 billion, were living in watersheds with less than 1700 m^3 per capita per year (Table W1), and almost 2.4 billion were living in watersheds with less than 1000 m^3 per capita per year (chronic water shortage).[i] Approximately 800 million people were living in watersheds with less than 500 m^3 per capita per year (extreme water shortage).

i. The methods used here to estimate future risks to water resources are summarised in the Annex.

Table W1: **Numbers of people (millions) living in water-stressed watersheds.** The figures for 2050 are based on a medium population growth assumption, and the ranges represent the effects of low and high growth assumptions.

	2010				2050			
	<1700m3/capita/year	<1000m3/capita/year	<500m3/capita/year	Population	<1700m3/capita/year	<1000m3/capita/year	<500m3/capita/year	Population
N. Africa	162	150	94	209	254 (226-326)	244 (213-282)	216 (153-248)	329 (292-383)
W. Africa	54	17	4	309	484 (373-610)	367 (185-489)	37 (20-117)	756 (616-926)
C. Africa	3	0	0	110	11 (10-14)	8 (6-9)	6 (0-8)	239 (202-277)
E. Africa	94	10	2	193	326 (272-441)	299 (159-381)	103 (13-221)	418 (349-496)
Sn Africa	47	20	0	210	186 (133-282)	101 (45-177)	24 (4-35)	488 (396-609)
S. Asia	1,394	1,172	199	1,706	2121 (1,906-2,526)	1,802 (1,512-2,183)	746 (628-1,003)	2,390 (2,151-2,722)
SE Asia	7	0	0	605	27 (25-31)	0 (0-0)	0 (0-0)	791 (728-889)
E Asia	1,202	691	386	1,546	1084 (1,035-1,184)	643 (613-660)	359 (340-388)	1,434 (1,375-1,510)
Central Asia	1	0	0	46	65 (57-80)	2 (1-2)	0 (0-0)	70 (62-84)
Middle East	166	93	71	214	356 (295-397)	310 (222-344)	190 (164-209)	379 (339-420)
Australasia	0	0	0	35	0 (0-0)	0 (0-0)	0 (0-0)	50 (50-45)
W. Europe	220	123	20	411	220 (239-165)	138 (166-55)	23 (24-15)	425 (441-344)
C. Europe	51	8	0	118	23 (24-20)	1 (8-1)	0 (0-0)	102 (103-96)
E. Europe	20	4	3	221	9 (8-18)	4 (3-4)	4 (3-4)	186 (178-196)
Canada	6	6	0	35	7 (8-5)	7 (8-5)	7 (8-0)	44 (45-31)
US	78	54	27	312	99 (102-75)	74 (76-56)	38 (39-26)	390 (402-303)
Meso-America	58	26	0	197	124 (112-154)	61 (53-101)	31 (28-37)	279 (250-346)
Brasil	0	0	0	195	0 (0-0)	0 (0-0)	0 (0-0)	237 (218-269)
South America	15	4	4	198	46 (29-56)	19 (17-25)	6 (5-7)	278 (251-329)
Global	3,576	2,376	809	6,868	5449 (4,853-6,382)	4,079 (3,286-4,774)	1,789 (1,430-2,317)	9,283 (8,444-10,273)

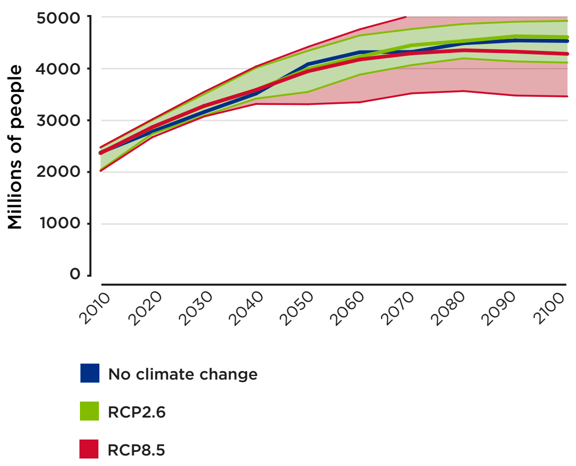
How will exposure to water stress change in the future?

Through the 21st century, changes in total population will result in changes in exposure to water resources stress. By 2050, under a medium population growth assumption,[5] the number of people living in watersheds with less than 1000 m^3 per capita per year will increase to around four billion – a bigger proportion of the global population than in 2010. The effects of population growth on the number of people living in watersheds with less than 500 m^3 per capita per year are even more pronounced: it will double by 2050 to around 1.8 billion people. The magnitudes of the changes are influenced to a certain extent by the assumed changes in population (as shown in Table W1[6]), but even under low-growth assumptions there are significant increases in exposure to water scarcity at global and regional scales.

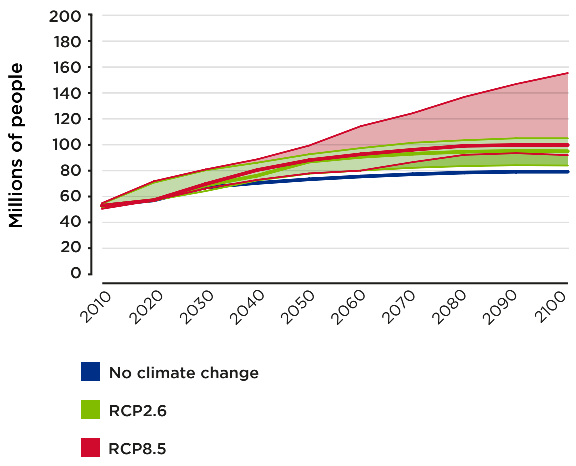
Climate change will also affect the number of people living in water-stressed conditions. Figure W1 shows the change in numbers of people living in watersheds with chronic water shortage (less than 1000 m^3 per capita per year) through the 21st century, for the globe as a whole and for five regions, under no climate change and under two different climate change pathways (RCP2.6 and RCP8.5, low and high greenhouse gas emission scenarios respectively). The shaded areas show the range of potential numbers due to uncertainty in the pattern of resource change due to climate change. The plots all assume the medium population growth projection.

Figure W1: **The number of people living in water-stressed watersheds (<1000m³/capita/year), with and without climate change.** The plots show two climate pathways (RCP2.6 and RCP8.5). The solid line represents the median estimate of impact for each pathway, and the shaded areas show the 10% to 90% range. A medium growth population projection is assumed.

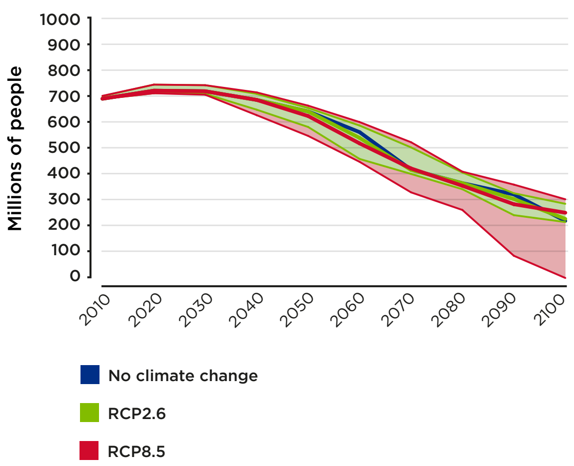
Global: water stressed population



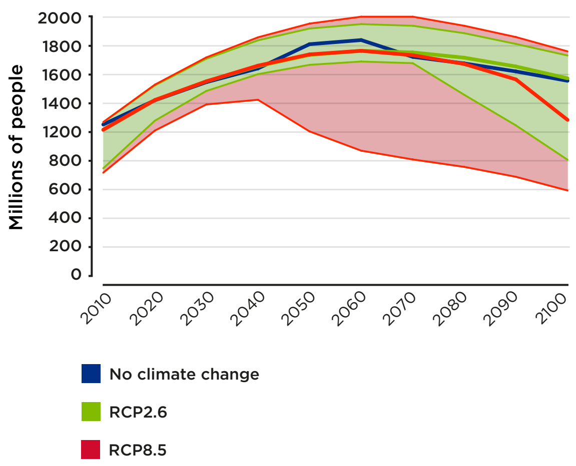
US: water stressed population



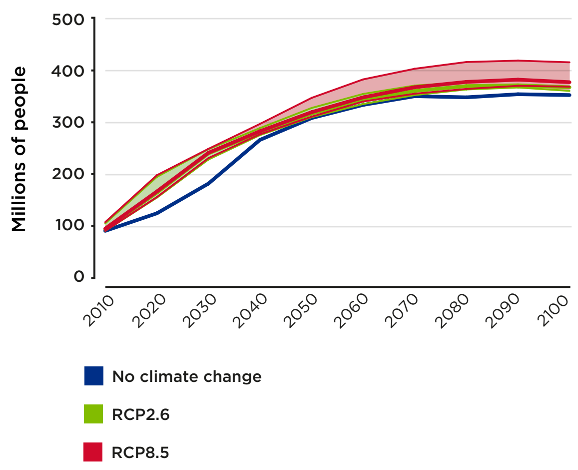
East Asia: water stressed population



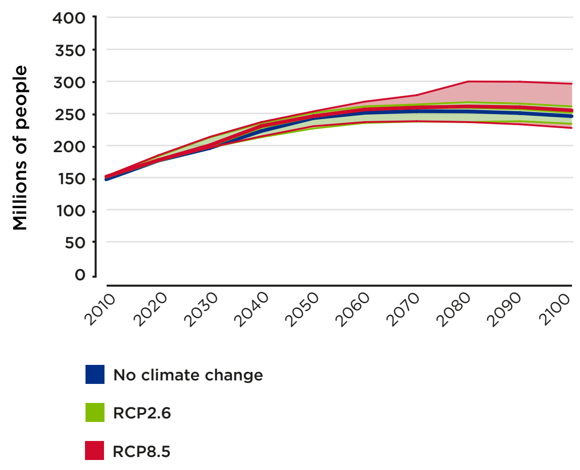
South Asia: water stressed population



Middle East: water stressed population



North Africa: water stressed population



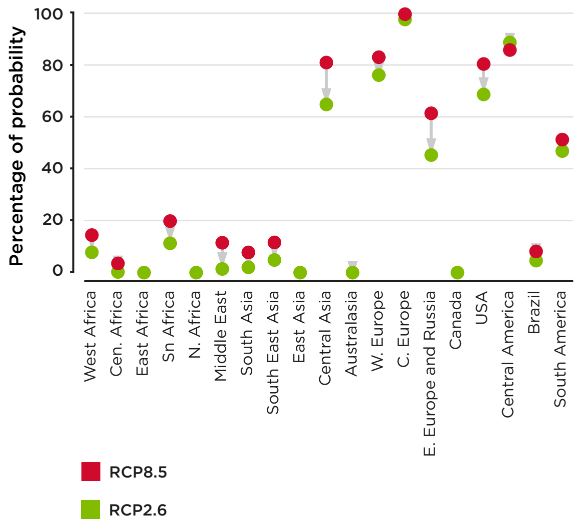
In the absence of future climate change, the numbers of people living in watersheds with chronic water shortage decreases in East Asia from 2030, and in South Asia from 2060. If climate change is included, it results in more rainfall and river runoff in East Asia. This combines with the reduction in population to reduce apparent water shortage – but there is a chance (shown by the shaded area) that climate change would slow the reduction in exposure to water shortage. Similarly, Figure W1 shows that climate change could substantially increase the number of people living in watersheds with chronic water shortage in south Asia – or reduce them. In the US and the Middle East climate change is very likely to increase exposure throughout the century, and in North Africa is more likely than not to produce an increase in exposure.

Calculating risk

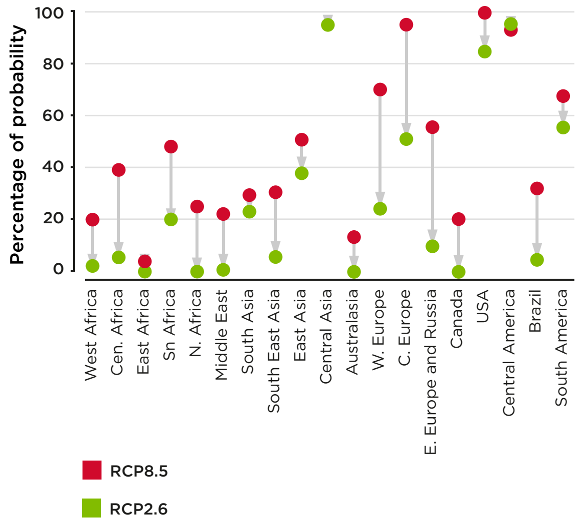
Figure W2 shows the risk by region that climate change increases by more than 10% the numbers of people living in watersheds with chronic water shortage under the two climate pathways. By 2050, the largest of these probabilities are in central Asia, Europe, the USA, Central America and southern America. By 2100, the probabilities that exposure to shortage will increase are considerably greater in most regions than in 2050. Under the low emissions climate pathway the probabilities are smaller in most regions than under the high emissions pathway, particularly by 2100.

Figure W2: **The risk that climate change increases by more than 10% the numbers of people living in water-stressed watersheds, relative to the situation with no climate change, under the two climate pathways**. A medium growth population projection is assumed.

2050: Probability number of people with chronic water shortage increasing by more than 10%



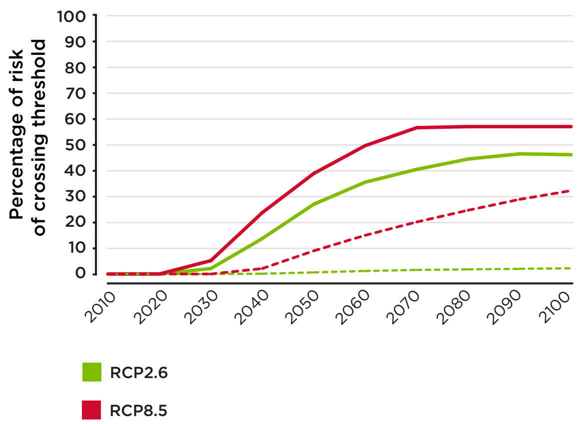
2100: Probability number of people with chronic water shortage increasing by more than 10%



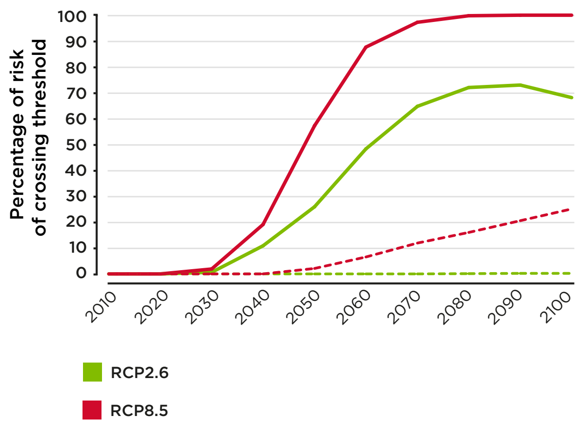
The risks posed by climate change to water scarcity can also be assessed at the basin scale. Figure W3 shows the probability that resources per capita falls below defined thresholds in nine major basins that are, or likely will be, exposed to water resources stresses (note that the thresholds vary between basins). The dotted lines show probability of falling below the thresholds under the two climate pathways assuming population remains at 2010 levels, and the solid lines show probability under the medium growth population projection. The difference between the solid and dotted lines represents the effect of population change on probability (and of course this difference varies with population projection).

Figure W3: **Risk of resources per capita falling below specified thresholds for nine illustrative watersheds under two climate pathways (note that the thresholds vary between watersheds).** The dotted line shows risk with current (2010) population, and the solid line shows risk under the medium population growth projection

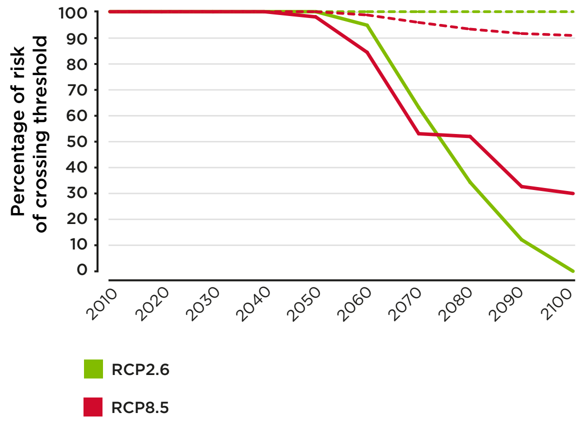
Sacramento: risk of falling below 1700m³/capita/year



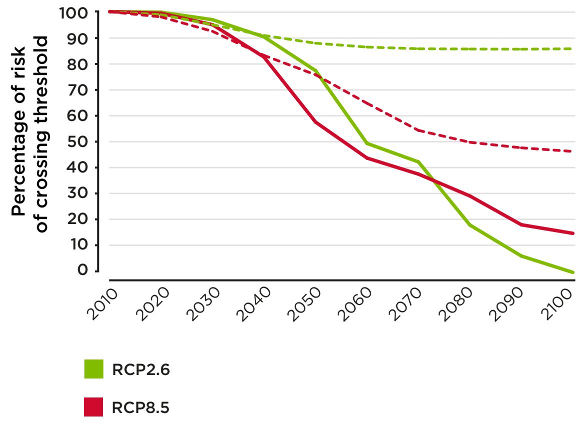
Rio Grande: risk of falling below 1000m³/capita/year



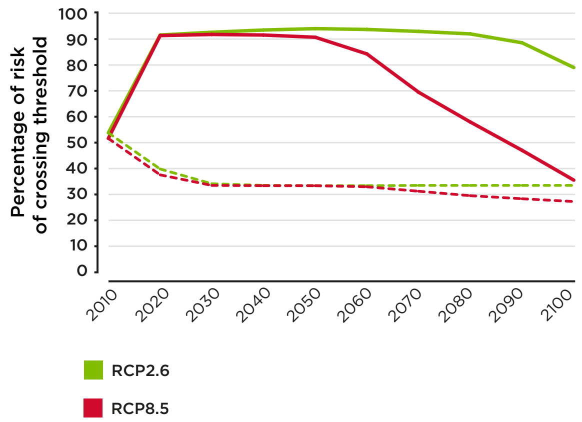
Yangtse: risk of falling below 1700m³/capita/year



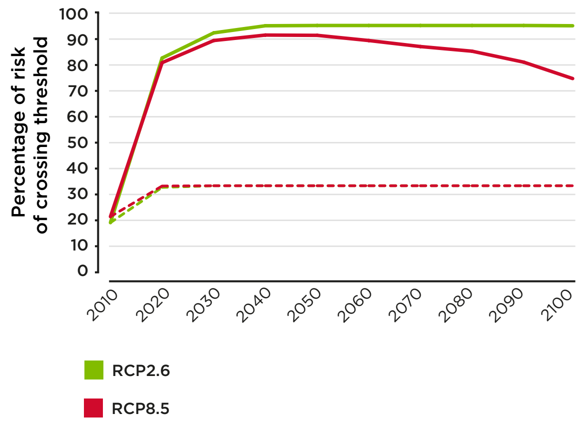
Huang He: risk of falling below 500m³/capita/year



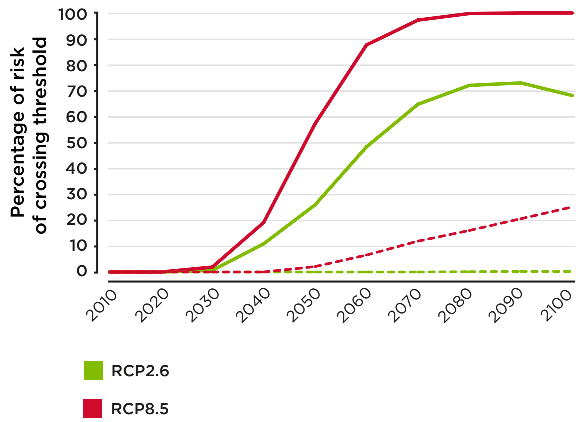
Ganges: risk of falling below 1700m³/capita/year



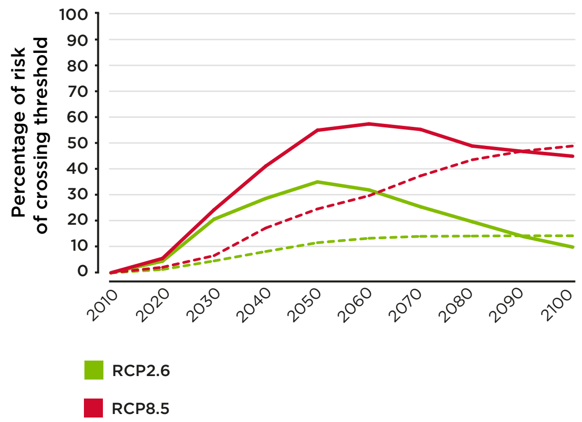
Indus: risk of falling below 500m³/capita/year



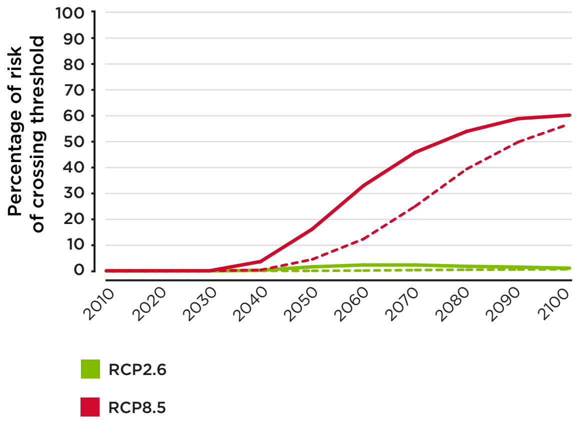
Tigris-Euphrates: risk of falling below 500m³/capita/year



Karun: risk of falling below 1000m³/capita/year



Moulouya: risk of falling below 500m3/capita/year

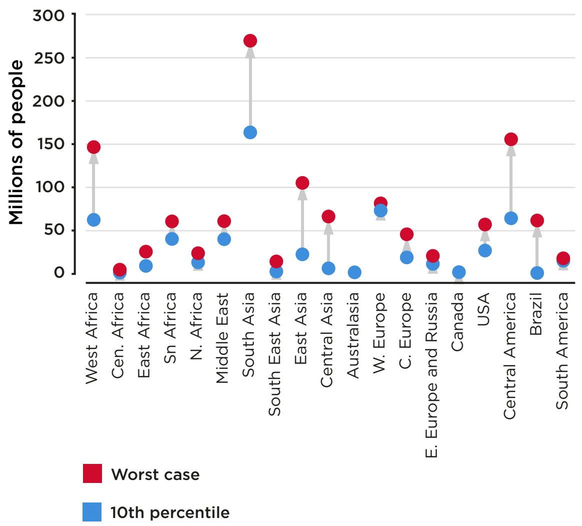


What is a plausible worst case for water stress due to climate change?

There are considerable uncertainties in the projected impacts of climate change on water stress, even assuming a single projection for changes in population. The chance of impacts exceeding some defined threshold – as shown in the previous section – represents one aspect of this uncertainty, but another assessment of risk can be based on a plausible 'worst case'.

By 2050, up to 620 million people may be added to the 4 billion people (Table W1) living in watersheds with chronic water shortage, under high emissions and the most extreme climate scenario. Figure W4 shows the 'worst case' by region in 2050, along with the 10th percentile from the distribution of impacts (the upper part of the shaded region in Figure W1). In some regions the worst case is little different to the 10th percentile, but in others is considerably larger reflecting greater uncertainty in projected impacts. However, the worst cases shown in Figure W4 do not occur simultaneously: the global 'worst case' is not equal to the sum of the regional worst cases. Under no one plausible pattern of climate change does every water-stressed region see the maximum reduction in runoff.

Figure W4: **Plausible 'worst case' impacts of climate change in 2050 on water stress.** The graph shows the increase in numbers of people living under chronic water shortage under the RCP8.5 climate pathway and the medium growth population projection. There is a 10% probability that the impact is greater than that shown by the blue dots, and the red dots show the maximum calculated impact



The assessment in Figure W4 is based on the assumption that all the climate models used to estimate impacts are equally plausible, and that they span the range of potential regional climate change impacts. This, of course, is not necessarily the case. The global-scale impacts are largely dominated by impacts in south and, to a lesser extent, east Asia, and are therefore very sensitive to projections of how the south Asian monsoon may change (see box on Variation in the Indian monsoon).

Variation in the Indian monsoon

Professor Brian Hoskins, FRS

In impact studies, it is assumed that the set of available projections of future climate from the state-of-the-art climate models spans the space of possible climates. In particular, in determining the risk posed by increasing greenhouse gases it is assumed that the worst case scenarios in any region are included amongst the model projections. However, climate models developed and tested in the context of the climate of the 20th century have known deficiencies, some of which are common to most models. Some of these deficiencies are likely to influence the simulation of future extreme climate changes. Further, it is not clear that the climate models are able to simulate any major climate change due to the crossing of a threshold in the climate system that could occur. This could, for example, be of the nature of the onset of significant greenhouse gas emissions from melting permafrost, the destabilization of the West Antarctic Ice Sheet or a drastic reduction in the overturning circulation in the Atlantic Ocean. Palaeo-climate runs with the models show that they are unable to simulate just how different the monsoon systems of the world have been in the past. For example the Sahara was green with vegetation some seven thousand years ago. However, climate models do not produce this big change in rainfall. One recent study concluded, *"State-of-the-art climate models are largely untested against actual occurrences of abrupt change. It is a huge leap of faith to assume that simulations of the coming century with these models will provide reliable warning of sudden, catastrophic events."*[7]

The amazing thing about the Indian summer monsoon is the large effect of a small variation from one year to year: 10% more rainfall and there are floods, 10% less and there are huge problems for farmers. In any year monsoon active and break periods occur. Breaks that last more than a couple of weeks also cause major agricultural problems. Climate models are in general projecting a slight strengthening of monsoon rainfall, but it should be recognized that the changes in particular monsoons, such as that in India, could be much more significant than this suggests. Given the large perturbation of the climate system due to greenhouse gas emissions, we should be prepared that the future Indian Monsoon could have average rainfall outside the current normal range, and the variability between one year and another and in the active-break cycle could be very different.

What do we know, what do we not know, and what do we think?

Our estimates of future risks are based on (i) projections of regional future climate change, (ii) projections of hydrological consequences of climate change and (iii) projections of future population and exposure to water resources stress. What happens in practice also depends on future adaptation.

Projections of regional future change depend partly on the assumed rate of growth in emissions and partly on the projected patterns of changes in regional and seasonal climate – particularly precipitation. Whilst the broad patterns of precipitation changes are reasonably consistent between models, the details and the precise magnitudes of change differ. The quantitative estimates of impacts on water stress therefore vary, and these tend to be larger than the apparent differences in precipitation change between climate models. This is because exposure to water shortage is concentrated in particular regions of the globe, and it is at the local to regional scale that the differences between climate models are greatest.

As climate models improve their representation of atmospheric dynamics and the distribution of precipitation then the precise quantitative estimates of impacts on water stress will change, but for years to come differences between models will remain and there will therefore be a distribution of potential climate change impacts for any one place.

The impacts of climate change on water shortage are assessed by using a hydrological model to translate climatic changes to changes in runoff. As with climate models, different hydrological models can give different responses to the same input data. Comparisons of the effects of hydrological model uncertainty are still in their infancy,[8] but early indications are that adding impact model uncertainty adds to the range of potential impacts. Moreover, it is likely that hydrological models have similar biases (they all tend to overestimate river flows in dry regions, for example) and none yet explicitly incorporate the effects of changes in glacier volumes which may affect future resources in some regions.

Projections of future population are also uncertain (as shown in Table W1), because they are based on different assumptions about changes in fertility rates, mortality rates and migration. It is not possible to assign likelihoods to different population projections, so it is necessary to estimate risks separately under different plausible population narratives and projections.

Finally, the actual effects of climate change on 'real' water shortages will depend on the management infrastructure and institutions which are put in place to cope with water shortage. There is already a very considerable difference between developed and developing countries. Some management interventions will offset the effects of climate change, but others may not. The effects of future adaptation on the 'real' consequences of future water shortages will therefore depend on (i) the extent to which adaptation takes place (limited by a number of factors including finance and institutional capacity, alongside potential physical constraints such as the availability of feasible locations for storage reservoirs) and (ii) how effective the adaptation measures are in practice.

Lessons from risk assessment

The key conclusions from this section are therefore:

- Climate change alters substantially the future risk of exposure to water shortages, but the effects are strongly exaggerated or reduced by changes in population. Put the other way, the pressures on water resources posed by increasing populations are substantially altered – exaggerated or reduced – by climate change.

- Climate change reduces the probability of exposure to water shortages in some regions – particularly in parts of east and south Asia - but this may be associated with substantial changes in flood risk (see chapter 14).

- The risks posed by climate change are typically less under low emissions than high emissions, but the difference varies from place to place depending on how close watersheds in a region are to the water shortage threshold. In some cases, risks are less under high emissions than low emissions, because larger increases in runoff are enough to push watersheds out of the water shortage category.

Production of this chapter was supported by the AVOID 2 programme (DECC) under contract reference 1104872.

Endnotes

1. Jimenez-Cisneros, B.E., Oki, T., Arnell, N.W., Benito, G., Cogley, J.G., Doll, P., Jiang, T. & Mwakalila, S.S. (2014) 'Freshwater resources. In Field', C.B., Barros, V. et al. (eds) Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge. 229-269.
2. Falkenmark, M., Berntell, A., Jagerskog, A., Lundqvist, J., Matz, M. & Tropp, H. (2007) On the verge of a new water scarcity: a call for good governance and human ingenuity. SIWI Policy Brief. Stockholm International Water Institute. Rijsberman, F. (2006) Water scarcity: fact or fiction? Agricultural Water Management 80 (1-3) 5-22.
3. Falkenmark, M., Berntell, A., Jagerskog, A., Lundqvist, J., Matz, M. & Tropp, H. (2007) On the verge of a new water scarcity: a call for good governance and human ingenuity. SIWI Policy Brief. Stockholm International Water Institute. Kummu, M., Ward, P.J., de Moel, H & Varis, O. (2010) Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. Environ. Res. Lett. 5 (July-September 2010) 034006 doi:10.1088/1748-9326/5/3/034006
4. Falkenmark, M. (1989) 'The massive water scarcity now threatening Africa: why isn't it being addressed?' Ambio 18 (2) 112-118
5. Shared Socio-economic Pathway (SSP) 2. https://secure.iiasa.ac.at/web-apps/ene/SspDb/. This is similar to the UN 2012 medium population projections.
6. SSP1 and SSP3 are used to represent the extremes: these are very similar to the UN 2012 low and high population projections.
7. Valdes, P. (2011). 'Built for stability'. Nature Geoscience 4, 414-416. doi:10.1038/ngeo1200
8. Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N.W., Clark, D.B., Dankers, R., Eisner, S., Fekete, B., Colon-Gonzalez, F.J., Gosling, S.N., Kim, H., Liu, X., Masaki, Y., Portmann, F.T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., Warszawski, L. & Kabat, P. (2014) Multi-model assessment of water scarcity under climate change. Proceedings of the National Academy of Sciences 111, 3245-3250 doi.10.1073/pnas.1222460110

13 THE RISK OF DROUGHT

Professor Nigel Arnell, Director of the Walker Institute for Climate System Research

What do we want to avoid?

Drought is a major challenge to people, agriculture and economies across the world. Broadly speaking, there are four types of 'drought'.

- **A meteorological drought** – a lack of precipitation
- **An agricultural drought** – a lack of water in the soil
- **A hydrological drought** – a deficit in river flows and groundwater levels
- **A water resources drought** – a deficit in the amount of water available for distribution to consumers (such as irrigators).

One type of drought does not necessarily map directly onto another. Droughts – of whatever type – also vary in their duration, intensity (amount of deficit) and spatial extent. It is therefore much more difficult to characterize both the 'impact' and the 'risk' of drought than the impact and risk of flooding. There are also many different indicators of drought, tailored to different characterizations of drought.

This section focuses on meteorological drought, and characterises drought on the basis of an indicator of accumulated deficits of precipitation. More particularly, it looks at the average proportion of cropland at any given time experiencing 'extreme' drought. We have defined 'extreme drought' for this purpose as being the level of precipitation deficit that occurs approximately 2% of the time in the current climate.[i] It is important to note that this measure does not take into account the effect of raised temperatures, which, by increasing rates of evaporation, will further increase the risk.

How does the likelihood of drought change over time?

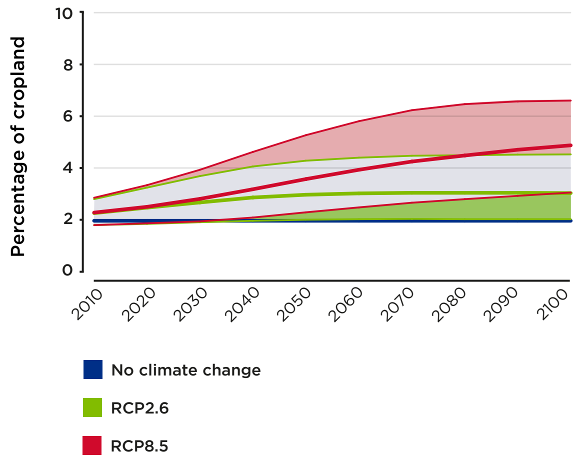
Figure D1 shows the proportion of cropland[ii] affected by drought under high (red) and low (green) emissions pathways, for the globe as a whole and for four major regions, as a function of time. This is equivalent to the probability that a given part of that cropland is in drought, in any given year.

For the high emissions pathway, the proportion of cropland exposed to drought increases by around 75% by 2050 and more than doubles by the end of the century, under the median estimate. On this pathway, the incidence of drought roughly triples in Southern Africa, and increases by about 50% in the US and South Asia, over the course of the century. For the low emissions pathway, the increases are much less. At the same time, what is very clear is that there is there is considerable uncertainty in the projections. The uncertainty ranges suggest that while in the best case, drought incidence could halve in some regions, in the worst case, it could increase by a factor of three or four.

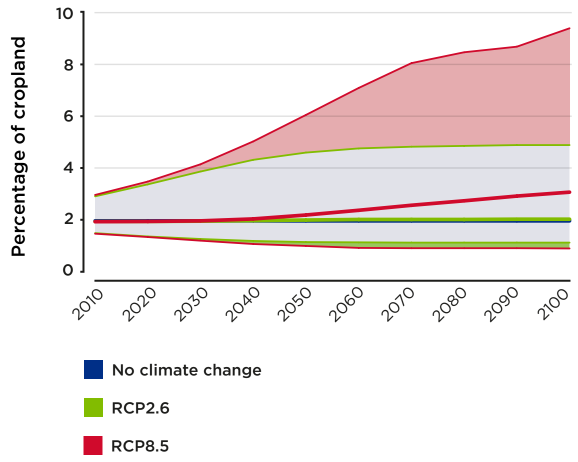
1. See Annex'
2. (assuming no change in total cropland area)

Figure D1: **The proportion of regional cropland affected by drought with and without climate change.** The plots show two climate pathways (RCP2.6 and RCP8.5). The solid line represents the median estimate of impact for each pathway, and the shaded areas show the 10% to 90% range.

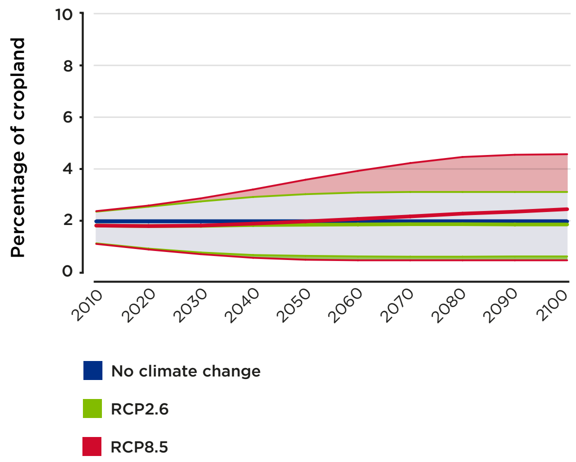
Global: drought affected cropland



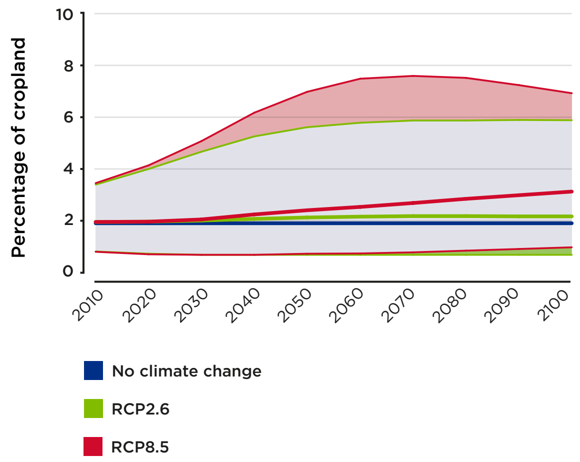
US: drought affected cropland



East Asia: drought affected cropland



South Asia: drought affected cropland



Southern Africa: drought affected cropland

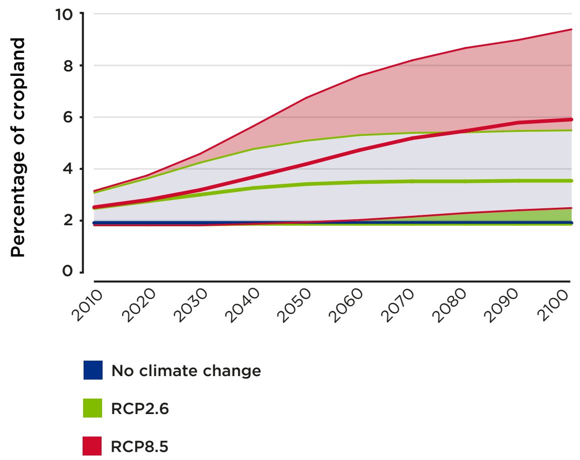
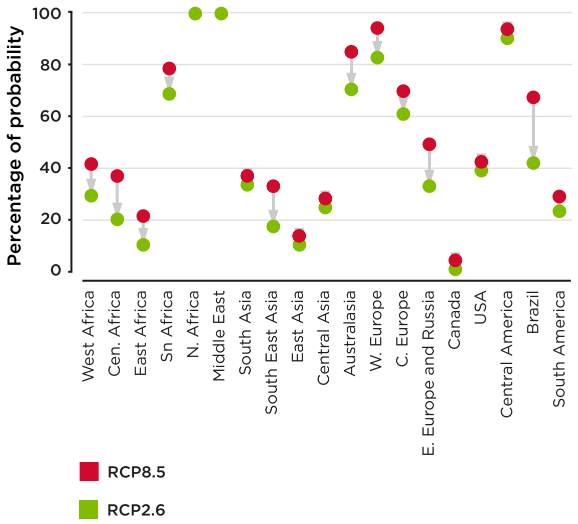
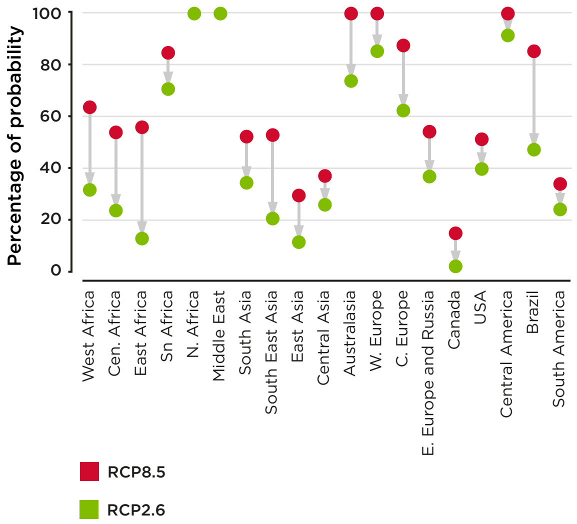


Figure D2: **The risk that climate change increases by more than 50% the average annual area of cropland affected by 'drought', relative to the situation with no climate change, under the two climate pathways.**

2050: probability of cropland area affected by drought increasing by >50%



2100: probability of cropland area affected by drought increasing by >50%



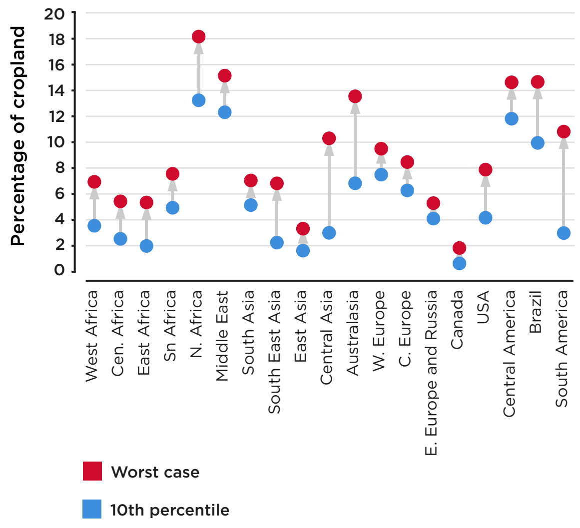
This uncertainty is illustrated in Figure D2, which shows the risk that climate change increases the average annual area of cropland in a region affected by drought by more than 50% in 2050 and 2100. By 2050, the probability is greater than 70% - under high emissions – in southern and northern Africa, the Middle East, Australasia, western Europe and central America. In contrast, there is a relatively low probability that climate change would increase drought extent in East Asia and Canada. Lower emissions reduce the risk, particularly by 2100.

What is a plausible worst case for changes in drought due to climate change?

At the global scale, there is a 10% probability that by 2050 the incidence of drought would have increased by 150%, and the plausible worst case would be an increase of 300% by the latter half of the century. The proportion of cropland affected by drought under the plausible worst case scenario more than doubles in every region (Figure D3) and in all except Canada and East Asia increases by a factor of at least three. The global worst case is not equivalent to the sum of the regional worst cases, because no one plausible climate scenario produces the biggest impact everywhere.

Figure D3 is based on the assumption that all the climate models used to estimate impacts are equally plausible and that they span the range of potential regional climate changes. This is not necessarily the case, so the numbers are to be regarded as indicative.

Figure D3: **Plausible 'worst case' impacts of climate change in 2050 on exposure to drought.** The graph shows the additional annual proportion of cropland affected by drought under the RCP8.5 climate pathway, relative to the proportion affected with no climate change. There is a 10% probability that the impact is greater than that shown by the blue dots, and the red dots show the maximum calculated impact. The average annual proportion of cropland affected by drought in the absence of climate change is just under 2%.



What do we know, what do we not know, and what do we think?

Estimates of how drought risk will change in the future are based on (i) projections of future regional climate change, (ii) projections of how these translate into changes in drought characteristics, and (iii) projections of future exposed land and people. There are uncertainties in all of these.

Projections of future regional climate change depend partly on the assumed rate of growth in emissions, and partly on projected changes in regional and seasonal precipitation. Climate model simulations typically show that whilst global precipitation goes up with climate change, there is strong variability across space. In general, wet regions get wetter, but dry regions get drier. However, the magnitude of the change in a region is uncertain, as are the boundaries of regions which see increases or decreases in rainfall. Temperature increases across all land areas with climate change, and this will exaggerate the effect of rainfall deficits by increasing evaporation.

The way in which changes in climate translate into changes in drought depends on local conditions. Most agricultural systems are tuned to local climatic conditions, so it is departures from those conditions that prove challenging. That is why our drought indicator is defined in relation to average local conditions, rather than being defined in absolute terms. However, different measures of drought are also possible to define, and these would give different indications of both current exposure and future risk.

Finally, the estimated future impacts on agriculture and society depend on changes in exposure to droughts and vulnerability to their effects. This will depend not only on population change, economic growth and the extent of croplands, but also on the degree to which drought mitigation measures (such as forecasting and warning, provision of supplementary water supplies or market interventions) are developed.

Production of this chapter was supported by the AVOID 2 programme (DECC) under contract reference 1104872.

14 THE RISK OF RIVER FLOODING

Professor Nigel Arnell, Director of the Walker Institute for Climate System Research

What do we want to avoid?

River flooding is the most serious and widespread weather hazard affecting the world. According to the Munich Re natural hazards catalogue, between 1980 and 2014 river floods accounted for 41% of all loss events, 27% of fatalities and 32% of losses.[1] By changing the timing and amount of precipitation, climate change has the potential to substantially alter flood regimes and therefore future flood losses.

River floods are generated through intense or prolonged rainfall or through snowmelt. There are three main scales of river flooding:

- Flash floods occur when the volume of water produced by intense heavy rainfall generates significant overland flow, and are typically localized and small-scale.
- Floods along major rivers with extensive floodplains typically occur following prolonged periods of heavy rainfall or snowmelt, and flood waters may persist for weeks.
- Between these two extremes are floods that are locally generated by rainfall and snowmelt within a catchment area.

The relative contribution of these three broad scales of flooding to the overall flood threat varies from country to country. At the global scale, there is little information on the numbers of people exposed to flash flooding, because the hazard is highly localised. Most information at the global scale therefore relates to flooding along major rivers and floodplains with catchments of several thousand square kilometres.

For the purposes of this assessment we shall take as our threshold floods of the magnitude of current 1 in 30 year flood events. In 2010 just over 700 million people were living in major floodplains[2] and – on average – over 20 million of these were affected by floods with a return period of greater than once every 30 years.[i] Almost half of these people live in South Asia. Some of the flood-prone populations are protected by flood defences so do not actually see their properties flooded, although they are likely to be indirectly affected through impacts on their communities and infrastructure.[3]

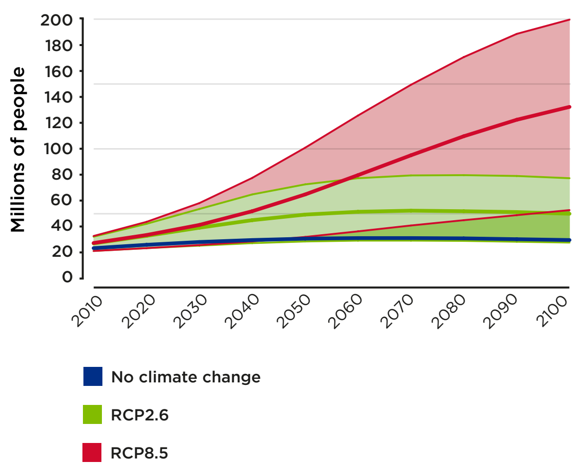
How could the impact of flooding change over time?

Population change alone will increase the numbers of people affected by flooding in the future. Climate change could increase the number further, in some regions. Figure F1 shows the numbers of people affected by floods greater than the current '30-year flood' globally and for four major world regions, for high (red) and low (green) emissions pathways, as a function of time.

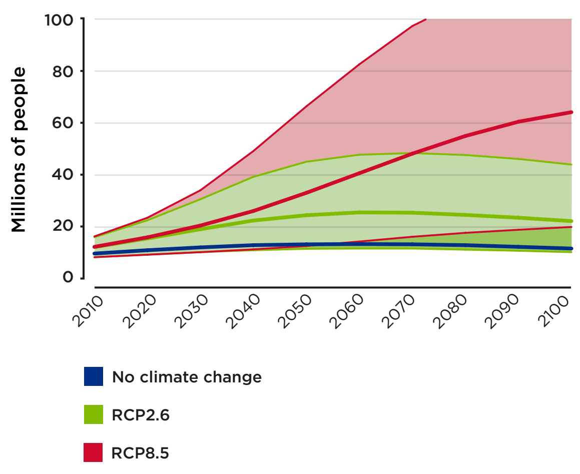
i. The methods used here are summarised in the annex

Figure F1: **The average annual number of people affected by river flooding with and without climate change.** The plots show two climate pathways (RCP2.6 and RCP8.5). The solid line represents the median estimate of impact for each pathway, and the shaded areas show the 10% to 90% range. A medium growth population projection is assumed.

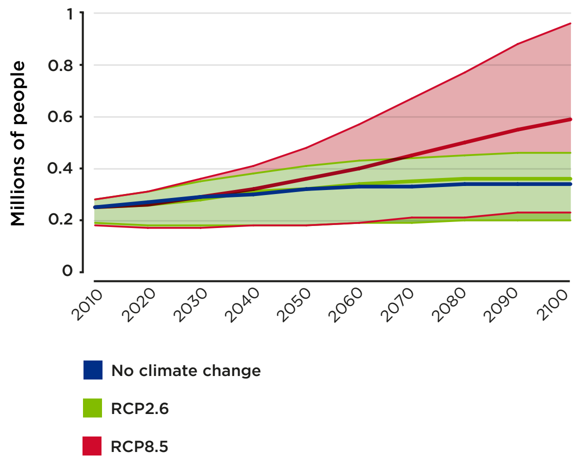
Global: flooded population



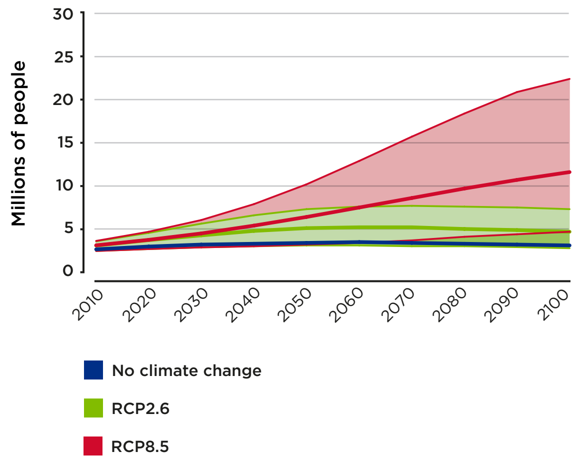
South Asia: flooded population



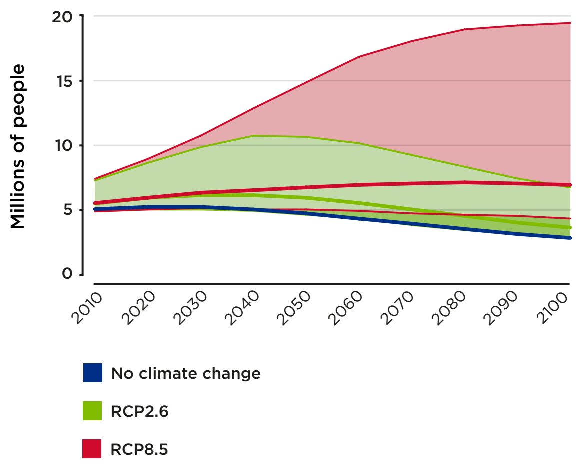
US: flooded population



South East Asia: flooded population



East Asia: flooded population

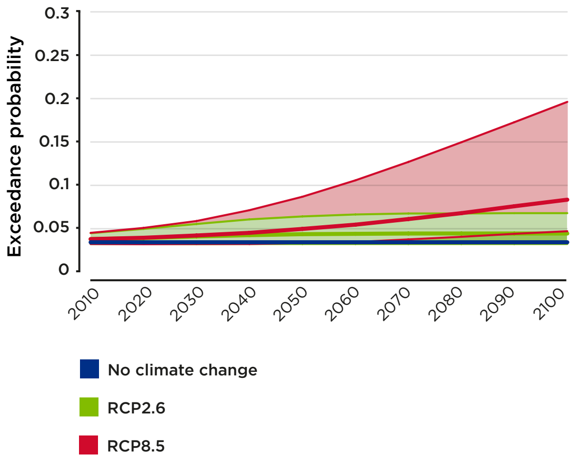


The global total increases very substantially – by around five or six times, over the course of the century for the high emissions pathway. This is largely due to increases in South, southeast and East Asia. There is a clear difference between the high and low emissions pathways, but there is also very high uncertainty in the numbers of people affected by flooding in the future due to uncertainty in changes in precipitation.

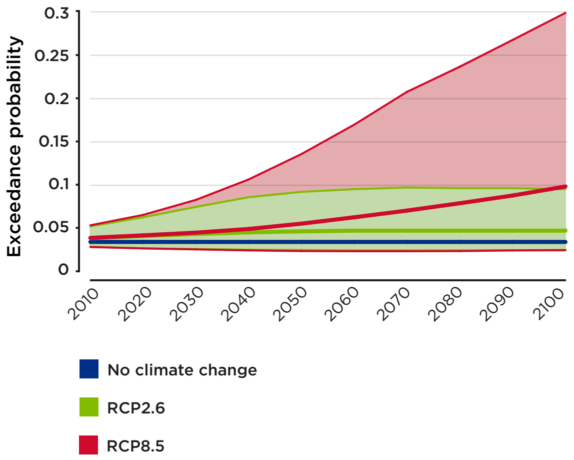
How could the likelihood of flooding change over time?

Figure F2: **The probability that flood magnitude in a given year exceeds the magnitude of the current 30-year return period flood in five illustrative catchments, under two climate pathways.**

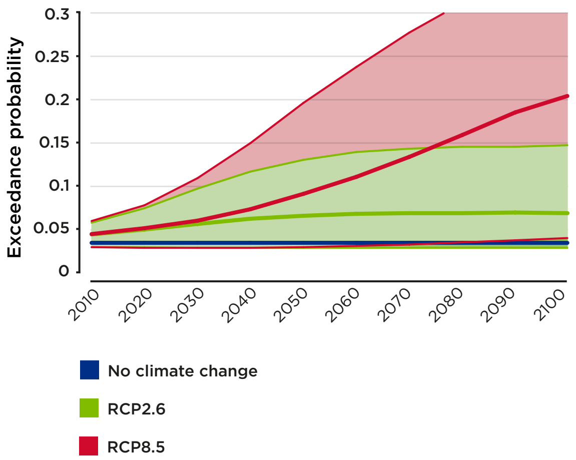
Yangtse: annual probability of exceeding current 30-year flood



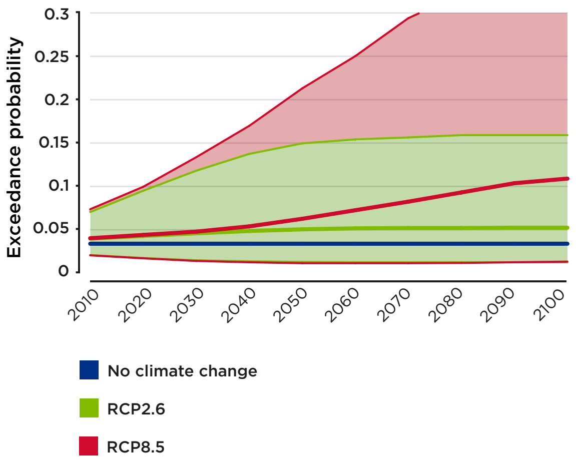
Huang Ho: annual probability of exceeding current 30-year flood



Ganges: annual probability of exceeding current 30-year flood



Indus: annual probability of exceeding current 30-year flood



Mississippi: annual probability of exceeding current 30-year flood

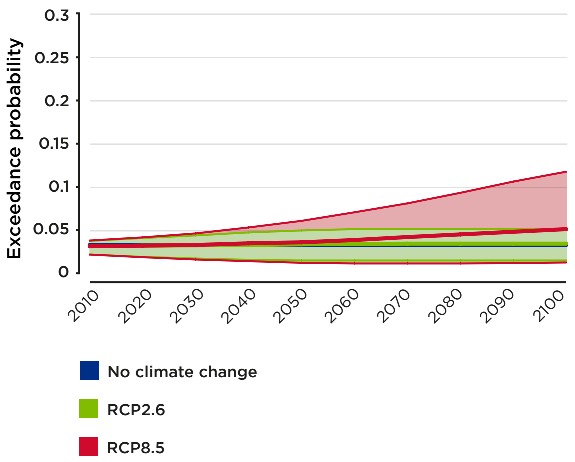
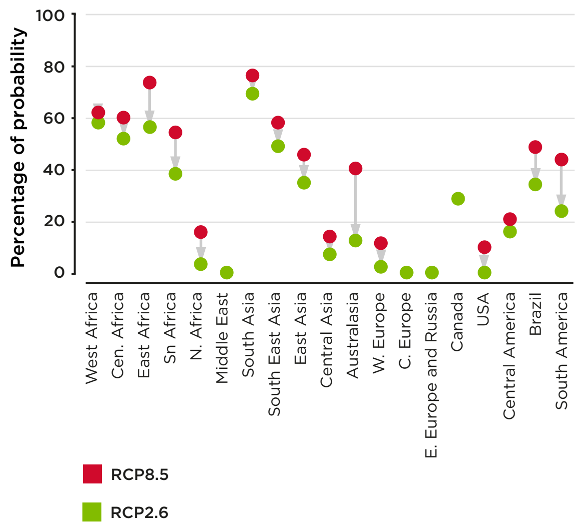


Figure F2 shows change through the 21st century in the probability of experiencing a flood greater than the baseline '30-year flood'. In the Asian examples, the probability of flooding increases very substantially under the high emissions pathway: tripling in the Huang He and Indus, and multiplying by six in the Ganges (becoming a 1 in 5 year event), over the course of the century, according to the central estimate. The increase in probability is considerably lower under the low emissions pathway. The figures show, however, that there is very large uncertainty in the change in future flood probability. In the best case, some regions could see a small reduction in probability. In the worst case, flooding on the Ganges, Indus and Huang He could be in the region of ten times more frequent by the end of the century.

Figure F3: **The risk that climate change increases by more than 50% the numbers of people affected by the current 30-year flood, relative to the situation with no climate change, under the two climate pathways.** A medium growth population projection is assumed.

2050: probability of number of people affected by flooding increasing by >50%



2100: probability of number of people affected by flooding increasing by >50%

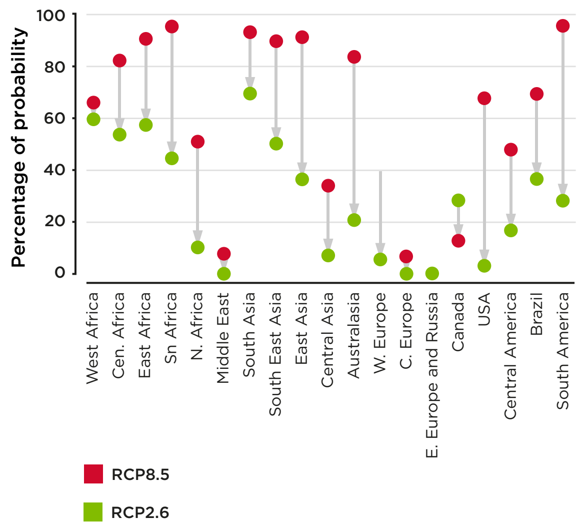


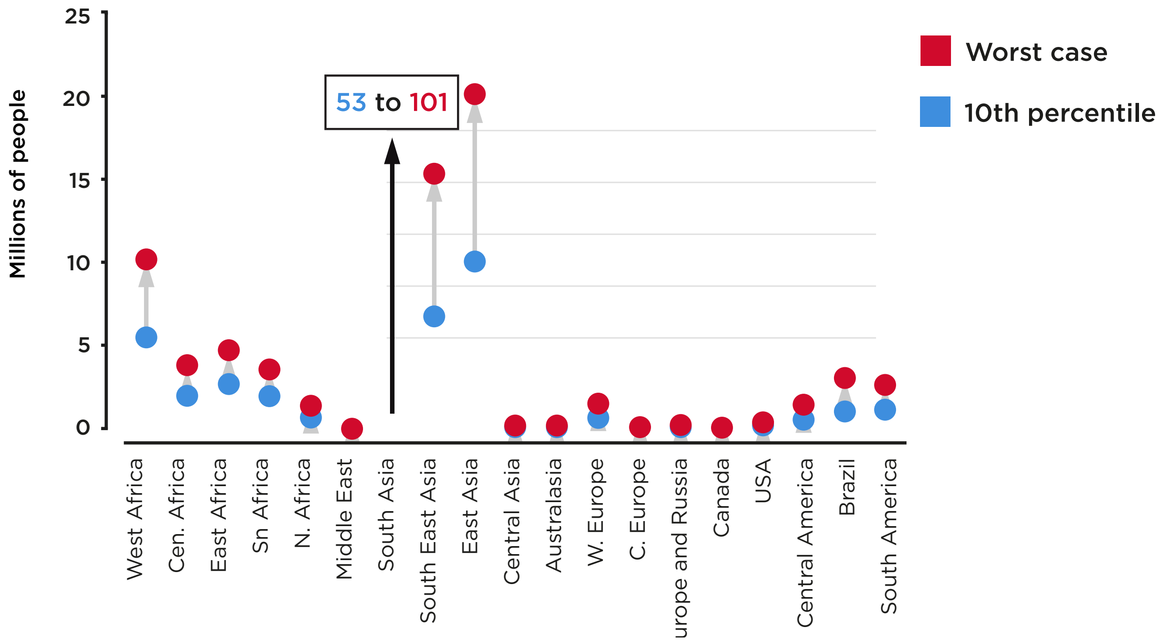
Figure F3 shows the risk by region that climate change increases by more than 50% the numbers of people affected by the current 30-year flood, relative to the situation without climate change. By the 2050s, there is at least a 50% chance that climate change alone would lead to a 50% increase in flooded people across sub-Saharan Africa, and a 30-70% chance that such an increase would be seen in Asia. By 2100 the risks are greater. Under the low emissions pathway the probabilities are lower in all regions than under the high emissions pathway, particularly in 2100.

What is a plausible worst case for changes in river flooding due to climate change?

It is clear from Figure F1 that there is considerable uncertainty in projected impacts of climate change. By 2050, under the 'worst case' climate scenario (the climate model pattern that projects the greatest increase in rainfall in the regions with the greatest flood-prone population), approximately 115 million extra people would be flooded in each year (relative to the situation with no climate change). Figure F4 shows the 'worst case' by region. In most regions the 'worst case' has approximately twice the impact of the 10th percentile impact. However, the worst cases shown in each region do not occur under the same plausible climate scenario: the global worst case is not the sum of the regional worst cases.

Figure F4 is based on the assumption that all the climate models used to estimate impacts are equally plausible and that they span the range of potential regional climate changes. This is not necessarily the case, so the numbers are to be regarded as indicative. Changes in south Asia (and therefore the global total) are strongly dependent on projected changes in the south Asian monsoon (see the previous chapter on water stress).

Figure F4: **Plausible ‘worst case’ impacts of climate change in 2050 on exposure to river flooding.** The graph shows the increase in numbers of people affected by flooding under the RCP8.5 climate pathway and the medium growth population assumption. There is a 10% probability that the impact is greater than that shown by the blue dots, and the red dots show the maximum calculated impact. Note that the impacts in south Asia are separately indicated, as they are far larger than those in other regions.



What do we know, what do we not know, and what do we think?

Estimates of how flood risk will change in the future are based on (i) projections of future regional climate change, (ii) projections of how these translate into changes in flood characteristics and (iii) projections of future exposed population and the implementation of flood defences.

Projections of future regional climate change depend partly on the assumed rate of growth in emissions, and partly on projected changes in regional and seasonal precipitation. From meteorological first principles, we would expect that – other things being equal – the frequency of high rainfall events would increase in a warmer world, simply because the hydrological cycle is enhanced and warmer air can hold more water. The frequency of flash flooding can therefore be expected to increase.

However, changes in atmospheric circulation patterns potentially have a greater impact on the magnitudes of persistent or prolonged heavy rainfall that have the greatest influence on flooding in most river basins, and these changes are currently uncertain. Wet regions are likely to get wetter, but the precise magnitude of change is uncertain, and the extent to which climate change alters the relative variability in rainfall from day to day and year to year is uncertain too. Higher temperatures would also in general mean that less precipitation would fall as snow during winter so there would be less snow to melt during the melt season – but this will vary from place to place depending on temperature regime, and may be offset or exaggerated by circulation changes generating more or less precipitation during winter.

The effects of changes in precipitation on river flood characteristics are typically estimated using a hydrological model, perhaps combined with a hydraulic model to simulate the routing of flood flows along the river network and through floodplains. Flood frequencies are estimated by fitting a statistical frequency distribution to time series of flood flows. All of these stages introduce uncertainty in the projected effect of a given change in precipitation regime.

Finally, the estimated future impacts on human society depend on changes in exposure to floods and vulnerability to their effects. This will depend not only on population and economic growth, but also on the extent to which physical flood defences are developed, buildings and infrastructure are sited to reduce exposure, and measures are implemented to help individuals and communities respond to and recover from floods and loss.

Production of this chapter was supported by the AVOID 2 programme (DECC) under contract reference 1104872.

Endnotes

1. MunichRe (2015) NatCatSERVICE: Loss events worldwide 1980-2014.
2. As defined in the UNISDR PREVIEW data base.
3. The UNDP estimates that around 50-60 million people are affected by river flooding each year, but this includes people affected by smaller magnitude floods. UNDP (2009) Risk and poverty in a changing climate: 2009 Global Assessment Report on Disaster Risk Reduction. UNDP: New York.

15 THE RISKS OF SEA-LEVEL RISE FOR COASTAL CITIES

Robert J. Nicholls,[i] **Tim Reeder**,[ii] **Sally Brown**,[iii] and **Ivan D. Haigh**.[iv]

Understanding the consequence of sea-level rise for coastal cities has long lead times and huge political implications. Civilization has emerged and developed during a period of several thousand years over which sea level has been unusually stable in geological terms. We have now moved out of this period and the challenge will be to develop a long-term proactive assessment approach to manage this challenge.

In 2005 there were 136 coastal cities with a population exceeding one million people and a collective population of 400 million people.[1] All these coastal cities are threatened by flooding from the sea to varying degrees[2] and these risks are increasing due to growing exposure (people and assets), rising sea levels due to climate change, and in some cities, significant coastal subsidence due to human agency (drainage and groundwater withdrawals from susceptible soils).

What is it that we wish to avoid?

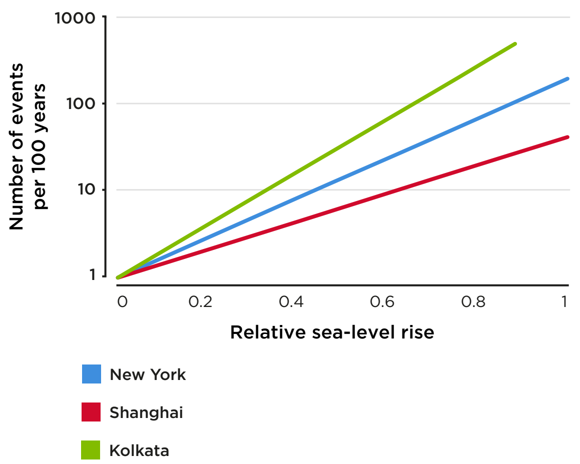
The population of New Orleans peaked at about 625,000, before being extensively flooded by Hurricane Betsy in 1965.[3] After that event the city's flood defences were upgraded and the city population recovered to about 500,000. In 2005, 80 percent of the city was flooded by Hurricane Katrina, with 800 deaths and more than US$40 billion damages.[4] Subsequently, improved defences have been provided costing US$15 billion,[5] but much of the city's economy has relocated and the current population is only about 300,000. Is this process the progressive abandonment of New Orleans due to repeated flooding and indicative of how coastal cities might be abandoned due to flooding and sea-level rise?

This example contains many of the things we wish to avoid in respect of sea-level rise and coastal cities: major flood events with associated deaths and damage, high costs of protection, and the potential for sudden abandonment or gradual decline.

How do risks grow with sea-level rise?

Flood risks grow with sea-level rise as it raises the likelihood of extreme sea levels. Figure 1 shows the increase in the frequency of current 100 year events in New York, Shanghai and Kolkata, as sea levels rise. Taking one example, a 1m rise in relative sea-level rise increases the frequency of current 100 year flood events by about 40 times in Shanghai, about 200 times in New York, and about 1000 times in Kolkata.

Figure 1: **The increase of frequency of present 100-year events (in the base year) as relative sea levels rise in three major coastal cities.**



Hallegatte et al (2013) came to the following conclusions concerning the future of coastal flooding in the 136 largest coastal cities (in 2005) over the next 50 years or so:[6]

- Damage could rise from US$6 billion/year to US$52 billion/year solely due to increase in population, property and its value.
- With additional climate change and subsidence, global losses could approach US$1 trillion or more per year if flood defences are not upgraded.
- Even if protection levels are maintained (i.e. flood probability is kept the same thanks to upgraded defences), annual losses will grow as individual floods become more severe due to flood depths increasing with relative sea-level rise. To maintain present levels of flood risk (average losses per year), protection will need to be upgraded to reduce flood probabilities below present values.
- Even with upgraded protection, the magnitude of losses when flood events do occur would increase for the reasons stated above, making it critical to also prepare for larger disasters than we experience today.

Beyond a 50 year time frame, sea levels will continue to rise and protection will have to be progressively upgraded into the future with uncertain consequences. This raises the question of whether there are potential thresholds (as discussed below) which, if passed, could reverse the current and forecast trends of growth for coastal cities.

What are the potential limits to cities' adaptation to sea level rise and when might they be reached?

Climate mitigation can stabilise the rate of sea-level rise, which makes adaptation more feasible. However, even if global temperature is stabilized, sea level will continue to rise for many centuries as the deep ocean slowly warms and the large ice sheets reach a new equilibrium: this has been termed the commitment to sea-level rise. This suggests that in coastal areas mitigation and adaptation must be considered together as the committed sea-level rise necessitates an adaptation response.[7] This perspective changes the mitigation discussion towards avoiding high end changes in climate over longer time spans than are typically considered.

There is not extensive literature or significant empirical information on the limits to adaptation in coastal cities. These limits are not predictable in a formal sense – while the rise in mean sea level raises the likelihood of a catastrophic flood, extreme events are what cause damage and trigger a response, be it abandonment, defence upgrade or something else.

Generalising the discussion, there are several types of potential limits that could be grouped into three broad categories, as discussed below:

- **Physical/engineering limits:** Adaptation and improving protection involve a number of steps as sea levels rise and increasing efforts are required to keep coastal areas dry. Each step involves higher costs. However, given the high value of cities, there is a strong incentive to mobilise large amounts of capital to fund adaptation. Important issues are rates of sea-level rise and maintenance. Accelerated rates of sea-level rise will present greater demands and hence challenges, although a rate of rise of a metre per century should present no major technical challenges. Maintenance requires annual investment of 1 to 2 percent of the capital value to maintain the defences. It is possible that there are other limits related to other issues such as ecology or related effects on local water supplies that will be reached at lower levels of sea-level rise.

i. Robert J. Nicholls is Professor of Coastal Engineering at the University of Southampton.
ii. Tim Reeder is a Senior Climate Change Adviser for the Environment Agency.
iii. Sally Brown is a Research Fellow at the University of Southampton.
iv. Ivan D. Haigh is a Lecturer in Coastal Oceanography at the University of Southampton.

- **Economic/financial limits:** At smaller levels of sea-level rise there will be a wide range of choices between retreat and continued protection. As sea levels rise higher, these adaptation choices will become starker, and the high costs of protection may lead to managed or unmanaged retreat if that becomes a less costly alternative. However, while relocation of major cities might be considered, the associated high costs can also provide a strong incentive to upgrade protection. In cost-benefit terms, protection is favoured,[8] but this of course depends on funds being available: poorer cities will be most challenged, with uncertain consequences. Further, a loss of confidence in a city due to a major flood could undermine its economic base, and hence the resources available for improving protection. If this occurs, it is probably a multi-stage process of decline over several events. However, once decline starts, it may be a self-reinforcing process.

- **Socio-political limits:** Thresholds and limits will vary dependent on the prevailing base conditions, confidence and attitudes to risk. Good governance will deliver effective and well-maintained protection systems. Cities with a strong background in flood protection will be better prepared and more likely to have a planned long-term approach to the radical actions that will be needed as sea level continues to rise. Those that have not prepared and have an unrealistic expectation of continuation of the present paradigm may well reach limits earlier. In many ways, this is the hardest limit to characterise and quantify, and yet it might be the most influential limit for coastal cities in practice.

If protection limits are reached, a few cities may have to be largely abandoned as most of their land area is in the flood plain. However, most coastal cities have large areas outside the coastal flood plain. Hence, in these cases, retreat would be about reconfiguring the city to the new land-water interface.[9]

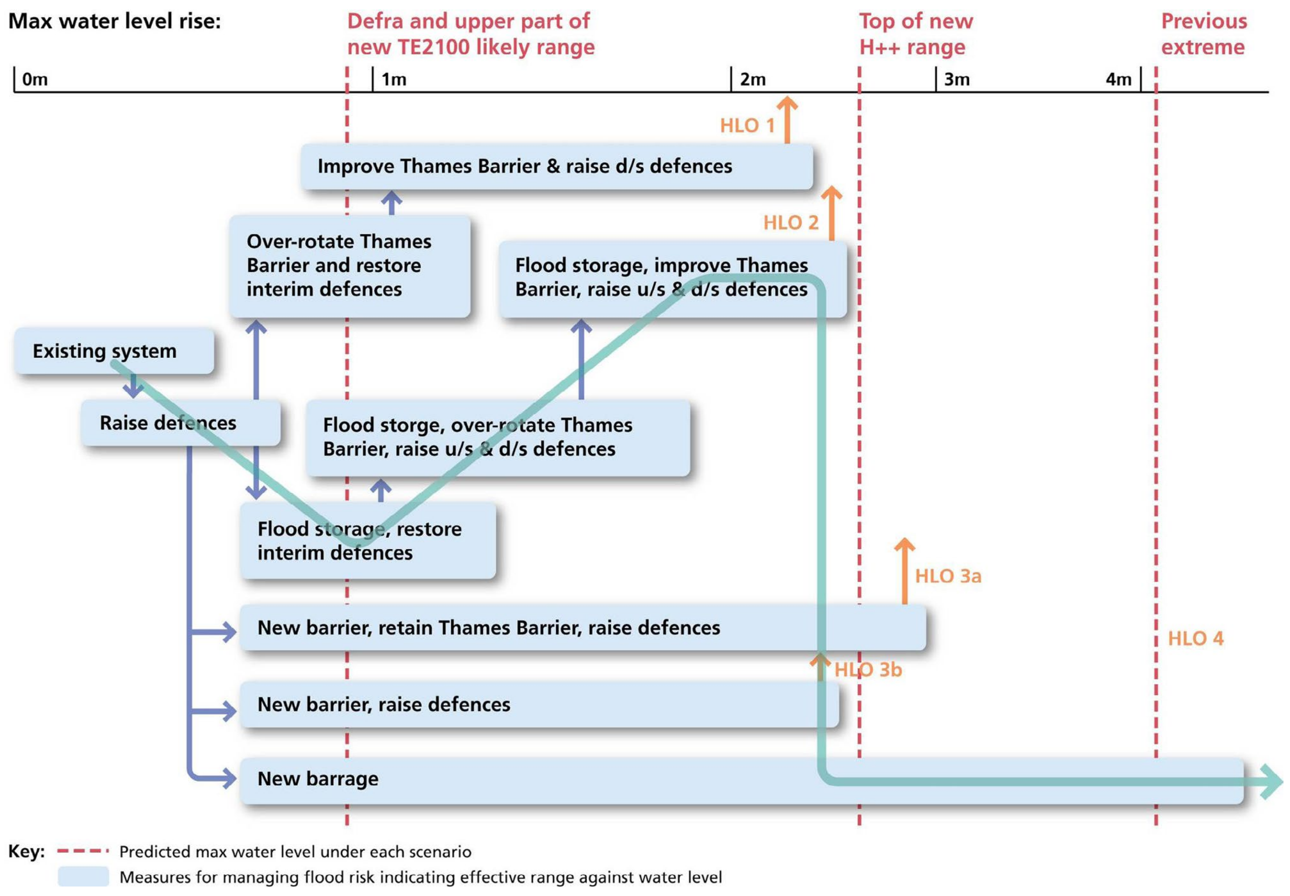
There are very few studies which quantify the sea level rise threshold at which cities will have to be abandoned, and in particular there has been little analysis of the art of the possible or feasible for adaptation beyond about 4 metres for any city. Exceptions include the Thames Estuary where a key threshold for adaptation of 5 metres of mean sea-level rise was identified related to limits of sea wall raising and tidal barrier construction in a closed system scenario. For sea levels higher than this, the entire discharge of the river Thames would need to be pumped to the sea.[10] In the Netherlands, the Delta Programme considered a sea level rise of 4 metres by 2200.[11] It was concluded that continuation of dyke-raising and beach and dune nourishment with sand could still be effective up to this level.

Conclusion

The lack of knowledge on sea level rise thresholds for coastal cities is of real concern. London's Thames Estuary 2100 (TE2100) plan[12] (illustrated in Figure 2), the Dutch Delta Programme[13] and New York[14] have defined adaptive pathways into the future. These define a portfolio of adaptation measures which can be progressively and flexibility applied to manage flood risk as sea level rises: more slowly or rapidly as circumstances demand. This is a best practice proactive approach for planning to address the issue. Such analysis illuminates where thresholds will be met in each city.

This approach could be applied widely to the coastal cities around the world to identify the adaptation choices.[15] This would include recognizing where protection might not be viable and a retreat approach may be needed. By taking a proactive approach to adaptation assessment the full scale of the long term challenge can be illuminated and the long term adaptive actions planned.

Figure 2: **TE2100 Project Plan High-level options and pathways developed by TE2100 (on the y-axis) shown relative to threshold levels increase in extreme water level (on the x-axis).** For example, the blue line illustrates a possible 'route' where a decision maker would initially follow HLO2 then switch to HLO4 if sea level was found to increase faster than predicted. The sea level rise shown incorporates all components of sea level rise, not just mean sea level.[16]



Endnotes

1. Hanson, S, Nicholls, R. J., Patmore, N, Hallegatte, S, Corfee-Morlot, J, Herweijer, C and Chateau, J (2011) A global ranking of port cities with high exposure to climate extremes. Climatic Change, 140, (1), 89-111. (doi:10.1007/s10584-010-9977-4)
2. Hanson et al., 2011; Hallegatte, Stephane, Green, Colin, Nicholls, Robert J. and Corfee-Morlot, Jan (2013) Future flood losses in major coastal cities. Nature Climate Change, 3, 802-806. (doi:10.1038/nclimate1979).
3. Grossi, P. and Muir-Wood, R. (2006) Flood Risk in New Orleans: Implications for Future Management and Insurability, Risk Management Solutions, Newark, USA, 31pp.
4. Kates, R.W., C. E. Colten, S. Laska, and S. P. Leatherman (2006) Reconstruction of New Orleans after Hurricane Katrina: A research perspective. PNAS, 103 (40) 14653-14660; doi:10.1073/pnas.0605726103
5. Link, L.E. (2010) The anatomy of a disaster, an overview of Hurricane Katrina and New Orleans. Ocean Engineering 37, 4–12.
6. Hallegatte et al (2013)
7. Nicholls, R.J., P.P. Wong, V.R. Burkett, J.O. Codignotto, J.E. et al. (2007). “Coastal systems and low-lying areas.” In: Parry, M.L. et al. (eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Fourth Assessment Report, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, pp. 315-356.; Wong, P.P., Losada, I.P., Gattuso, J.-P., Hinkel, J. et al. (2014). “Coastal systems and low-lying areas.” In: Field, C.B. et al (eds.) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Fifth Assessment Report, Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, UK, pp. 361-409.
8. e.g. Nicholls, Robert J, Tol, Richard S J and Vafeidis, Athanasios T (2008) Global estimates of the impact of a collapse of the West Antarctic ice sheet: an application of FUND. Climatic Change, 91, (1-2), 171-191. (doi:10.1007/s10584-008-9424-y).
9. Lonsdale, K.G, Downing, T.E, Nicholls, R. J, Parker, D, Vafeidis, A.T, Dawson, R and Hall, J (2008) Plausible responses to the threat of rapid sea-level rise in the Thames Estuary. Climatic Change, 91, (1-2), 145-169. (doi:10.1007/s10584-008-9483-0).
10. Reeder T, Wicks J, Lovell L, Tarrant T. (2009) Protecting London from tidal flooding: limits to engineering adaptation. In: Adger, N.W., Lorenzoni, I and O’Brien, K. (eds.) Adapting to climate change: thresholds, values, governance. Cambridge University Press, Cambridge, pp 54-63.
11. Deltacommissie (2008). Working together with Water. A living land builds for its future. Findings of the Deltacommissie. The Netherlands: Delta Commissie (Delta Commission).
12. Environment Agency (2012a) Thames Estuary 2100: managing risks through London and the Thames Estuary. TE2100 Plan; 2012. https://brand.environment-agency.gov.uk/mb/CtyxlR
13. Delta Commission, (2008) and the implemented programme described at http://www.government.nl/issues/delta-programme
14. New York City Panel on Climate Change (2010) Climate change adaptation in New York city: building a risk management response. Annals of the New York Academy of Sciences, 1196: 1–354.
15. Reeder, T. and Ranger N. (2011) “How do you adapt in an uncertain world? Lessons from the Thames Estuary 2100 project.” World Resources Report, Washington DC 2011. Available online at http://www.wri.org/sites/default/files/uploads/wrr_reeder_and_ranger_uncertainty.pdf
16. Reeder, T. and Ranger N. (2011)

16 GLOBAL SEA-LEVEL RISE[i]

Professor Daniel Schrag, Director, Harvard University Center for the Environment.

What we wish to avoid

As the previous chapter discussed, it is difficult to define thresholds in the height or rate of sea level rise that will cause significant problems for coastal cities. But it is clear that the faster sea level rises, the more difficult and expensive adapting to it will become. It may already be impossible to avoid long-term sea level rise of more than 10 metres from melting of polar ice sheets, but it may be possible to limit the rate of melting. So what we wish to avoid is any change that causes a significant acceleration in the rate of sea level rise.

What we know

Over 90% of the energy imbalance caused by increased greenhouse gas concentrations in the atmosphere is absorbed by the oceans (compared to roughly 3% that goes into warming the Earth’s surface). This extra energy is raising the heat content of the ocean, and correspondingly the volume, due to thermal expansion. In addition, ice is melting from the polar ice sheets and also from mountain glaciers, raising the volume of the oceans. Finally, mostly independent of climate change, groundwater is being pumped from aquifers on land, and then released to streams and rivers, also contributing to global sea level rise. Since pre-industrial times, the global average sea level has risen by about 20cm.[1] Based on precise measurements from satellite altimetry, we know that the rate of rise has averaged 3.4mm/year since the 1990s, and we know that this rate is accelerating.

Thermal expansion is the main contributor to sea level rise at present, but the main contributor in the future will be melting of polar ice sheets. These contain water roughly equivalent to a globally averaged sea level rise of:

- **Greenland ice-sheet: 7m**
- **West Antarctic ice-sheet: 6m**
- **East Antarctic ice-sheet: more than 50m**

What we do not know

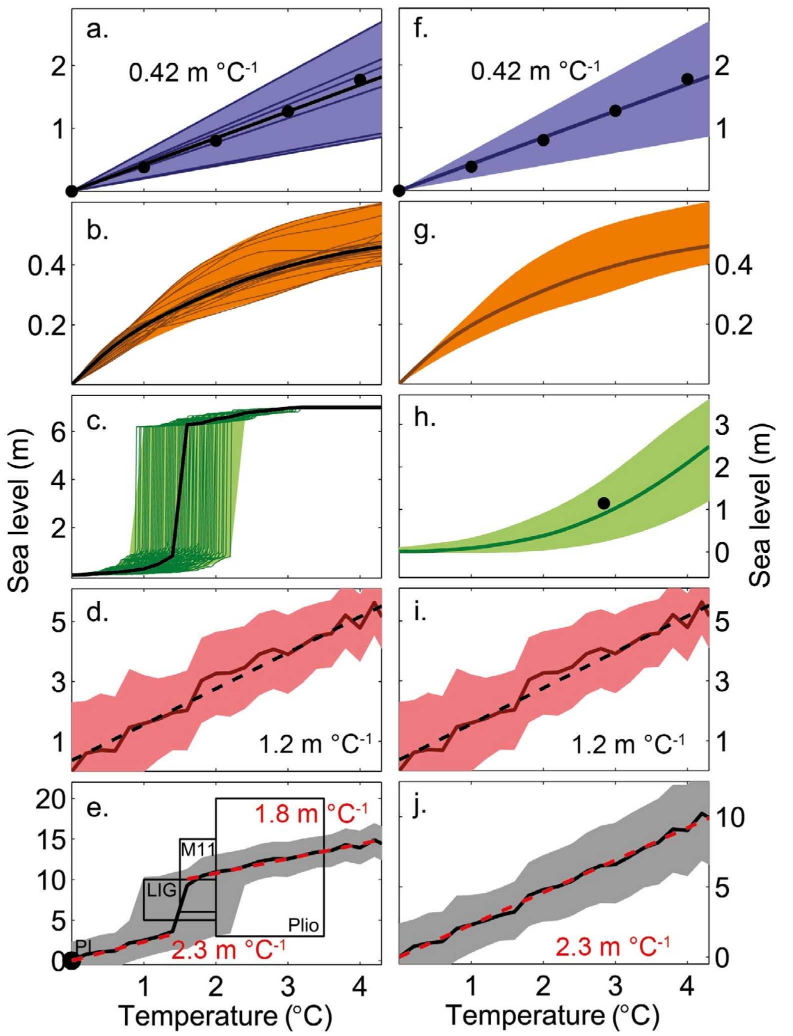
We do not know how quickly the melting of these ice-sheets could occur. This is deeply uncertain: neither observations nor models provide enough information. The timescale for the Greenland and West Antarctic ice-sheets could be hundreds of years, or thousands of years. The timescale for parts of the East Antarctic ice-sheet is likely to be longer because it is so cold and also less vulnerable to rapid collapse due to topography and glacial structure.

What we think

Paleoclimate data suggests that the Greenland ice-sheet probably cannot survive in a world where atmospheric carbon concentrations are above 400ppm (their current level), and almost certainly not in a 550ppm world – equivalent to a level in the lowest emissions scenarios that we have earlier in this report characterized as very unlikely. The same is probably true for the West Antarctic ice-sheet, and for small parts of the East Antarctic ice-sheet. This implies that we may already be committed to some 10-15m of sea level rise in the long-term future. Figure 1, taken from the IPCC, shows a central estimate of around 12m long-term committed sea level rise, if temperature rise is held steady at 2°C. But the rate is wildly uncertain: whether this will take 500 years or 10,000 years is really unknown.

i. This contribution is intended as a brief summary of the author’s opinion on the state of knowledge of risks of sea level rise, and not a comprehensive review of the existing literature. For additional information and references, readers should consult Chapter 13 of Working Group 1 from the IPCC AR5.

Figure 1: **committed sea level rise as a function of long-term global temperature increase.**[2] Committed sea level is the amount that will occur regardless of global efforts to stabilize global greenhouse gas emissions.



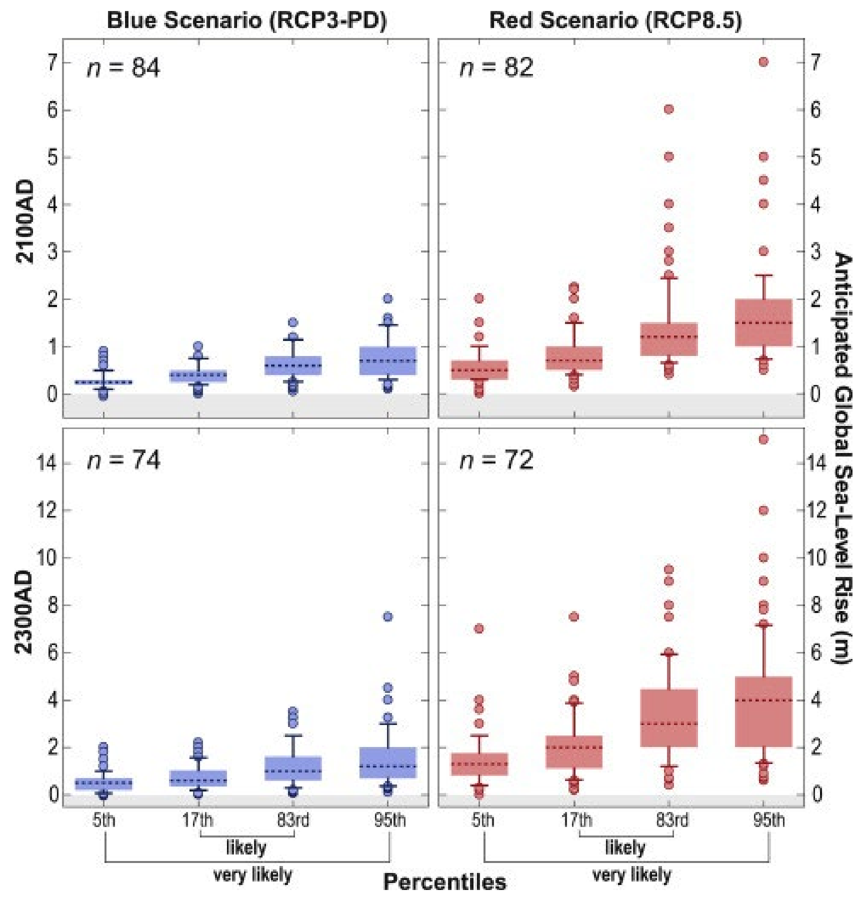
Full IPCC caption: (Left column) Multi-millennial sea level commitment per degree Celsius of warming as obtained from physical model simulations of (a) ocean warming, (b) mountain glaciers and (c) the Greenland and (d) the Antarctic ice sheets. (e) The corresponding total sea level commitment, compared to paleo estimates from past warm periods (PI = pre-industrial, LIG = last interglacial period, M11 = Marine Isotope Stage 11, Plio = Mid-Pliocene). Temperatures are relative to pre-industrial. Dashed lines provide linear approximations in (d) and (e) with constant slopes of 1.2, 1.8 and 2.3 m °C–1. Shading as well as the vertical line represents the uncertainty range as detailed in the text. (Right column) 2000-year-sea level commitment. The difference in total sea level commitment (j) compared to the fully equilibrated situation (e) arises from the Greenland ice sheet which equilibrates on tens of thousands of years. After 2000 years one finds a nonlinear dependence on the temperature increase (h) consistent with coupled climate–ice sheet simulations by Huybrechts et al. (2011) (black dot). The total sea level commitment after 2000 years is quasi-linear with a slope of 2.3 m °C–1.

The range of uncertainty is much smaller in the relatively short timescale of this century, but is still significant from a human perspective. IPCC projections for sea level rise have tended to increase over time. The Third Assessment Report estimated a range of 0.2 – 0.6m over the century; the Fifth Assessment Report estimates 1m as the upper end of the 'likely range', plus a few additional tenths of a metre in the event of a collapse of parts of the West Antarctic ice-sheet. Some more recent scientific findings have suggested that such a collapse has already begun.[3]

At the time of the IPCC's Third Assessment Report, it was predicted that the ice-sheets on Antarctica would grow, contributing a net decrease to the change in sea level. Satellite measurements of ice-sheet mass now show the opposite to be occurring. Antarctica as a whole is losing mass, although there are parts of the Antarctic ice sheet that are gaining mass from increased precipitation. The data for Greenland show an acceleration in mass loss, but as the observations only exist for slightly more than a decade, it is impossible to say whether this acceleration is part of a multi-decadal oscillation, or the beginning of a long-term trend.

For this century, sea level rise of at least 40cm looks likely, as anything less would require a slowing in the contribution of ice-sheets, which would be the opposite of what is being observed. More than 1m appears unlikely, but there is much more uncertainty over the upper end of the range. Figure 2 shows the extent to which expert opinion varies.

Figure 2: **Expert opinion on likely extent of sea level rise in 2100 and 2300, for low and high emissions pathways** (from Horton et al[4]).[5]



A plausible worst-case scenario

A plausible worst-case scenario would be a significant acceleration of sea level rise, as well as a commitment to even more rapid sea level rise of several times the current rate at the end of this century and throughout the next century. This could only occur if one of two things happens:

i. **A rapid acceleration of summer surface-melting on Greenland.** In the few locations on Greenland where there are outlet glaciers that bring ice directly into contact with the ocean, Greenland's glaciers are already moving at close to the maximum speed physically possible, which is constrained by friction. Some acceleration in the rate of mass loss is possible from an increase in the number of such locations, particularly around northern Greenland, but more substantial acceleration is likely to come from enhanced surface melting in summer. Satellite images show that the area of melting of the surface of the Greenland ice sheet has been expanding rapidly. The formation of melt-pools acts as a positive feedback. These processes are not yet well understood: deposition of black carbon may be important, as well as temperature rise. In addition, it is not known what effect the continuing retreat of summer sea-ice will have.

ii. **Collapse of the Ross ice shelf and other large ice shelves from Antarctica.** Temperatures on Antarctica are low enough that surface melting is not the major factor in creating ice loss, but rather ice discharge to the ocean. Currently, the discharge of glaciers on West and East Antarctica into the ocean are being slowed down by large ice-shelves – floating land ice that has been pushed out into the ocean – including the Ross ice shelf covering the Ross Sea. The collapse of the Ross ice shelf or other critical ice shelves would allow the rate of ice discharge to accelerate, adding several metres to sea level rise over a century or two. We do not understand exactly how this would occur, but some work has shown that ice shelves disintegrate when slightly warmer (0 - 2°C) water flows over the continental shelf beneath the ice shelf and melts it from below. Current observations are so limited that we do not know whether these processes are already taking place.

It is also important to emphasize that the two possibilities described above have different implications for the possibility of stabilizing or reversing sea level rise. The melting on Greenland could be stopped if warming was reduced, for example through proposals to cool the Earth through solar radiation management (or 'geoengineering'). But if a major ice shelf disintegrates, it will be much more difficult to stop or slow the glacial discharge, as the flow depends on gravitational instability of the ice sheet, and is very insensitive to surface temperature, at least over fairly long timescales. Thus, the consequent sea level rise would likely be unstoppable and irreversible.

Endnotes

1. IPCC (2013): 'Summary for Policymakers'. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
2. Fig. 13.14 from IPCC (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324.
3. http://www.sciencemag.org/content/348/6237/899 / http://www.the-cryosphere.net/9/1005/2015/tc-9-1005-2015.html
4. Horton et al (2014). 'Expert assessment of sea-level rise by AD2100 and AD2300'. Quaternary Science Reviewshttp://www.sciencedirect.com/science/article/pii/S0277379113004381
5. Box plots of survey results from all experts who provided at least partial responses to questions. The number of respondents for each of the four questions is shown in the top left corner; it is lower than the total of 90 participants since not all answered each question. Participants were asked to estimate likely (17 the 83rd percentiles) and very likely (5th - 95th percentiles) sea-level rise under two temperature scenarios and at two time points (AD 2100 and AD 2300), resulting in four sets of responses. Shaded boxes represent the range between the first and third quartiles of responses. Dashed horizontal line within the box is the median response. Whiskers (solid lines) represent two standard deviations of the responses. Filled circles show individual responses that are beyond two standard deviations of the median.

17 LARGE-SCALE ABRUPT OR IRREVERSIBLE CHANGES

Professor Jason Lowe, Head of Mitigation Advice, UK Met Office Hadley Centre.

What we wish to avoid

Many elements of the climate system are capable not only of steady, gradual change over long time-periods, but also of non-linear change when critical thresholds are passed. Some of these may result in relatively abrupt change and some may be irreversible. Both types may have large-scale consequences for the climate, both directly and indirectly, often with disproportionate impacts in some regions of the world.

As discussed in the previous chapter, an acceleration in the melt rate of the Greenland or Antarctic ice-sheets could lead to a significant acceleration in global sea level rise; on time scales of several centuries or more this would very likely be irreversible. Similarly, an acceleration of temperature rise could result from large-scale thawing of permafrost and the release of extra carbon dioxide or methane into the atmosphere, or from the release of sub-sea methane hydrates (as discussed in the chapter on global temperature increase).

Changes in atmospheric circulation patterns are very difficult to predict, and could potentially be abrupt. As noted in the chapter on water stress, large-scale changes in monsoons cannot be ruled out. Changes to the El Niño phenomenon, linked to extreme weather in many parts of the world, are also possible. Ocean circulation patterns could also change: and in particular, the Atlantic meridional overturning circulation could weaken or collapse. This would affect temperature, rainfall, and some extreme weather over large parts of the northern hemisphere. On a regional scale, changes in rainfall and temperature in combination with other factors could cause large-scale die-back of tropical forests, such as the Amazon, which in turn would weaken the natural sink for atmospheric carbon dioxide and produce a further amplification of warming.[1]

When could these changes occur?

There is great uncertainty over when, or at what degree of global temperature rise, thresholds associated with these large-scale changes might be passed. However, the evidence suggests that the probability of crossing such thresholds increases with global temperature rise, and if temperature rise continues, there is potential for crossing several of them during the 21st century. Improving our understanding of these trigger points is a priority for climate research.

The IPCC's Fifth Assessment Report reviewed recent evidence of both the likelihood and the consequences of experiencing these large-scale changes in the current century.[2] These findings are summarised in the table shown below, which is adapted from the recent IPCC report ('table 12.4').[3] More recent published research has reinforced these findings.[4]

From a risk assessment perspective, it is important to understand what this evidence-based expert judgement is saying with respect to magnitude of impact, probability, and time.

Magnitude of impact: For some of these changes, the magnitude of impact being considered is a very high one. For example, for a methane hydrate (clathrate) release, the magnitude being considered is 'catastrophic'. For ice-sheet collapse, what is being considered is 'near-complete disintegration', which would result in sea level rise of many metres – considered exceptionally unlikely this century. In some cases, a lower impact threshold may also be significant: for example, the likelihood of partial ice-sheet collapse causing an acceleration of sea level rise in the short-term, and commitment to higher sea level rise in the long-term, may be much higher. The IPCC's Summary for Policymakers estimates that 'Risks [of large-scale singular events] increase disproportionately as temperature increases between 1–2°C additional warming and become high above 3°C, due to the potential for a large and irreversible sea level rise from ice sheet loss.'[5]

Table: **Components in the Earth system that have been proposed in the literature as potentially being susceptible to abrupt or irreversible change. Column 2 defines whether or not a potential change can be considered to be abrupt under the AR5 definition. Column 3 states whether or not the process is irreversible in the context of abrupt change, and also gives the typical recovery time scales. Column 4 provides an assessment, if possible, of the likelihood of occurrence of abrupt change in the 21st century for the respective components or phenomena within the Earth system, for the scenarios considered in this chapter.[6]**

Change in climate system component	Potentially abrupt (AR5 definition	Irreversibility if forcing reversed	Projected likelihood of 21st century change in scenarios considered
Atlantic MOC collapse	Yes	Unknown	Very unlikely that the AMOC will undergo a rapid transition (high confidence)
Ice sheet collapse	No	Irreversible for millennia	Exceptionally unlikely that either Greenland or West Antarctic Ice sheets will suffer near-complete disintegration (high confidence)
Permafrost carbon	No	Irreversible for millennia	Possible that permafrost will become a net source of atmospheric greenhouse gases (low confidence)
Clathrate methane release	Yes	Irreversible for millennia	Very unlikely that methane from clathrates will undergo catastrophic release (high confidence)
Tropical forests dieback	Yes	Reversible within centuries	Low confidence in projections of the collapse of large areas of tropical forest
Boreal forests dieback	Yes	Reversible within centuries	Low confidence in projections of the collapse of large areas of boreal forest
Disappearance of summer Arctic sea ice	Yes	Reversible within years to decades	Likely that the Arctic Ocean becomes nearly ice-free in September before mid-century under high forcing scenarios such as RCP8.5 (medium confidence)
Long-term droughts	Yes	Reversible within years to decades	Low confidence in projections of changes in the frequency and duration of megadroughts
Monsoonal circulation	Yes	Reversible within years to decades	Low confidence in projections of a collapse in monsoon circulations

Probability: The estimates of likelihood given above may be read with reference to the IPCC's standard approach to expressing estimated ranges of likelihood in qualitative terms. The ranges corresponding to the terms used here are: 'Exceptionally unlikely': 0-1%; 'Very unlikely': 0-10%; 'Likely': 66-100%.[7] Although in the IPCC report many of these changes are reported as being "very unlikely" in the IPCC's calibrated terminology, the probability estimates are what many risk adverse stakeholders might still consider unacceptably high when viewed in parallel with the magnitude. It is notable that for several of the large-scale changes, the uncertainty around their likelihood is so great that no estimate is given.

Time: The probability estimates noted above are given only with respect to the current century. As noted above, these probabilities are expected to increase with global temperature rise, and as the chapter on that subject showed, under medium and high emissions scenarios global temperature rise is projected to continue beyond the end of the century. The consequences of these changes are also expected to continue beyond the century time-scale.

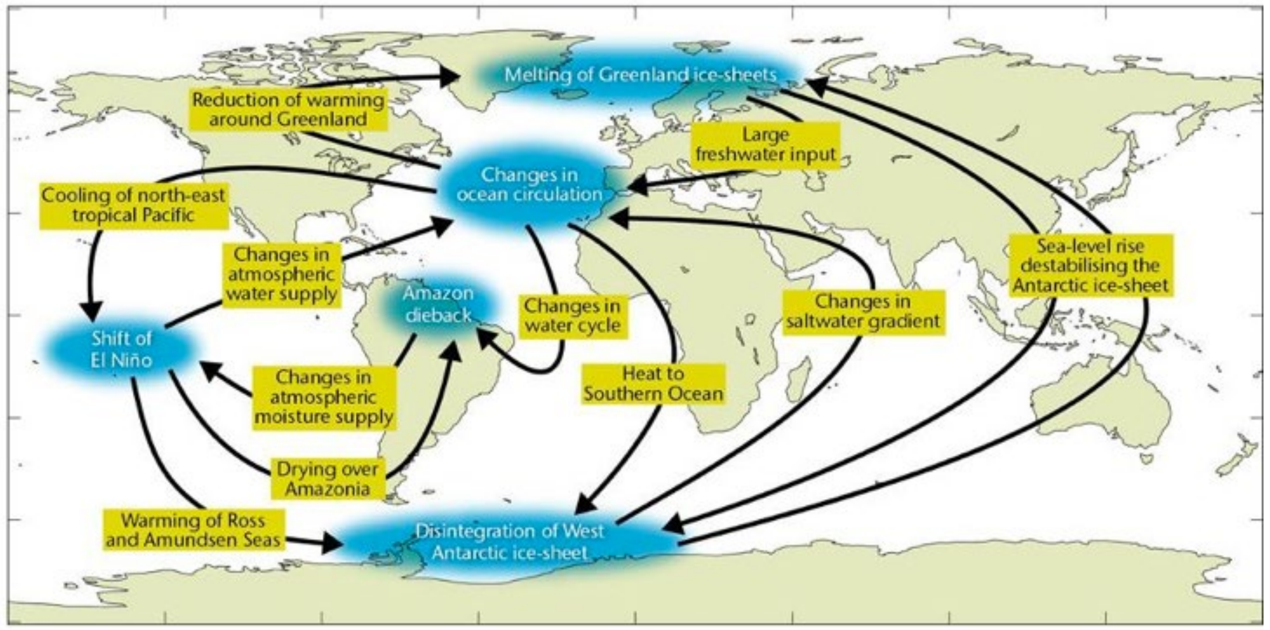
All three of these factors – magnitude of impact, probability, and time – have to be taken into account in reaching a view on the scale of the risks presented by these possible large-scale changes.

Systemic interactions

An additional aspect to consider is the potential for interaction between these large-scale climate system changes, with one change leading to a cascade of other major events. For instance, we can speculate that enhanced melting from the Greenland ice-sheet could not only raise sea level but also slow the Atlantic over-turning circulation. One consequence of changes in Atlantic circulation and sea surface temperatures is expected to be a shift in atmospheric circulation, which could have negative impacts on the health of the Amazon forest and its ability to take up atmospheric carbon. At the same time, the rise in sea level from Greenland might also affect the stability of the ice shelves and ice sheets in the southern Hemisphere, leading to further sea level rise.

Figure 2 captures some of these effects (this is based on an earlier figure by Kriegler et al.)[8] It effectively highlights the fact that the concomitant effects of climate change can cause widespread impacts in a number of areas, presenting significant systemic risks. This is an area explored in greater detail in the next section of this report. It is clear that if we are to have a full understanding of climate change risks, we must assess the likelihood of large-scale climate changes, the interactions between them, and the critical thresholds at which they could be triggered. The recent emergence of complex earth system models is finally providing a tool that will allow climate scientists to start to explore these interactions.

Figure 2: **Possible interaction of large-scale climate disruption.[9]**



Production of this chapter was supported by the AVOID 2 programme (DECC) under contract reference 1104872.

Endnotes

1. Kriegler, E., Hall, J.W., Held, H., Dawson, R., and Schellnhuber, H.J. (2009). 'Imprecise probability assessment of tipping points in the climate system'. PNAS 106, 5041-5046. doi: 10.1073/pnas.0809117106.
2. Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner (2013). 'Long-term Climate Change: Projections, Commitments and Irreversibility'. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
3. Table 12.4, p. 1115 in IPCC, (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324. IPCC AR5 WG1 Table 12.4
4. Good, P. et al. (2014). An updated view of tipping points and the relevance for long-term climate goals. Available at http://avoid-net-uk.cc.ic.ac.uk/wp-content/uploads/delightful-downloads/2015/02/AVOID2_WPA5_v2_final.pdf.
5. IPCC (2014). 'Summary for policymakers'. Climate Change 2014: Impacts, Adaptation, and Vulnerability.Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 12.
6. Table from Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner (2013). 'Long-term Climate Change: Projections, Commitments and Irreversibility.' Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
7. IPCC (2013). 'Summary for Policymakers'. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. p.4
8. Kriegler et al. (2009).
9. Adapted from Kriegler et al. (2009).

18 CONCLUDING COMMENTS

In this chapter, we have considered various forms of threshold in the severity of climate change and its impacts. These include:

- Thresholds in the physical climate system itself: for example, the degree of warming at which an ice-sheet may be committed to collapse;
- Biophysical thresholds, such as the degree of heat and humidity that is potentially fatal to humans, or the temperature that exceeds the tolerance of a crop;
- Socioeconomic thresholds, such as the quantity of per capita water resources required to meet basic human needs, or the point at which it becomes less costly to retreat from coastal areas than to protect them against flooding;
- Thresholds defined by political decisions, such as the 2°C temperature target.

It is clear that in many cases, when a threshold is passed, there is a non-linear increase in the severity of impact. For example: a significant acceleration in the rate of sea level rise; a very severe decrease in crop yield instead of a moderate decrease; the death of a person from heat stress instead of the experience of non-fatal heat stress. Avoiding these impacts is likely to be a high priority for a decision-maker, so assessing their likelihood should be a high priority for a risk assessment.

Our assessment looked, where possible, at how the probability of crossing these thresholds might increase over time, or as a function of global temperature rise. In several cases, it appeared that there could be a non-linear increase in probability, once a certain point of time or temperature was passed.

The idea of there being thresholds of impact, or limits to adaptation that might be important, is not new. The chapter on 'Adaptation opportunities, constraints and limits'[1] in the IPCC's Fifth Assessment Report provides an authoritative overview of this subject. However, the approach we have taken – presenting the probability of crossing these thresholds as a function of time (or of global temperature increase) – does not seem to be the generally preferred method. The IPCC Fifth Assessment Report's Working Group II report included only one graph in this format (showing the risk of mass coral mortality),[2] compared to some twenty graphs that showed severity of impact as a function of time.[3]

As we discussed at the beginning of this section, an approach that first defines what it is we wish to avoid, and then assesses its likelihood as a function of time, seems consistent with the principles of risk assessment. If results presented it this way make it plain that under a certain course of action (e.g. a high emissions pathway), that likelihood could become very high, then this will be useful information for a decision-maker.

There seems to be considerable scope for developing this approach further. For example, more locally relevant socioeconomic thresholds could be defined, and better ways to estimate probabilities could be developed.

A limitation of this approach may be that it will tend to focus on individual impacts of climate change, rather than the effect of many impacts in combination. In the real world, different impacts of climate change will frequently overlap and interact. The difficulty of anticipating such interactions – especially if human actions are also taken into account – may mean that the risks arising from them are easily overlooked. The IPCC found that *"Interactions of climate change impacts on one sector with changes in exposure and vulnerability, or with adaptation and mitigation actions affecting the same or a different sector, are generally not included or well integrated into projections of risk. However, their consideration leads to the identification of a variety of emergent risks that were not previously assessed or recognized."*[4]

This most difficult area of risk assessment – the interactions between the impacts of climate change and complex human systems – is the subject of the next part of our report.

Endnotes

1. Klein, R.J.T., G.F. Midgley, B.L. Preston, M. Alam, F.G.H. Berkhout, K. Dow, and M.R. Shaw (2014). 'Adaptation opportunities, constraints, and limits. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 899-943.
2. Fig 30-10 in Hoegh-Guldberg, O., R. Cai, E.S. Poloczanska, P.G. Brewer, S. Sundby, K. Hilmi, V.J. Fabry, and S. Jung (2014). 'The Ocean'. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1655-1731.
3. See graphs at: https://ipcc-wg2.gov/AR5/report/full-report/
4. Oppenheimer, M., M. Campos, R. Warren, J. Birkmann, G. Luber, B. O'Neill, and K. Takahashi (2014). 'Emergent risks and key vulnerabilities'. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1053.

RISK ASSESSMENT PART 3:

SYSTEMIC RISKS

Martin Bureau/AFP/Getty Images

RISK ASSESSMENT PART 3:
SYSTEMIC RISKS

19 INTRODUCTION

Our human civilization and the natural environment on which it depends are both examples of complex, dynamic systems. The defining characteristic of such systems is that they are made up of large numbers of interacting, interdependent components. These interactions are often non-linear: their causes and effects are not proportional to each other. Small changes can sometimes have very large effects. For this reason, the behaviour of these systems is very difficult to predict.[1]

A high degree of uncertainty, if it affects our objectives or things we value, can correspond to a high degree of risk. Systemic risks may be simply defined as 'risks that can trigger unexpected large-scale changes of a system, or imply uncontrollable large-scale threats to it'.[2]

In this part of our risk assessment, we are concerned with the risks that could arise from the interaction of climate change with human social and economic systems. As we noted at the beginning of this report, human civilization developed during a period of several millennia of unusual climatic stability. We are now, through our emissions of greenhouses gases, applying a forcing to the climate system – disturbing its stability. As described in previous chapters, this could lead to large changes in the natural world, far outside the range of human experience. Intuitively, we might guess that if small changes can sometimes produce very large effects in complex systems, then very large changes could be quite likely to produce very large effects.

The systemic risks of climate change may be very large, but they are much less straightforward to assess than the direct risks considered in earlier chapters. In this section, we begin with an example of the systemic risks experienced by a city in relation to a current climate event. We then consider the observed changes and future risks to systems in a region – the Arctic – and the way in which these changes could affect the rest of the world. Finally, we explore in depth two categories of risk that could be significant at the international scale: climate change risks to global food security, and climate change risks to national and international security.

An example of systemic risks at the city level: drought in São Paulo

Dr Jose Marengo is Research Director at the National Center for Monitoring and Early Warning of Natural Disasters in São Paulo, Brazil. Since October 2014 he has served on a crisis task force set up to advise the Brazilian government on its handling of the drought in the southeast of the country. Here he describes some of its effects.

The São Paulo Metropolitan Area is the largest metropolis in South America, and accounts for a third of Brazil's national GDP. For the last year, it has been affected by an exceptional drought. Rainfall over the reservoir system surrounding the city fell in 2014 to the lowest level recorded since 1940, and this coincided with a period of high temperatures. The extent to which climate change affected the likelihood of such low rainfall is difficult to assess, but it may well have played a role in increasing the likelihood of the high temperatures.[3,4] (As chapter 13 discussed, in future, climate change could increase the risks of drought in many parts of the world.)

While the low rainfall decreased water availability, high temperatures led to increased water use – in agriculture, industry, and people's homes. The city's rapid development over recent decades had increased its vulnerability: population growth increased water demand; forests and wetlands that had historically soaked up rainwater and released it slowly into reservoirs were destroyed; and poor-quality infrastructure continued to leak some 30-40% of its water.

The most direct impact, obviously, has been a lack of water. The state-run utility company has reduced its extraction from reservoirs by a third, cut its pump pressure at night, and offered discounts to customers who reduce their consumption. Parts of the city now rely on water-trucks for their supply.

Lack of water has hampered the functioning of schools, hospitals and businesses. Agriculture has suffered: the price of products such as tomatoes and lettuce increased by around 30% at the height of the drought; other affected crops included sugar cane, oranges and beans.[5] Meanwhile, the number of forest fires in the region increased by 150% from 2013 to 2014.[6] Electricity generation has also been affected. More than 70% of Brazil's electricity supply comes from hydroelectric power, and around 70% of this is generated in the São Paulo region. By the end of 2014, the reservoirs supplying this power generation were almost dry. As a result, energy tariffs were predicted to increase by 20-25% in 2015.[7]

The effects of the water shortage, including water rationing, increased water bills, and other inconveniences have even led to protests and social unrest in some parts of the city. The overall loss to the economy from the drought so far has been estimated at US$5 billion, making it the fifth most expensive natural disaster in the world in 2014.[8]

An example of systemic risks at the regional level: climate change in the Arctic

Dr Tero Mustonen works for the Snowchange Cooperative and the University of Eastern Finland. His work gives him contact with scientists and indigenous peoples from around the Arctic who are observing and documenting the changing climate and its effects. Here he describes a few of these observed changes, and some future risks.

The Artic is warming at twice the rate of anywhere else on Earth,[9] so the changes we observe there at present give us some idea of the scale of the changes we could witness elsewhere in future. The changes already seen in the Arctic are profound. Rising average temperatures have led to heat extremes that were previously unheard of: a peak temperature of 37.2°C has been recorded in boreal Finland.[10] Melting of the Greenland ice-sheet has accelerated, while the extent of summer sea-ice has reduced by some 40%, at a rate faster than most scientific models predicted.[11] In many areas the permafrost – previously permanently frozen ground – is beginning to thaw. The whole region is under-going a system-shift, with potentially major consequences for ecosystems and human societies.[12]

The indigenous peoples of the Arctic are directly affected by these changes in ecosystems. Unpredictable weather patterns have already disrupted the traditional calendar of the Kola Sámi in northwestern Russia.[13] In the Eurasian North, the Skolt Sámi people, anticipating the severe impacts of climate change on reindeer herding habitats, are beginning to adapt their culture to rely instead upon in-land fishing.[14] The Inuit's hunting and food-sharing culture is under threat, as reduced sea ice results in the decline of populations of the animals they hunt. In the future, the Arctic Council assessed that reductions in species' ranges and availability, less predictable weather, and threats to safe travel caused by the changing ice conditions would 'present serious challenges to human health and food security, and possibly even the survival of some cultures.'[15]

Industrialised societies of the region face disruption too. While the retreat of the sea ice may enable the expansion of shipping and offshore oil extraction, the thawing of the permafrost threatens to destabilize buildings, roads, pipelines, and airports.[16] Communities and industrial facilities may need to be relocated. Transportation on ice roads and across tundra, as well as oil and gas extraction in terrestrial locations will be more difficult as the frozen periods of the year become shorter and less predictable.[17] The unstable ground even poses a serious risk to the safe operation of nuclear facilities, such as the Bilibino Nuclear Power Plant in northeastern Siberia.[18]

These changes in the Arctic have the potential to increase the risks in the rest of the world. As noted in earlier chapters, the thawing of the permafrost could accelerate the rise in global temperatures, and the melting of the Greenland ice-sheet could add significantly to global sea level rise.

Systemic risks at the international level

As part of the UK government's first national climate change risk assessment, a study[19] was commissioned to look into the 'indirect' risks of climate change to the UK: those which arose not from climate change impacts within the country's borders, such as flooding, but which affected the country indirectly as a result of its interactions with other countries.

The study reached a striking conclusion: 'Climate change impacts around the world multiply existing threats to the UK, and some of these could be an order of magnitude greater than threats from domestic climate impacts' (emphasis added). While the study only considered a scenario in which global emissions were aligned with the target of limiting global temperature increase to 2°C, it noted that higher emissions scenarios could lead to much more severe impacts, particularly over the longer term.

Most of the largest risks identified in that study fell into two categories: risks to global food security, and risks to national and international security. For this risk assessment, we considered those two categories of risk in some depth. The next two sections summarise our findings.

Endnotes

1. Helbing, D. (2010). 'Systemic Risks in Society and Economics'. Paper prepared for IRGC Workshop on Emerging Risks, December 2009. Available at http://irgc.org/IMG/pdf/ Systemic_Risks_Helbing2.pdf .
2. Helbing, D. (2010). Page 2
3. Nobre, C.A., J. A. Marengo, M. E. Seluchi, A. Cuartas, L. M. Alves, H. Camargo (2015). 'The Record Drought and Water Crisis of 2014 in Southeastern Brazil.' Submitted to Bull. Amer. Met. Soc., 2015
4. For more details on the underlying climatic patterns and similar droughts, see Cavalcanti IFA, Kouksy VE (2001) 'Drought in Brazil during summer and fall of 2001 and associated circulation features', Climanalise, 1: 1-10 (available from: http://climanalise.cptec.inpe.br/~rclimanl/revista/pdf/criseing.pdf); DAEE (2013) Macrometrópole. 'Sumario Executivo-Plano Diretor de Aproveitamento de Recursos Hídricos para a Macrometrópole Paulista'. Departamento de Aguas e Energia Elétrica (DAEE). Secretaria de Planejamento e Desenvolvimento Regional, Secretaria do Meio Ambiente, Secretaria de Saneamento e Recursos Hídricos. Governo do Estado de São Paulo, São Paulo, Brasil, pp. 44; and Obregón, G. O., J. A Marengo, C. A. Nobre (2014), 'Rainfall and climate variability: long-term trends in the Metropolitan Area of São Paulo in the 20th century', Climate Research, 61: 93–107, 2014, doi: 10.3354/cr01241
5. According to the Centre for Food Storage and Market Distribution of the State of São Paulo (CEAGESP), the Brazilian Citrus Association, the Cereal Stock Market of São Paulo and the Brazilian Union of Sugar Cane Producers (UNICA).
6. According to INPE (www.inpe.br)
7. Electric Energy Commercialization Chamber of Brazil
8. Munich Re (2015) Natural catastrophes 2014. Analyses, assessments, positions. TOPICS-GEO 2014. Munich, Germany. 67 pp.
9. Overland, J., Hanna, E., Hansses-Bauer, I., Kim, S.-J., Walsh,J, Wang, M., Bhatt, U.S. (2014) 'Air Temperature', Arctic Report Card: Update for 2014, available at http://www.arctic.noaa.gov/reportcard/air_temperature.html
10. According to the Finnish Meteorologial Institute
11. See page 9 of IPCC (2013). 'Summary for Policymakers'. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. and Larsen, J.N., O.A. Anisimov, A. Constable, A.B. Hollowed, N. Maynard, P. Prestrud, T.D. Prowse, and J.M.R. Stone (2014). 'Polar regions'. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1567-1612.
12. Arctic Council (2013). Arctic Resilience Interim Report 2013. Stockholm Environment Institute and Stockholm Resilience Centre, Stockholm.
13. Helbing, D. (2010). 'Systemic Risks in Society and Economics' Paper prepared for IRGC Workshop on Emerging Risks, December, 2009, http://irgc.org/IMG/pdf/ Systemic_Risks_Helbing2.pdf
14. Feodoroff, P and Mustonen, T. Näätämö and Ponoi River Collaborative Management Plan. Kontiolahti: Snowchange Cooperative, 2013.
15. Arctic Council (2005). Arctic Climate Impact Assessment. Cambridge University Press, Cambridge. p. 6
16. Arctic Council (2005). p. 6
17. Helbing, D. (2009)
18. Bellona 2015a. Glitching safety system at Russia's aged Bilibino NPP causes emergency reactor shutdown http://bellona.org/news/nuclear-issues/nuclear-issues-in-ex-soviet-republics/2010-11-glitching-safety-system-at-russias-aged-bilibino-npp-causes-emergency-reactor-shutdown. Cited 13th April, 2015.
19. PwC (2013). International threats and opportunities of climate change for the UK http://www.pwc.co.uk/sustainability-climate-change/publications/international-threats-and-opportunities-of-climate-change-to-the-uk.jhtml

Climate change risks to global food security

To better understand the systemic risks of climate change to global food security, the UK Foreign and Commonwealth Office and the UK Government Science and Innovation Network jointly commissioned the UK's Global Food Security programme to bring together a cross-disciplinary task-force of academics, industry and policy experts from the UK and US to make an assessment. The task-force considered the risks of extreme weather to the global food system in the current climate, and how these risks have already increased and could increase further due to climate change. The task-force's full report *Extreme weather and resilience of the global food system*, which includes recommendations for how these risks can be managed and reduced, can be found at http://www.foodsecurity.ac.uk/assets/pdfs/extreme-weather-resilience-of-global-food-system.pdf.[1]

The following section presents a summary of the report's risk assessment.

20 EXTREME WEATHER AND RESILIENCE OF THE GLOBAL FOOD SYSTEM

Prepared for the UK-US Taskforce on Extreme Weather and Global Food System Resilience

Lead Authors in alphabetical order (*=coordinating lead authors)

Rob Bailey*,[i] Tim G. Benton*,[ii] Andy Challinor,[iii] Joshua Elliott*,[iv] David Gustafson*,[v] Bradley Hiller,[vi] Aled Jones*,[vii] Chris Kent,[viii] Kirsty Lewis*,[ix] Theresa Meacham,[x] Mike Rivington,[xi] Richard Tiffin*[xii] & Donald J. Wuebbles.[xiii]

Food demand and supply and the impact of weather in a changing world

Demand for food, at a global level, is increasing faster than yields are growing, leading to increasing pressure on land.[2] By 2050, the FAO estimates that demand will increase over 60% above the current situation. Demand growth is driven by population and demographic change, and increasing global wealth. This, in turn, leads to greater per capita food demand, often associated with demand for more livestock produce. In 2007/8, a small weather-related production shock, coupled with historically low stock-to-use levels, led to rapid food price inflation, as measured by the FAO Food Price Index and associated with the main internationally traded grains.[3] This increase was compounded by some countries imposing barriers to local export, to ensure their own food security, leading to an FAO price spike of over 100%. A similar price spike occurred in 2010/11, partly influenced by weather in Eastern Europe and Russia.[4]

These spikes created a number of significant impacts around the world. In rich countries, where food is freely available, food price inflation was marked and the poorest suffered, resulting in people trading down on food quality or quantity, and in the process spending significantly more. In poorer countries, especially those with fragile governance, rapid food price inflation undermined civil order, and, in part was a spark for the Arab Spring and the consequences that have followed.[5] In 2012, the worst drought to hit the American Midwest for half a century triggered comparable spikes in international maize and soybean prices.

This sequence of price spikes, and their consequences, re-alerted the world to the need to focus on global food availability and the volatility in its supply. In 2012, Sir John Beddington, then UK Government Chief Science Advisor, commissioned a report on food system resilience from the UK's Food Research Partnership. That report concluded: *"The evidence is not available properly to describe with any certainty how*

i. Chatham House, UK.
ii. UK Global Food Security Programme. University of Leeds, UK.
iii. University of Leeds. UK.
iv. NASA Goddard Institute for Space Studies, Columbia University, USA.
v. ILSI Research Foundation, Washington, USA.
vi. Global Sustainability Institute, Anglia Ruskin University, UK.
vii. Global Sustainability Institute, Anglia Ruskin University, UK.
viii. Met Office, UK.
ix. Met Office, UK.
x. UK Global Food Security Programme.
xi. Met Office, UK.
xii. The James Hutton Institute, Aberdeen, Scotland, UK.
xiii. Department of Atmospheric Sciences, University of Illinois, USA.

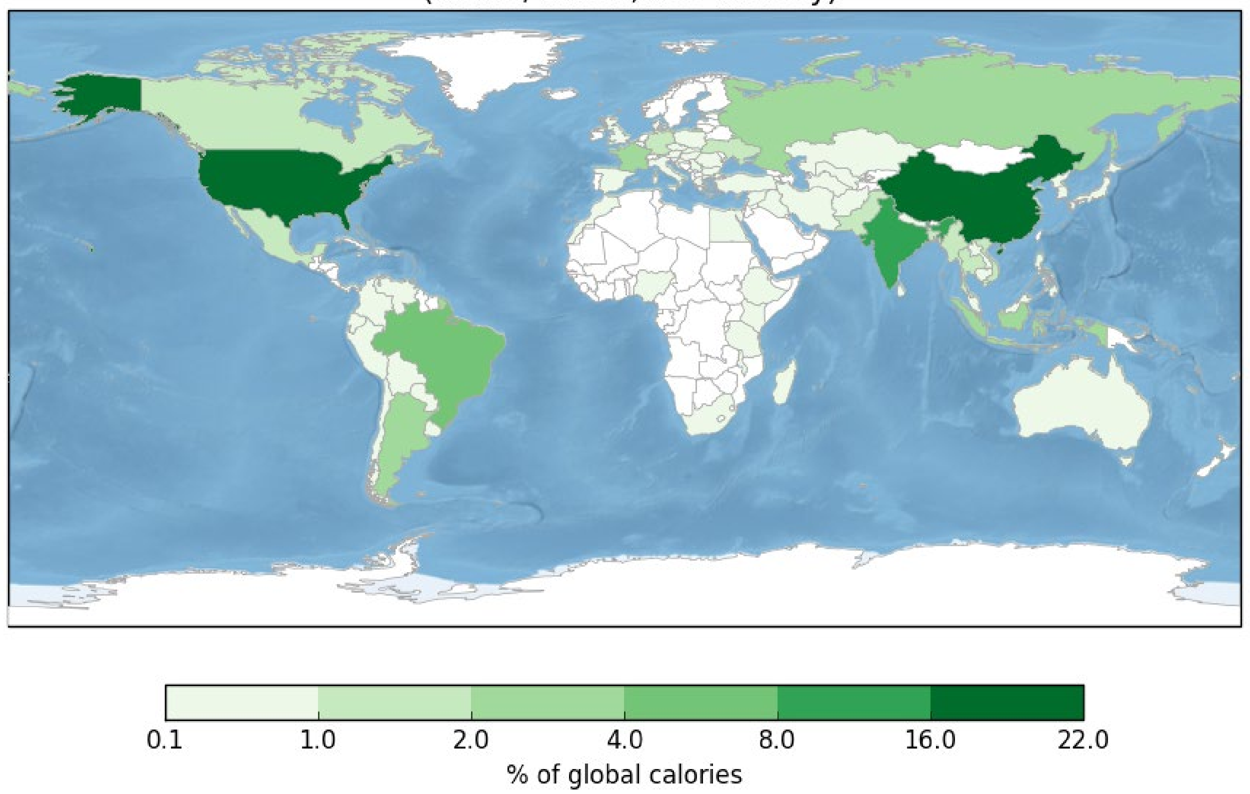
variable weather will impact on food production systems and worldwide trade, but our contention is that we need greater investigation of what they could be, with perhaps greater consideration being given to reasonable 'worst case scenarios'. … Given that the frequency of weather extremes is increasing, the potential for large impacts, and unprecedented ones, is growing."[6]

Here we summarise the outputs from the Taskforce into three areas: (i) how the changing weather may create shocks to the global food system, and, from this the development of a 'plausible' worst case scenario for a shock; (ii) plausible market and policy responses to the worst case scenario; and (iii) how the combination of scenario and responses may impact upon different societies, economies and the environment.

Weather and shocks to the global food system

Food production of the globally most important commodity crops (maize, soybean, wheat and rice) comes from a small number of major producing countries. The exposure of a large proportion of global production of the major crops is therefore concentrated in particular parts of the globe (Fig 1), and so extreme weather events in these regions have the largest impact on global food production. Simultaneous extreme weather events in two or more of these regions – creating a multiple bread basket failure – would represent a serious production shock, however understanding the covariance of extreme weather events in different production regions is currently under-researched. There is an urgent need to understand the driving dynamics of meteorological teleconnections, such as the El Niño – which may be becoming more extreme[7] - in order to quantify the likelihoods of coincident production shocks in major food-producing regions.

Figure 1: **Proportion of the total calories coming from the main four commodity crops per country.** Within each country, agricultural production is also typically concentrated (see fig S7a in Foley 2011 for a spatially resolved map). For example, the bulk of calories produced in the US come from soy and maize in the Midwest, in Brazil agricultural production, mainly soy, is concentrated inland from the SE coast; rice predominantly comes from the Indo-Gangetic plain, SE China and SE Asia; and wheat production is concentrated in NW Europe and around the Black Sea.



By examining production shocks in the recent past, we show that weather events, particularly drought, are a major driver of these shocks. Using the example of these past events we generated a set of scenarios, in the present or near-future, of weather-driven production shocks for each of the four crops. These we combined to create a plausible worst case scenario.[8]

Plausible scenario for extreme weather's impacts on crop production

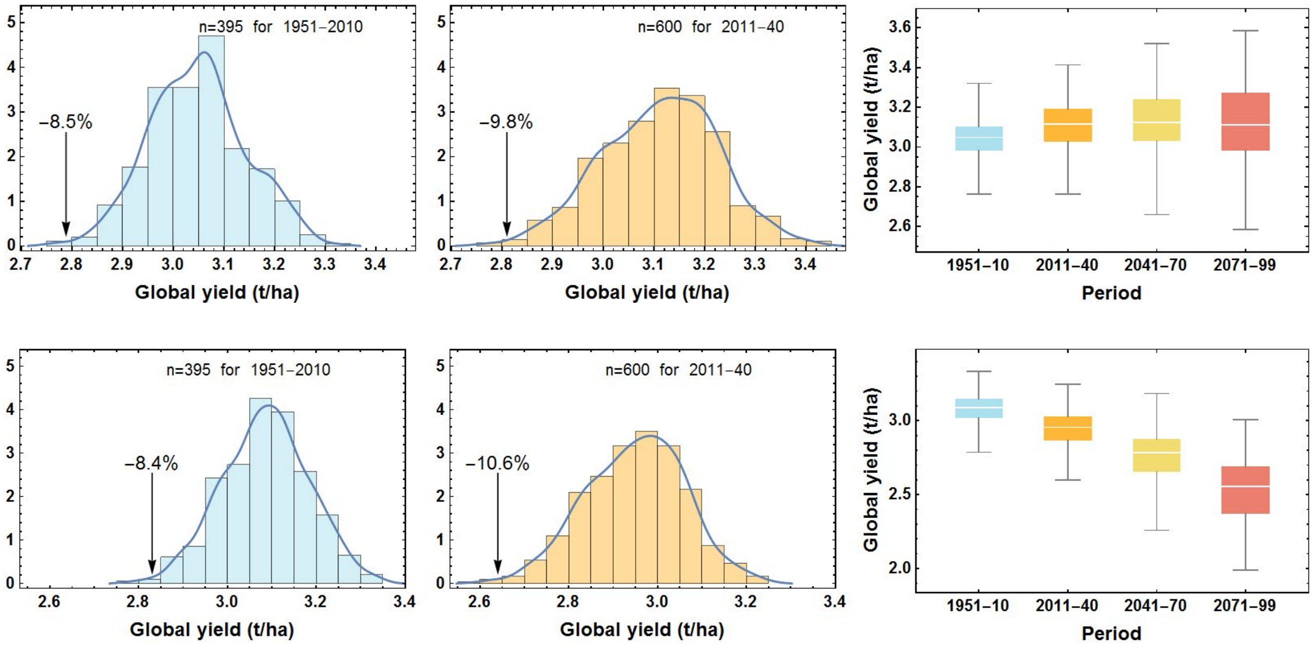
Analysis of the historical records indicated that in 1988/89 there was a significant drought-related impact on the yields of maize and soybean, with global production decreasing by 12% and 8.5% respectively. In 2002/3, drought impacted on wheat in Europe, Russia, India and China and rice in India, with global production of wheat decreasing by 6%, and of rice by 4%. Our plausible worst case scenario is that the two patterns of weather - that resulted in maize and soy, and wheat and rice being significantly affected - occur simultaneously. Without further work we cannot quantify the risk of this scenario, but we consider that a significant impact on all four crops of these magnitudes is plausible.

Changing profiles of risks over time: a first analysis

Through the use of climate models coupled to crop models, we can explore the changing risk of major shocks to the food system. To gauge whether we should be concerned about changing risks, we undertook an initial exploration using an ensemble of agriculture and climate impact models.[9] In terms of global calorie-weighted yields of maize, soy, wheat and rice produced, the ensemble produces a distribution of yields in response to modelled weather (shown in Fig 2 as histograms for 'historical' and 'near-term' future, and as box plots for 4 time periods). Comparing the histograms, there are changes in the shape of the distribution in future relative to the last decades: they 'flatten out'. This change in shape represents a significant increase in variance between the modelled historical and the near term future, and this increasing variability continues to increase throughout the century (Fig 2, top right hand panel).

This ensemble analysis suggests that what we would call an extreme food production shock in the late 20th century will become more common in the future (Fig 2). These data indicate that a 1-in-200 year event for the climate in the late 20^{th} century equates to a loss of approximately 8.5% (Fig 2 top), and over the next decades (2011-2040), a 1-in-200 year event is about 15% larger in magnitude and equivalent to the loss of 9.8% of calorie production. Furthermore, according to the ensemble, an event that we would have called 1-in-100 years over the period 1951-2010 may become as frequent as a 1-in-30 year event before the middle of the century.

Figure 2: **Model-based distributions of global calorie-weighted yield of maize, soy, wheat, and rice for the historical (1951-2010) and near-future (2011-2040) period** with (top row) and without (bottom row) the effects of fertilization from increasing atmospheric CO_2 included. The estimated magnitude of a 1-in-200 year event in each period is indicated by arrows on the histograms. The box plots summarise the distributions and show the likely increasing variability continuing throughout the century.



The analysis shown in the top row of Fig 2, assumes full effectiveness of CO_2 fertilization. Recently questions have been raised about the magnitude of this beneficial effect.[10] If we assume instead that there is no CO_2 fertilization at this large scale, we find similar but even more severe effects in later decades (Fig 2 bottom): a 1-in-200 year event in the near-term future is ~25% greater magnitude and the extreme left tail indicates the potential for historically unprecedented events. Without CO_2 effects, a historically 1-in-100 year event is estimated to occur more than once every 10 years by the second half of the 21st century.

These results are a preliminary analysis and are limited by the availability of high-resolution global climate model runs. Significant work is needed to reduce the uncertainty and better understand the way extreme weather may change. Nonetheless, the indications are clear that the global food system is facing increasing risks due to more frequent extreme weather.

Policy and market responses to weather-influenced production shocks

Global food trade has increased in recent years, bringing well understood benefits. Trade allows countries with limited productive potential to meet domestic demand; it facilitates specialisation and efficiency; and it generally increases resilience by smoothing local disruptions. However, not all disruptions are equal. As Section 3 highlighted, the system is not robust to a shock in one or more major production regions, pointing to inherent systemic risk in the geographical concentration of global food production.

As noted by May (regarding financial and ecosystem networks, but similarly applies to the global food network which shares some network properties) there is a complex interplay between robustness and vulnerability. Greater interconnectedness reduces countries' vulnerability[11] to local production shocks, but may increase vulnerability to shocks in distant breadbasket regions. It also means the food system is more vulnerable to a sudden reversal in connectivity, for example due to an outbreak of trade restrictions. A recent study examining the evolution of trade networks over the period 1992-2009 concluded:

> *"…the global food system does exhibit characteristics consistent with a fragile one that is vulnerable to self-propagating disruptions. That is, in a setting where countries are increasingly interconnected and more food is traded globally over the [last two decades], a significant majority of countries are either dependent on imports for their staple food supply or would look to imports to meet any supply shortfalls.[12]"*

In essence, through deeper trade food importing countries have reduced costs and vulnerability to localized production shocks, but at the expense of increased exposure to systemic risks such as a shock in a major production hub or a sudden deterioration in connectivity. Recent price spikes illustrate clearly the systemic risks associated with disruptions in major production regions and/or outbreaks of trade restrictions. Other factors thought to have amplified these price spikes include biofuel mandates, low ratios of stocks relative to demand and depreciation of the US dollar.[13]

Historically, following past production shocks, individual grain prices have more than doubled in a short space of time.[14] The food system's resilience to a weather-related shock can be defined by how much food prices, access and availability are affected by it. Resilience therefore depends on the magnitude of the physical shock, and on the policy and market responses that may amplify or buffer its effects as it propagates through the system.

In response to the last decade's food price spikes, many governments have developed strategic responses to better manage food production. However, other key problems pertaining to demand and trade responses remain unaddressed. If we are to avoid the worst impacts of future production shocks, we need to develop greater understanding of how responses may amplify, or mitigate, the price impact of production shocks. These responses are determined by the actions of agents mediated through markets. Governments are significant players in this, both through their direct influence on markets and their indirect influence on the other agents including farmers, food manufacturers and retailers, consumers and relief agencies.

To capture the potential market and government responses to food production shocks in wheat, maize, soybean and rice, we conducted a literature review, undertook a historical data analysis and completed ~50 interviews with experts from industry and policy around the world. Taking the plausible worst case production shocks set out in Box 1 as a starting point, we developed a detailed scenario of how weather and responses may interact on a global scale to produce a significant market shock. This scenario for 2016 involves export restrictions being put in place by major food producing countries, and large-scale purchases and consumption subsidies being used by major importers or highly import-dependent countries. The scenario is described in detail in the full version of this report [www.foodsecurity.ac.uk/assets/pdfs/extreme-weather-resilience-of-global-food-system.pdf], together with a scenario for 2026 that assumes a plausible deterioration in global food system resilience to have occurred in the intervening period.

Economic modelling of the price impacts of these scenarios has not been possible, and in any case, typical economic simulation models are poorly suited to modelling short-run prices during periods where markets are in disequilibrium and the magnitude of the shock is significantly 'out-of-sample'. Nevertheless, it is our judgement that the combined production shock and responses outlined below in the 2016 plausible worst case scenario could see the FAO food price index reach record highs, surpassing 250 compared to around 170 at the time of writing, with a likely trebling in the price of individual grains. By way of comparison, the index reached 226 in 2008 and 238 in 2011. All other things being equal, the 2026 scenario would be expected to result in an even higher price spike. Economic modelling of these scenarios would be one subject for subsequent research.

Factors that may amplify the impact of future production shocks in 2026

The consequences for global food security of any production shock depends not only on the responses of key actors, but critically also on the overall resilience of the food system and prevailing macroeconomic conditions. It is far from difficult to develop a plausible worst case scenario for 2026 in which system resilience is lowered over the next decade and macroeconomic conditions are unfavourable, making the global food system considerably more vulnerable to the same shocks.

Factors that would cumulatively reduce the resilience of the global food system to supply shocks and increase the likelihood of a price crisis include: low stock-to-use ratios; the reduced self-sufficiency of China; increasingly inelastic demand; the recovery of oil prices; cumulative underinvestment in infrastructure in key exporting regions; and the depreciation of the US dollar. Under this set of preconditions the production shocks considered here would almost certainly result in a more dramatic price response. Consequently, the responses of societies and governments would likely be more extreme. A larger number of countries would probably experience civil unrest. This would raise the stakes for governments, and result in more states intervening.

How would a plausible worst case scenario impact on societies, economies and the environment?

The preceding section set out a plausible worst case scenario in 2016, comprising a weather-related global production shock amplified through the responses of market actors that could plausibly result in a spike of the FAO food price index to over 250 in 2016. Based on this scenario, it is possible to consider the potential consequences for human populations and national economies. Information on possible country level impacts was collected through an expert interview process. An 'Interview Questionnaire' was developed and a panel of experts from academia/research institutions, government and the private sector were interviewed about the likely impacts in Brazil, China, Egypt, Ethiopia, Europe, India, Russia, Saudi Arabia, and the United States.

This analysis revealed the following broad expectations of how the plausible worst case scenario might unfold at the national and societal level. These are highly consistent with the impacts observed during the 2007/8 and 2010/11 price spikes.

- **The hardest impacts would be felt by import dependent developing countries,** particular in Sub-Saharan Africa. These countries would be expected to experience the most pronounced short-term deteriorations in poverty rates and nutrition security. At the economy level, impacts would likely include inflation, deteriorations in the balance of payments and budgetary pressures arising from higher food subsidies and social transfers.

- **Other import dependent countries could experience social unrest.** In particular, in the wake of the Arab Spring and ongoing instability in the region, the highly import dependent countries of the Middle East and North Africa region could be particularly vulnerable.

- **Impacts on major economies would be muted.** Consumers in large industrialised countries such as the US and EU, where food represents a small share of household expenditures, would be relatively unaffected.[15] The crop sectors of these economies, and other major agricultural producers, would likely benefit from higher prices, though other sectors could suffer. Poor food consumers in China would likely be relatively unaffected due to government intervention to buffer these households from food price inflation through the use of strategic reserves and price controls.

- **The supply response may have negative consequences in the longer term.** In response to the price spike, agricultural output would likely increase through a combination of extensification and intensification. In the short-term, this would increase supply and help stocks to recover, facilitating a decline in food prices. However, if extensification occurred at the expense of high carbon value and/or high biodiversity value land such as forest, this could have long-term environmental costs. Similarly, unsustainable intensification could degrade soils, deplete freshwater supplies and increase greenhouse gas emissions and eutrophication. The risk of unsustainable production responses is likely to be higher in the event of a dramatic price spike, with potential long-term consequences for the resilience of food production.

Conclusion

We have argued that the risk of a serious weather-related shock to global food production appears to be increasing rapidly due to climate change. Such an event could have serious implications for the stability of global grain markets and human security in vulnerable countries. In our full report, we set out five broad areas where action can begin to be taken in order to address this.[16] First, and perhaps foremost, is to better understand the risks. In particular, we need to better understand the evolving risk of weather-related shocks. In addition, there is also a need to better understand the ways a shock propagates through the trade network, and the immediate actions that can mitigate its effects. Finally, there are strategic actions that can be taken to create structural changes that build the resilience of the global and local food systems.

Endnotes

1. See also http://www.foodsecurity.ac.uk/assets/pdfs/climate-and-global-crop-production-shocks.pdf, http://www.foodsecurity.ac.uk/assets/pdfs/review-of-responses-to-food-production-shocks.pdf and http://www.foodsecurity.ac.uk/assets/pdfs/country-impacts-of-global-grain-production-shocks.pdf.
2. Bajzelj, B.et al. (2014). 'Importance of food-demand management for climate mitigation'. Nature Clim. Change, 4, 924-929.
3. Global Food Security (2014). 'Food price spikes and global markets'. Insight 3, pp. 1-3 http://www.foodsecurity.ac.uk/assets/pdfs/1404-gfs-insight-food-price-spikes.pdf
4. Coulibaly, A.L. (2013) The Food Price Increase of 2010–2011: Causes and Impacts Background Paper No. 2013-02-E. Library of Parliament. http://www.parl.gc.ca/Content/LOP/ResearchPublications/2013-02-e.htm
5. Lagi, M., Bertrand, K.Z., and Bar-Yam, Y. (2011). 'The food crises and political instability in North Africa and the Middle East.' arXiv preprint arXiv:1108.2455; Bellemare, M. F. (2015). 'Rising Food Prices, Food Price Volatility, and Social Unrest'. Am. J. Agricultural Economics, 97, 1-21; Natalini, D.,,et al.(2015) , 'Quantitative assessment of approaches to measuring likelihood of food riots in countries', Sustainability, 7 (4), 4360-4385
6. Benton, T. et al. (2012). Sever weather and UK Food Chain Resilience: Detailed appendix to synthesis report. http://www.foodsecurity.ac.uk/assets/pdfs/frp-severe-weather-uk-food-chain-resilience.pdf
7. Cai, W., et al. (2014). 'Increasing frequency of extreme El Nino events due to greenhouse warming'. Nature Clim. Change, 4, 111-116.
8. The global production loss estimated from the historical and simulated anomalies using the Global Gridded Crop Model Intercomparison (GGCMI) data for the four crops in 1988/9 and 2002/3.
9. The AgMIP/ISI-MIP model ensemble https://www.agmip.org/ag-grid/ggcmi/
10. Foley, J. A. et al. (2011). 'Solutions for a cultivated planet'. Nature, 478, 337-342.
11. O'Leary, G. J., et al. (2015). 'Response of wheat growth, grain yield and water use to elevated CO_2 under a Free-Air CO_2 Enrichment (FACE) experiment and modelling in a semi-arid environment'. Global Change Biology. doi: 10.1111/gcb.12830; Feng, Z., Rütting, T., Pleijel, H., Wallin, G., Reich, P.B., Kammann, C.I., Newton, P.C.D., Kobayashi, K., Luo, Y., Uddling, J., 2015. Constraints to nitrogen acquisition of terrestrial plants under elevated CO_2. Global Change Biol. (in press); Myers, S.S., Zanobetti, A., Kloog, I., Huybers, P., Leakey, A.D., Bloom, A.J., Carlisle, E., Dietterich, L.H., Fitzgerald, G., Hasegawa, T., 2014. Increasing CO_2 threatens human nutrition. Nature 510, 139-142.
12. May, R.M., 2013. Networks and webs in ecosystems and financial systems. Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences 371, 20120376.
13. World commodity prices are priced in dollars. Depreciation of the dollar leads to cheaper prices in other currencies. This leads to either reduction in supply or an increase in demand, which then drives up world prices.
14. Page 11 in Puma, M. J. et al. (2015). Assessing the evolving fragility of the global food system. Environmental Research Letters,10(2), 024007.
15. Charlebois, P. and Hamann, N. (2010) The consequences of a strong depreciation of the USD on agricultural markets Catalogue A38-4/21-2010E-PDF Project 10-055-r http://www.agr.gc.ca/pol/index_e.php
16. This is on average. Analysis of UK purchases following the 2007/8 food price spike show a complex pattern of changes in response to food price increases: as prices increased UK households bought 4.2% less. They also traded down to save money, by buying cheaper alternatives. Nonetheless, trading down didn't compensate prices rises and overall the food bill for an average family rose and was 12% more in 2011 than 2007. The poorest spent 17% more in 2011 compared to 2007, so their relative food bill increased by 40% more than average (https://www.gov.uk/government/publications/family-food-2011).
17. Global Food Security (2012). Global Food Systems and UK Food Imports: Resilience, Safety and Security. Available at http://www.foodsecurity.ac.uk/assets/pdfs/gfs-and-uk-food-imports.pdf.

21 CLIMATE CHANGE RISKS TO NATIONAL AND INTERNATIONAL SECURITY

Contributors to this section: **Vice Admiral Pradeep Chauhan (Retd)**,[i] **Vice Admiral Lee Gunn (Retd)**,[ii] **Major General A N M Muniruzzaman (Retd)**,[iii] **Professor Shi Yinhong**,[iv] **Sarang Shidore**,[v] **Dr Arunabha Ghosh**,[vi] **Catherine Trentacoste**,[vii] **ED McGrady**,[viii] **Francesco Femia**,[ix] **Caitlin E. Werrell**,[x] **Nadia Schweimler.**[xi]

The security risks of climate change may be the hardest of all climate risks to assess, because they involve the longest chains of causation or influence, and the most unpredictable factors. However, since they may be the biggest risks of all,[1] assessing them to the fullest extent possible is essential.

There is potential for confusion and underestimation of risk if assessments of climate security risks do not make clear the degree of climate change they are considering. A focus on risks in the current climate may well be enough to inform policy on adaptation and resilience, but to inform decisions with long-term implications (such as those relating to global emissions), a longer-term view is also necessary. Here we deliberately make clear distinctions wherever possible between risks in the present climate, risks in the future under low degrees of climate change, and risks in the future under high degrees of climate change.

Climate change risks to security in the present

A growing body of credible, empirical evidence has emerged over the past decade to show that the climate change that has occurred thus far – involving an increase of 0.8°C in global average temperatures – is already influencing dynamics associated with human, sub-national, national and international security. This evidence does not generally attempt to pinpoint precise causal relationships, but instead considers how climate change may have altered probabilities and interacted with other factors to increase the risks. Here we give three examples.

Drought, displacement and conflict in Syria

The Middle East, North Africa and Mediterranean region has experienced a drying trend over the last few decades, with a notable decline in winter precipitation. Climate change is thought to have played a significant role in this trend, as was forecast by previous climate modelling,[2] and to have made the extreme drought suffered by Syria between 2007 and 2011 some two to three times more likely.[3] During the drought, crop failure and the loss of livestock were severe and widespread. This contributed to a mass internal displacement of farmers and herders – around two million people – many of whom fled to urban areas which were already stressed with Iraqi and Palestinian refugees.[4] By 2009, more than 800,000 Syrians had lost their entire livelihood as a result of the droughts; by 2011, around 1 million were extremely food insecure, and 2-3 million had been driven into extreme poverty.[5] While many other factors were important in driving the political unrest and conflict that followed, it is difficult to imagine that this widespread impoverishment and large-scale displacement did not play a role.

i. Vice Admiral Pradeep Chauhan, AVSM & Bar, VSM, I.N. (Retd), Former Commandant of Indian Navy, and Assistant Chief of Naval Staff, Foreign Cooperation, Strategic Threats and Transformation
ii. Vice-Admiral Lee F Gunn, US Navy (Retd.) Former Inspector General of the Department of the Navy (Navy and Marine Corps), formerly Commander of Expeditionary Strike Group Three, and most recently President of the Institute for Public Research at CNA
iii. Major General A N M Muniruzzaman, Chairman, Global Military Advisory Council on Climate Change, President, Bangladesh Institute of Peace and Security Studies
iv. Professor Shi Yinhong, Professor of International Relations, Chairman of the Academic Committee of the School of International Studies, Director of the Centre on American Studies, Renmin University of China
v. Sarang Shidore, Visiting Scholar, University of Texas at Austin, formerly co-leader of strategic futures project at the Institute for Defense Studies and Analyses, New Delhi
vi. CEO, Council on Energy, Environment and Water
vii. Catherine Trentacoste, Research Scientist, CNA Corporation
viii. Ed McGrady, Director of Gaming, CNA Corporation
ix. Francesco Femia, Co-Founder and Director, The Center for Climate and Security
x. Caitlin E. Werrell, Co-Founder and Director, The Center for Climate and Security
xi. Nadia Schweimler, Climate and Development Knowledge Network, PwC

Heat waves, food price spikes, and civil unrest

In the summer of 2010, Russia suffered an extreme heat wave. Climate change is estimated to have made this event approximately three times more likely to occur than it would have been otherwise.[6] The heat wave combined with and contributed to drought and fire, and reduced Russia's wheat production that year by more than 30%.[7] At the same time, related droughts affected wheat harvests in Ukraine and China. Reduced production, protectionist measures, commodity speculation, and large-scale purchases on the global market all contributed to a more than doubling of the global wheat price in the second half of 2010.[8, 9] In highly import-dependent countries such as Egypt, the price of wheat rose by 300% in late 2010 and early 2011.[10]

The top nine wheat-importing countries in the world, on a per capita basis, are all in the Middle East and North Africa. Seven of these countries – Libya, Jordan, Algeria, Tunisia, Yemen, Egypt and Iraq – are ranked lower than 'very high' on the Human Development Index, and spend between 35% and 45% of their average household income on food. All seven experienced political protests resulting in civilian deaths in 2011.[11] In many of these countries, food prices are recognized to have been one of the factors that led to the unrest – notably in Tunisia, Jordan and Yemen, where demonstrators waved baguettes on the streets.[12] In Egypt, although urban protests primarily focused on other social and economic concerns, bread protests occurred in rural areas across the country in parallel to the events in Tahrir Square, and may have broadened the appeal of the revolution to rural communities.[13]

Clearly, climate change did not on its own cause any of these events. But it appears to have played a role, combining with other stresses and weaknesses to destabilize environmental, economic, social and political systems.

Climate variability, change, and conflict

Evidence of the influence of climate change on sub-national conflict in Africa has materialized over the past five years. Across the continent, rainfall variability has been found to affect 'both large-scale and smaller-scale instances of political conflict'.[14] A strong correlation has been detected between climate change, resource stress and range wars among pastoralists in East Africa.[15]

Recent research has investigated climate change and conflict across wider ranges of temporal and geographical scales, and found evidence of similar relationships.[16] One evaluation of sixty primary studies and forty-five conflict data sets found that the likelihood of violence at a number of levels, from interpersonal to international, increases significantly with climatological changes.[17] These studies have deliberately excluded consideration of mitigating circumstances, such as governance and wealth, in order to attempt to detect a trend in the changing likelihood of conflict. This is a weakness, in terms of the practicality of the results. However, it is a strength in terms of identifying a statistically-significant correlation between climatic changes (particularly precipitation), and the likelihood of conflict, across time and space, and across a range of scales.

Climate change risks to security in the future

In the near term future, population and economic growth are expected to significantly increase pressure on resources. Global demand for food, water and energy is projected to increase by approximately 35%, 40% and 50% respectively, by 2030 as compared to 2012.[18] At the same time, climate change could negatively affect the availability of these resources. National security and intelligence assessments of several governments have recognised the potential for this confluence of trends to contribute to security risks.[19]

With regard to security risks in the long term, relatively little analysis is available. The IPCC found that: *"Much of the current literature on human security and climate change is informed by contemporary relationships and observation and hence is limited in analyzing the human security implications of rapid or severe climate change."* [20]

To support our assessment of how security risks could vary between low degrees of climate change in the near term, and potentially high degrees of climate change in the long term, we commissioned the CNA Corporation, experts in futures analysis and wargaming, to design and conduct a wargame and scenarios exercise. This was held in Delhi in March 2015, hosted by the Council on Energy, Environment and Water. The twenty-four participants included senior scientists, security experts, diplomats, and retired military personnel from countries including India, China, the US, the UK, Bangladesh, Germany, the Netherlands, and Finland. The game investigated the decisions made by participants as they played the roles of leaders of major countries and regions, aiming to further national economic and security interests in the context of a changing climate over the next half-century or more. The scenarios exercise consisted of round-table discussions to identify the most significant near-term and long-term security risks in a scenario where climate change progressed at a rate close to the upper end of what is currently assessed as the likely range.[21] Both exercises were conducted by four independent groups of participants operating in parallel. The assumptions used in both exercises were reviewed for reasonableness and plausibility by the Climate Change Science Institute of Oak Ridge National Laboratory.

Here we discuss some of the biggest security risks identified, grouping them by theme. Analysis from the wargame and scenarios exercise conducted for this assessment is presented together with some more detailed comments from individual participants, and with relevant findings from a few other published studies that have explicitly considered the security risks of high degrees of climate change. References note where other assessments have reached similar conclusions.

State failure

Our scenarios exercise found that in the near-term future, climate change would be most likely to increase the risks of state failure in states that are already highly water stressed or food insecure, at the same time as suffering from poverty, social tensions, and poor governance. We considered that countries in the Middle East and North Africa region may be at particular risk: most are already water-stressed, many of them to an extreme degree.[22] The large population increases projected for many countries in the region – in the range of 50% for Egypt, 70% for Syria, 90% for Yemen, and 130% for Iraq, between 2010 and 2050, will further decrease per capita water resources. At the same time, climate models predict a drying trend for the region. One study projects a reduction in streamflow of 10-30% in large parts of the region, and of 30-50% in the worst affected areas, with a global temperature rise of 2.7°C.[23]

We also considered that countries where a high proportion of the population relies on subsistence farming may be at particular risk of instability due to climate change impacts on agriculture. Sub-Saharan Africa already has the highest proportion of food insecure people in the world, with more than a quarter of the population undernourished in 2010-2012, and more than half in some areas.[24] Many of the countries in the region – more than 30 in the continent as a whole – are projected to double their populations by mid-century,[25] and for a significant number, this will reduce arable land per capita to below a threshold of extreme stress.[26] At the same time, land temperatures in Africa are projected to rise faster than the global land average, and it is thought very likely that climate change will reduce cereal crop productivity, with strong adverse effects on food security.[27] Clearly, economic development and adaptation to climate change will be critical, and the risks will be greatest where these efforts are less successful.

Climate change is likely to increase environmental stresses on many countries at the same time. A report by the German Advisory Council on Global Change suggested that this, in combination with the tendency of failed states to destabilize their neighbours, could lead to the emergence of 'failing sub-regions' in parts of the world where climate change impacts are particularly severe.[28] Vice-Admiral Chauhan (retd.) of the Indian Navy gives an example of how stresses affecting the countries of South Asia could interact with each other.

A perspective on climate change and the risk of state failure

Vice Admiral Pradeep Chauhan, AVSM & Bar, VSM, I.N. (Retd)

Nation-states are far from being inherently stable. Many have suffered near-continuous internal tensions throughout their histories, arising from ethno-religious differences and socio-economic inequalities. The extent to which the writ of nation states runs is often quite limited, both in terms of its robustness, and in terms of geography. Historically, the resilience of government structures in the face of unexpected and large-scale crises has frequently been found to be severely wanting. State failure is not a precisely defined term, but it may be characterised by: (a) an inability to provide security to the population resulting from failure to retain a monopoly on the legitimate use of force; (b) an inability to provide and equitably distribute essential goods and services; (c) a serious erosion of the power to make and enforce collective decisions; and (d) the involuntary movement of populations including refugees.

High degrees of climate change could increase the risks of state failure in countries that are economically underdeveloped, resource stressed, or already unstable for other reasons. In South Asia, drought in Afghanistan and Pakistan, and incessant flooding and loss of land to the sea in Bangladesh, could put those countries' governments under great stress, and precipitate large-scale migration into India. In India, this would combine with an internal population shift from rural to urban areas, further increasing demographic pressure in cities – many of the largest of which – including Kolkata, Chennai and Mumbai – are coastal, and will be increasingly vulnerable to flooding both from sea level rise and from more intense rainfall. At the same time, both the influx of internal and external migrants, and the increasing variability of the monsoon, could further destabilise the 'Red Corridor', a swathe of economic deprivation and misgovernance that cuts through almost all the eastern states of India, in which Marxist-Leninist rebels are waging a campaign of violence against the state. The temptation to solve this problem through military intervention could become overwhelming.

At the high degrees of climate change possible in the long-term future, participants in our scenarios exercise considered that there could even be risks to the political integrity of states that are currently considered developed and stable. These could arise from the combined effects of food and water insecurity, social stresses caused by inequality and large-scale internal migration, the increasing expense and difficulty of protecting coastal cities, and the breakdown of infrastructure systems subject to multiple stresses.[xii]

Terrorism

Participants in our exercise saw the risk of terrorism as closely linked to the risk of state failure. While terrorism has complex causes, the power vacuum left by a failing or collapsed state provides conditions in which terrorist groups can become established and grow stronger. Participants considered that the inequality of climate change impacts between countries, and the potential for large-scale displacement of people, could further increase the risk. Here Vice Admiral Lee Gunn (Retd.) describes how climate change could increase the appeal of terrorism, at the same time as terrorism itself is becoming more dangerous.

A perspective on climate change and terrorism

Vice-Admiral Lee Gunn, US Navy (Retd.) Former Inspector General of the Department of the Navy (Navy and Marine Corps), formerly Commander of Expeditionary Strike Group Three, and most recently President of the Institute for Public Research at CNA

No society, however prosperous overall it may be, appears to be entirely immune to terrorists' recruiting. Terrorism can arise when two essential conditions are met: the presence of an appealing, unifying, or disruptive idea, and the social disenfranchisement of a section of society. The more the members of a segment of society feel themselves to be economically, culturally, or politically disenfranchised or marginalised, and the more difficult or distasteful their circumstances, the more fertile their community may become for terrorists' recruiting.

Even in the current climate, some nations already struggle to provide for the basic needs of their populations (security, health, employment, freedom from want); while other nations have failed to do so entirely. As a result there are already marginalised populations where the appeal of terrorism is strong, and territories that are effectively ungoverned where terrorist groups are left to operate with little constraint. Climate change will disproportionately affect the countries that are already the weakest, and the people within them who are already the most vulnerable. It has the potential to significantly increase the ranks of disenfranchised populations within countries, as well as to increase the extent of ungoverned spaces.[29] At the same time, terrorism is becoming more dangerous as some of these groups take advantage of new technologies and globalisation, and we can expect this trend to continue.

xii. A similar conclusion was reached by the 'Age of Consequences' scenarios study undertaken by a group of scientists, security experts and historians in the US in 2007. This study suggested that in a 'severe' climate change scenario (defined by a temperature increase of 2.6°C by 2040), 'massive nonlinear events in the global environment give rise to massive nonlinear social events... The internal cohesion of nations will be under great stress, including in the United States'; and that in a 'catastrophic' scenario (5.6°C by 2100), 'The collapse and chaos associated with extreme climate change futures would destabilize virtually every aspect of modern life' and the range of problems could 'overwhelm the traditional instruments of national security (the military in particular) and other elements of state power and authority'.

Migration and displacement

There are many ways in which climate change could lead to migration and displacement, with attendant security risks, as described here by Major General A N M Muniruzzaman (Retd).

A perspective on climate change and security risks from migration and displacement

Major General A N M Muniruzzaman, ndc, psc (Retd), President of Bangladesh Institute of Peace and Security Studies, Chairman of Global Military Advisory Council on Climate Change

Historically, people have moved from place to place in search of a better life and to escape danger. Usually, their decision to migrate has a number of influences, and cannot be attributed to a single cause. In the coming century, climate change could emerge as an increasingly powerful influence. The ways in which this could happen include:

- Sea level rise, with attendant flooding and coastal erosion, is likely to displace populations from low-lying coastal areas, and small island states. Millions of people in Bangladesh could be displaced, and around 40 small island states could face partial or complete submergence.
- River flooding can displace people both directly, and indirectly through disruption of agricultural livelihoods. Flooding is projected to increase in many regions, but it could be a particular problem in South Asia due to the contribution of melting glaciers.
- Desertification and drought are both projected to increase with climate change. Both can be drivers of migration, especially of pastoral societies or those depending on rain-fed agriculture.
- Natural disasters tend to lead to short-term displacement, but persistent extreme events in a region can lead to migration. In future, this could include persistent dangerous heat extremes.

It has been speculated that the number of people displaced or migrating as a result of future climate change could run into the hundreds of millions,[30] but it is impossible to make an estimate with any confidence, and it will depend greatly on the rate and extent of climate change that is experienced. The security risks that could arise from large-scale migration have been widely recognized,[31, 32, 33, 34] and include:

- **Destabilized borders:** Migrants and refugees may be forcibly resisted by local populations or by governments. This can lead to conflict between groups, and potentially between states.
- **Conflict over resources:** Environmental migration has been found to be more likely to lead to conflict when the destination country is already resource stressed.[35] With climate change, this could often be the case, as countries within a region are affected in similar ways.
- **Ethnic and cultural conflict:** Migrants and displaced people often have to endure difficult living conditions and discrimination, which can lead to social division and tensions. Historically, conflict appears to have been more likely when migrants and destination country residents are from different ethnic groups, or when there is already distrust between their respective nations or social groups.[36]
- **Disease:** Displaced populations often lack appropriate sanitary and medical facilities. This can contribute to the spread of disease across borders.

All four groups of participants in our scenarios exercise identified migration – both within and between countries – as a significant security risk. Concerns were as much about the management of political and social tensions as about economic costs and pressure on resources. Participants from large countries were particularly concerned about how governance structures could cope, and social cohesion be maintained, in situations where the differing local severity of climate impacts led to large-scale internal migration. At the same time, it was felt that the pressure of increasing numbers of international migrants and refugees could result in a rise of xenophobia and nationalism. In the game, it was notable that increasing numbers of refugees contributed to several large countries becoming more isolationist in their foreign policies.

Studies that have considered migration under high degrees of climate change have judged that the complexity of causes seen at present could be reduced to a more simple equation. The UK Government's *Foresight* report[37] found that: 'some impacts of environmental change… may give rise to significant permanent displacement of whole populations as a result of existing settlements being, in effect, uninhabitable'. Similarly, a study cited by the IPCC argues that 'the most significant difference between the nature of human migration in response to 4°C of warming relative to 2°C would be to remove many people's ability to choose whether to stay or leave when confronted with environmental changes.'[38] In this context, the number of people forced to move could be of an order of magnitude greater than anything experienced in human history.[39]

As was noted in our scenarios exercise, if a high degree of climate change is reached, then by that time, much more will be known about the actual emissions path that the world has followed, about climate sensitivity, and about the impacts of climate change. It will then be fairly clear whether or not further climate change, with even more adverse consequences, is to be expected. The incentive for populations – and even states – to attempt to move to more favourable territory would then be correspondingly higher.

Humanitarian crises, nationalism, and global governance

Participants in our exercise considered it extremely likely that climate change would exacerbate humanitarian crises over the coming decades.[40] The greater uncertainty was around the extent to which the international community would have the capability and willingness to respond to these crises in the future. In the scenarios exercise, participants suggested that the multiple pressures could contribute to a shift towards nationalism, and away from values associated with human rights, democracy, and cooperative global governance.

Post-game analysis found that as climate conditions had worsened, and the number of regions requiring aid and humanitarian assistance had increased, in all four instances of the game at least one major developed country reduced its assistance so as to concentrate on solving its own internal problems, and in some instances a majority of countries did so. In such cases, countries only turned their gaze outward again when prompted by refugees or terrorism. Countries that persisted with an internationalist approach suffered an increasingly unsupportable burden.

A similar risk was identified by the German Advisory Council on Global Change, which argued that, given how difficult the international community finds dealing with a few failed states in the current climate, the consequences of high degrees of climate change could over-stretch conventional security policy, and pose a risk to the global governance system as a whole.[41]

Resource competition and inter-state conflict

We noted above how resource stress, intensified by climate change, could increase the risks of state failure. Here we consider whether the same stresses could be a factor in inter-state conflict. First, Sarang Shidore addresses the case of water stress.

A perspective on transboundary water resources and conflict risks

Sarang Shidore, Visiting Scholar, University of Texas at Austin, formerly co-leader of strategic futures project at the Institute for Defense Studies and Analyses, New Delhi

While many research studies have considered the links between climate change and sub-national conflict, relatively few have taken on the question of climate-influenced inter-state conflict. Those that have, have tended to focus primarily on transboundary water resources, drawing on a long history of interdependencies and disputes.[42] In general, there is little support for the hypothesis of 'water wars' - the idea that scarcity necessarily leads to increased armed warfare between states. In fact, a number of studies have dissected the many cooperative mechanisms that states have voluntarily put in place, even under fraught conditions. Some of these examples are the Indus Water Treaty between India and Pakistan, the Mekong River Commission, and treaties and consultations on the use of the Nile river in Africa.

Nevertheless, there is evidence that water scarcity and variability can increase political tensions between states sharing a common water resource, especially if their relations are poor due to other reasons, and can lead to diplomatic, trade, and other forms of non-military conflict.[43] Political tensions over water have arisen in South Asia with respect to the Indus, Ganges, and Brahmaputra rivers (India, Pakistan, Bangladesh, and China), in Central Asia with the Syr Darya river (Kyrgyzstan, Uzbekistan, and Kazakhstan), and in Africa with the Nile (Egypt, Ethiopia, and Sudan). Other potential sites for water scarcities enhancing latent interstate tensions include the Jordan river (Israel-Palestine and Jordan), the Tigris-Euphrates (Turkey, Syria and Iraq), and a number of rivers in the water-stressed regions of northern, eastern and southern sub-Saharan Africa such as the Kuito river (Namibia, Angola, and Botswana).

An important caveat to bear in mind is that most of the existing body of research relates to the current climate. The variabilities, scarcities, and (in some cases) surpluses induced by climate change in, for example, a 3°C world are likely to be much greater than any recorded in modern history, and could act as major destabilizing factors at a range well beyond the ambit of existing studies of past resource-conflict events.

Post-game analysis found that in all four games, meeting national requirements for resources including food, fuel and water became an increasingly high priority — in some cases rising above traditional national security priorities — as time went on. One action that was noticeably absent from the game was the decision to use military force to invade a region to gain control of the region's resources. This may have been related to the fact that climate change tended to have the most severe impact on the resources of countries that were already relatively weak in terms of both military and economic power, reinforcing inequality between countries.

The game was not resolved in enough detail to investigate the tensions that could arise over specific transboundary rivers; however, in the scenarios exercise it was considered to be a significant risk that over the long term, water stress in parts of the Middle East, Central Asia and South Asia could become so dire that the historical trend of water insecurity driving cooperation between conflicting parties could be broken. It was recognised that desalination could be an important technology, but its high energy cost could prove a constraint for some developing countries, especially for regions far from the coast.

Participants in the scenarios exercise highlighted the risks linked to the stability or otherwise of global food markets, as Professor Shi Yinhong describes here.

A perspective on global food security and conflict risks

Professor Shi Yinhong, **Professor of International Relations, Renmin University of China**

The severity of the impact of high degrees of climate change on food production is not well known; neither is our ability to adapt to it. In a plausible worst case scenario where production does not keep up with growing demand, food could become the single most sought-after resource globally. Global markets could be destabilised, with prices high and volatile. Large fluctuations in price, or constraints on availability, could contribute to state failure in highly import-dependent countries.

In developed, high-consuming countries, pressure for secure, affordable supply, together with a loss of confidence in the markets, would result in a high priority being placed on the security of imports. This could lead to competition for the leasing or acquisition of arable land in developing countries, with contracts being enforced, where necessary, with both soft and hard national power. The risk of conflict would be significant in situations where the developing countries themselves faced shortfalls. At the same time, the importance of overseas assets to food security would lead great powers to invest more in defending strategic trade routes, which could themselves become subject to military confrontation.

None of these events are inevitable. While history contains many examples of hardship leading to aggression, examples of the contrary may be found as well – particularly in Asian nations, where Buddhism and Daoism are widely practiced. It is possible that the hardship of future climate change could lead to greater international cooperation in addressing common problems, and a positive transformation of the global political culture. However, from today's perspective, few would have firm confidence in such an outcome.

Climate geo-engineering

In two of the four instances of the game, participants decided to invest in climate geoengineering (in the form of solar radiation management) in order to limit global temperature rise. While this was widely perceived as having significant risks of its own, participants were balancing these against the increasing risks of loss of governance, national isolation, and resource depletion (food, fuel, and water). Participants considered that security risks could arise from the fact that there was no recognised authority for decision-making on climate geoengineering, and no means of preventing unilateral action by a country, region, corporation, or even an individual.[44]

Conclusions

Participants in our exercise acknowledged the deep uncertainty involved in any attempt to consider how human society and civilization might develop even a few decades into the future. Technological development, and the future of governance at the national and global levels, were both identified as particularly important unknowns.

Certain areas of technology were identified that could have a direct bearing on some of the risks: rates of progress in desalination of water, breeding or modification of crops, and renewable energy with storage technologies would all be likely to affect relative levels of resource stress, and the risks that could arise from such stress. In addition, there were the 'unknown unknowns' of future technologies that have not yet been invented. The contribution of any technologies to mitigate the risks would depend not only on rates of progress, but also on the equity or otherwise of their availability for use. This would depend in turn on governance.

Governance would play a critical role in determining whether systems broke down or remained resilient under stress. Participants in our exercise felt that beyond the familiar distinctions between democracy and dictatorship, centralised or decentralised, nationalist or internationalist, there were possibilities for future models of governance to emerge which, like unknown technologies, have yet to be imagined. The relative importance of markets, militaries, religions, states, alliances, regional associations, and global structures could all change.

Despite the depth of these uncertainties, it was recognised that the human economy existed within the natural physical environment, and could not be separated from it. Climate change would subject many parts of that environment to intense pressure, and create stresses that would be difficult for any system of governance to manage. As levels of stress increased, so would the scale of the systems at risk – from city infrastructure, to state governments, to international systems of transport and trade. The risk of disruption was considered likely to be very significant even at low degrees of climate change, and likely to increase in a non-linear manner as climate change progressed to higher degrees, or at a faster rate.

Endnotes

1. As suggested by PwC (2013). International threats and opportunities of climate change for the UK http://www.pwc.co.uk/sustainability-climate-change/publications/international-threats-and-opportunities-of-climate-change-to-the-uk.jhtml
2. Hoerling et al. (2012), 'On the Increased Frequency of Mediterranean Drought' Journal of the American Meteorological Society – see also NOAA press release: http://www.noaanews.noaa.gov/stories2011/20111027_drought.html
3. Kelley, C.P., Mohtadi, Shahrzad M., Cane, M. A., Seager, R. and Kushnir,Y. (2015). 'Climate change in the Fertile Crescent and implications of the recent Syrian drought'. Proceedings of the National Academy of Sciences 11, pp. 3241 - 3246
4. Femia, F. and Werrell, C. (2012). 'Syria: Climate Change, Drought and Social Unrest'. The Center for Climate and Security. http://climateandsecurity.org/2012/02/29/syria-climate-change-drought-and-social-unrest/ ; Femia, F. and Werrell, C. (eds.) (2013). The Arab Spring and Climate Change. Center for American Progress, The Center for Climate and Security, Stimson. https://climateandsecurity.files.wordpress.com/2012/04/climatechangearabspring-ccs-cap-stimson.pdf ; Gleick, P. (2014) Water, Drought, Climate Change, and Conflict in Syria Weather, Climate and Society 6, 331 – 340, available at http://journals.ametsoc.org/doi/abs/10.1175/WCAS-D-13-00059.1
5. Femia, F. and Werrell, C. (eds.) (2013). pp25-27
6. Otto, F. E. L., N. Massey, G. J. vanOldenborgh, R. G. Jones, and M. R. Allen (2012), Reconciling two approaches to attribution of the 2010 Russian heat wave, Geophys. Res. Lett.,39, L04702, doi:10.1029/2011GL050422.
7. Femia, F. and Werrell, C. (eds.) (2013). p7

8. Porter, J.R., L. Xie, A.J. Challinor, K. Cochrane, S.M. Howden, M.M. Iqbal, D.B. Lobell, and M.I. Travasso (2014). 'Food security and food production systems'. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485-533.
9. Sternberg, T. (2011) 'Regional drought has a global impact'. Nature 472, 169. doi:10.1038/472169d
10. Femia, F. and Werrell, C. (eds.) (2013).
11. Femia, F. and Werrell, C. (eds.) (2013). pp12-13
12. Femia, F. and Werrell, C. (eds.) (2013). pp17-19
13. Mahr, K. (2011). 'Bread is life: food and protest in Europe'. Time. http://science.time.com/2011/01/31/bread-is-life-food-and-protest-in-egypt/
14. Hendrix, S. and Saleyhan, I. (2012) 'Climate change, rainfall, and social conflict in Africa'. Journal of Peace Research 49, pp. 35-50
15. Butler, C.K and Gates, S. (2012). 'African range wars: climate, conflict, and property rights'. Journal of Peace Research 49, pp. 23-34.
16. Hsiang, S. M. and Burke, M. (2013). 'Climate, conflict, and social stability: what does the evidence say?' Climatic Change 123, pp. 39-55
17. Hsiang, S. M., Burke, M. and Miguel, E. (2013). 'Quantifying the influence of climate on human conflict'. Science 341, pp. 1212 - 1226
18. National Intelligence Council (2012). Global Trends 2030: Alternative Worlds. https://globaltrends2030.files.wordpress.com/2012/11/global-trends-2030-november2012.pdf
19. For example: The U.S. Department of Defense's Quadrennial Defense Reviews in 2010 and 2014 identify climate change as an "accelerant of instability" and a "threat multiplier," respectively (http://www.defense.gov/QDR/QDR%20as%20of%2029JAN10%201600.pdf and http://www.defense.gov/pubs/2014_Quadrennial_Defense_Review.pdf). The UK's 2010 Strategic Defense and Security Review (HM Government (2010). Securing Britain in an Age of Uncertainty: The Strategic Defence and Security Review https://www.sis.gov.uk/media/pdfs/strategic-defence.pdf) acknowledged the security risks of a changing climate, specifically tasking the FCO with addressing the issue. Australia's 2013 National Security Strategy (Australian Government (2013). Strong and Secure: A Strategy for Australia's National Security http://apo.org.au/files/Resource/dpmc_nationalsecuritystrategy_jan2013.pdf) stated that: "The more severe effects of climate change, in particular the increase in frequency and severity of natural disasters, compounded by competition over scarce natural resources, may contribute to instability and tension around the globe, especially in fragile states."
20. IPCC (2014). 'Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects.' Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 779
21. The aim being to assess something close to a 'plausible worst case' rather than the most likely case.
22. Based on data from UN Statistics Division (2011) – Environmental Indicators: Inland Water Resources. http://unstats.un.org/unsd/ENVIRONMENT/waterresources.htm The thresholds of 1,700 and 1000 m3 of freshwater resources per capita per year are often used to indicate water stress and water scarcity respectively, as proposed by Malin Falkenmark in 1989. They are based on estimated minimum requirements for household, agricultural and industrial use.
23. See Figure 3-4, IPCC, (2014). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.
24. See section 7.1.2 of Porter, J.R., L. Xie, A.J. Challinor, K. Cochrane, S.M. Howden, M.M. Iqbal, D.B. Lobell, and M.I. Travasso (2014). 'Food security and food production systems. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485-533.
25. United Nations, Department of Economic and Social Affairs, Population Division (2013). World Population Prospects: The 2012 Revision. Available at http://esa.un.org/wpp/Documentation/publications.htm
26. Combing population data and projections from UN Population Division – World Population Prospects, the 2012 Revision, with arable land per capita data from the Food and Agriculture Organization as shown at http://data.worldbank.org/indicator/AG.LND.ARBL.HA.PC, and using 0.07 Ha per capita as the definition of extreme land stress, as used by UN organizations – see http://www.un.org/en/events/environmentconflictday/pdf/GN_Renewable_Consultation.pdf and http://www.fao.org/fileadmin/templates/solaw/files/thematic_reports/TR_02_light.pdf
27. See Executive Summary of Niang, I., O.C. Ruppel, M.A. Abdrabo, A. Essel, C. Lennard, J. Padgham, and P. Urquhart, (2014). 'Africa'. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199-1265.

28. German Advisory Council on Global Change (2007). World in transition: climate change as a security risk. http://www.wbgu.de/fileadmin/templates/dateien/veroeffentlichungen/hauptgutachten/jg2007/wbgu_jg2007_kurz_engl.pdf
29. US Department of Defense - Quadrennial Defense Review 2014 – as cited in CNA Military Advisory Board (2014). National Security and the Accelerating Risks of Climate Change, p2 https://www.cna.org/sites/default/files/MAB_2014.pdf
30. Myers, N. (2005). "Environmental Refugees: An Emergent Security Issue." Presented at the 13th Economic Forum, Prague, 23-27 May; and Christian Aid (2007). Human tide: the real migration crisis. London: Christian Aid.
31. Population Action International (2010). Climate Change, Migration, and Population Growth. http://pai.org/wp-content/uploads/2012/01/climatemigration.pdf
32. The CNA Corporation (2007). National Security and the Threat of Climate Change. Alexandria, Virginia: The CNA Corporation.
33. High Representative and the European Commission (HREC) (2008). Climate Change and International Security, Paper to the European Council, S113/08, p. 4.
34. Guterres, A. (2009). 'Climate change, natural disasters and human displacement: a UNHCR perspective.' The United Nations Refugee Agency.
35. Reuveny, R. (2007). 'Climate Change-Induced Migration and Violent Conflict'. Political Geography 26, 656-673.
36. Reuveny, R. (2007). 'Climate Change-Induced Migration and Violent Conflict'. Political Geography 26, 656-673.
37. Government Office for Science (2011). Migration and Global Environmental Chaneg: Future Challenges and Opportunities. The Government Office for Science, London. Retrieved from http://www.bis.gov.uk/assets/foresight/docs/migration/11-1116-migration-and-global-environmental-change.pdf
38. Gemenne, F. (2011). 'Why the numbers don't add up: a review of estimates and predictions of people displaced by environmental changes'. Global Environmental Change 21, S41-S49. Cited in Smith, K.R., A. Woodward, D. Campbell-Lendrum, D.D. Chadee, Y. Honda, Q. Liu, J.M. Olwoch, B. Revich, and R. Sauerborn (2014). 'Human health: impacts, adaptation, and co-benefits'. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 709-754.
39. Campbell, K. M., Gulledge, J. McNeill, J. R., Podesta, J. Ogden, P., Fuerth, L. Woolsey, J., Lennon, A. T. J., Smith, J., Weitz, R., Mix, D. (2007). The Age of Consequences: The Foreign Policy and National Security Implications of Global Climate Change. Center for Strategic and International Studies, Center for a New American Security. http://csis.org/files/media/csis/pubs/071105_ageofconsequences.pdf
40. Ministry of Defence (2014). Strategic Trends Programme: Global Strategic Trends – Out to 2045. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/348164/20140821_DCDC_GST_5_Web_Secured.pdf
41. German Advisory Council on Global Change (2007). World in transition: climate change as a security risk. http://www.wbgu.de/fileadmin/templates/dateien/veroeffentlichungen/hauptgutachten/jg2007/wbgu_jg2007_kurz_engl.pdf
42. Bernauer, T. and Kalbhenn, A. (2010). 'The Politics of International Freshwater Resources,' in Denemark, R. A. (ed.) International Studies Encyclopedia (Hoboken, NJ: Wiley-Blackwell), 5800-5821.
43. Devlin, C. and Hendrix, C. S. (2014). 'Trends and Triggers Redux: Climate Change, Rainfall, and Interstate Conflict'. Political Geography 43, 27-39. Also see Bernauer, T. and Siegried, T. (2012). 'Climate Change and International Water Conflict in Central Asia'. Journal of Peace Research 49, 227-239.
44. Ghosh, A. (2014) "Environmental Institutions, International Research Programmes, and Lessons for Geoengineering Research". Geoengineering Our Climate Working Paper, 25 February. Available at: http://geoengineeringourclimate.com/2014/02/25/environmental-institutions-international-research-programmes-and-lessons-for-geoengineering-research-working-paper/.

RISK ASSESSMENT PART 4:

VALUE

RISK ASSESSMENT PART 4:

VALUE

As we noted at the beginning, risk is as the effect of uncertainty on our objectives, or on the things that we value. The previous three parts of this risk assessment have described some of the effects of climate change. It remains to discuss how we value those effects – how much we care about them.

In this section, we start with economics, and consider what it can and cannot tell us about the value of the risks of climate change. Then we provide one person's perspective on the ethical issues at stake. Finally, for the sake of transparency, we give our own opinion.

22 ECONOMICS

The Stern Review is probably the most famous report on the economics of climate change. It is most widely cited for its conclusion that action on climate change would cost far less than inaction. The costs of action were estimated at some 1-2% of global GDP per year , and the costs of inaction were estimated to be equivalent to losing something in the region of 5-20% of global GDP each year.[1]

What is less widely recognized about the Stern Review is that it framed climate change primarily as a question of risk management. The cost-benefit comparison described above was only one of four options it presented for ways people could compare the values of action and inaction, and take decisions. The others were:

i. An approach focused on reducing the probability of undesired outcomes (such as a certain degree of temperature increase) to a tolerably low level. The cost of reducing the probability was assessed quantitatively, but the risks associated with the undesired outcomes were not. (This was the approach taken in most sections of the Review).

ii. A comparison of the implications of action and inaction for the prospects of long-term economic growth and development.

iii. A comparison of the nature of the world and the quality of life that would arise with action or inaction on climate change.

The Stern Review's section on economic modeling acknowledged the difficulties and shortcomings inherent in its attempt to estimate the aggregate costs of climate change, and urged readers to 'avoid an over-literal interpretation of these results'. Only two years after the Review's publication, its author Nicholas Stern wrote: *"Looking back, I think the Stern Review assumptions led to an underestimation of the costs of inaction whichever of these four approaches are adopted."*[2] In 2013, Stern went further: in a paper entitled *The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models*,[3] he concluded that: *"It is vital that we treat policy analysis as that of a risk-management problem of immense proportions and discuss risks in a far more realistic way... Many scientists are telling us that our models are, grossly, underestimating the risks. In these circumstances, it is irresponsible to act as if the economic models currently dominating policy analysis represent a sensible central case."*

Quite apart from the question of underestimation of risk, a deeper problem has been apparent ever since the earliest attempts to estimate the economic costs of climate change. This is that such estimates, if not presented transparently, may be misinterpreted as being purely objective, while important subjective value judgments implicit in them could be obscured.[4]

Here the economist Cameron Hepburn explains what the limitations of economic cost estimates are, why economic models tend to underestimate the risks of climate change, and how this relates to decision-making.

Dangerously incomplete climate economic models

Cameron Hepburn, **Professor of Environmental Economics, University of Oxford**

Introduction

The economic analysis of climate change has had a real influence on the formulation of climate policy. So it ought to. Climate policy cannot be determined solely by scientists, because there are interests and values at stake that go well beyond climate science. Moral philosophers can help us think through some of the relevant issues, including how to account for lives saved, and the trade-offs between the interests of different people and across different generations. And at some point there must be a reckoning of some kind in order to answer questions for decision makers. Should climate action be more or less ambitious? What are the various advantages and disadvantages of different policy interventions? Who can, should and will pay? How ought the inherent risk and ambiguity be evaluated? These are political questions in which economic and political analysis is unavoidable.

A standard and influential tool used by economists for conducting the reckoning is the Integrated Assessment Model (IAM). Such models often start with a baseline economic scenario that incorporates an assumed level of emissions. The models then consider the costs and benefits, at the margin, of reducing emissions to limit the damages that might result from climate change. In other words, the marginal costs of abating a tonne of carbon dioxide emissions are estimated and compared with estimates of the marginal social damage inflicted by that tonne. The latter is also referred to as the 'social cost of carbon' (SCC).

When the process of estimating the SCC arrives at a single number for application to policy, without any further questions, there is a real risk that decision makers will be misled. It is only natural for a decision maker to want to know what 'the number' is, and some decisions do effectively require such a number. But there is so much scientific uncertainty in determining the social cost of carbon that any single number implies a false precision, as discussed in section 1 of this paper. The scientific uncertainty sits alongside choices that are ethically contentious, addressed in section 2. And the numbers themselves may be biased, as noted in section 3.

Nevertheless, such numbers are nevertheless estimated and used. For instance, the United States Office of Management and Budget and Environmental Protection Agency have conducted a joint analysis of the appropriate social cost of carbon for use in government policy. A high profile and influential group of economists emerged at the answer that the social cost of carbon was US \$36/t CO_2. Eighteen months later, after a period of reflection, the number was updated to US \$37/t CO_2, where it stands today in June 2015. The rest of this short paper considers the three key points to bear in mind when interpreting and using such SCC estimates.

1. Scientific uncertainty about damages remains substantial

While the relationship between carbon dioxide emissions and increases in global mean temperatures are now fairly well understood, the uncertainty over the specific impacts in specific places at specific times remains substantial. Economists have, primarily for convenience, proxied the relationship between aggregate damages and temperature with a simple 'damages function'. This expresses the fraction of GDP lost in a given year due to the relevant increase in temperature. Damages are often assumed, for convenience, to be a quadratic function of temperature increase. So it is assumed that damages increase smoothly as temperatures rise, with no abrupt shifts. There are, of course, other possible damages functions, and the evidence from the physical sciences suggests that functions with thresholds and triggers are far from ruled out.

Analysis of IAMs suggests that the carbon price can vary quite strongly on the specific response of ecosystems to temperature rises. As just one example, modelling by Ceronsky et al with FUND, a fairly standard IAM, suggests that if the thermohaline circulation were to shut down, the corresponding social cost of carbon (SCC) could increase to as much as US \$1,000/t CO_2. In short, the applicable social cost of carbon is very difficult to pin down because of the wide array of risks that could occur from our meddling with the climate system.

2. Value judgments cannot be avoided

Even if we were able to isolate and eliminate all scientific uncertainty in the chain of linkages between emissions, concentrations, temperatures and economic impacts, it would remain impossible to credibly specify a single estimate for the social cost of carbon. This is because a range of unavoidable social value judgments must be made in order to derive any estimate. These value judgments arise in a range of areas, but the four most contentious and important relate to valuing:

- **Impacts on future people:** The weight placed on impacts in the distant future, compared to impacts today, is reflected in the discount rate. This was one of the most contested parameters following the publication of the Stern Review, which used a lower discount rate than previous studies, and in part for that reason concluded that the social cost of carbon was substantially higher.

- **Risk preferences:** Value judgements about risk preference are important too, given the risks involved in allowing Earth's climate to heat. Higher aversion to risk tends to imply a higher social cost of carbon.

- **Inequality preferences:** It is expected that the impacts of climate change will fall more harshly upon the poor than the rich. How to value these effects strongly depends upon the assumed aversion to inequality.

- **Human lives:** Because climate change is expected to lead to a large number of deaths, the monetary valuation of a human life, if used, comprises a significant uncertainty in the overall estimate of the social cost of carbon.

These various value judgments have been debated at length by the economists and philosophers who work on the integrated assessment modelling of climate change. This is not the place to rehearse those arguments in detail. However, it is worth noting that the use of market prices and market data – such as using market interest rates for government bonds as a proxy for the social discount rate – does not avoid these philosophical questions. The very decision to use the market is itself a (contested) philosophical choice.

3. Omission bias may lead to misleadingly low estimates

Finally, just as important as the scientific uncertainty and the inevitability of value judgments in SCC estimates is the concern that estimates emerging from IAMs may be systematically biased. The main source of concern is that IAMs only model the effects that they are capable of modelling. The implication is that a wide range of impacts that are uncertain or difficult to quantify are omitted.

It is likely that many of these impacts carry negative consequences. Indeed, some of the omitted impacts may involve very significant negative consequences, including ecosystem collapse or extreme events such as the catastrophic risks of irreversible melting of the Greenland ice sheet with the resulting sea level rise. Other consequences – such as cultural and biodiversity loss – are simply very difficult to quantify and are hence just omitted. While it is also likely that some omitted climate impacts are positive, it is highly probable that on balance such omitted impacts are strongly negative, leading to SCC estimates that are systematically too low, and corresponding policy on climate change to be too weak. Indeed, the United Nations' IPCC assessment reports themselves accept that their own estimates should be viewed as being conservative, consistent with the prevailing culture of scientific enquiry.

Conclusion

Some scholars have concluded that given these limitations, IAMs are damaging or, at best, useless. It should certainly be openly and loudly acknowledged that estimates of the social cost of carbon are highly uncertain, subjective and potentially biased. Estimates should be accompanied with a corresponding warning of these weaknesses and advice to take any particular estimate with a grain of salt.

But not having models is not a solution either. Ignoring the intellectual challenges that are intrinsic to the economics of climate change does not make them vanish. Instead, economists need to do better, with much more transparent models – where value judgments and uncertainties are clear and can be played around with by policymakers and the general public – and where wide ranges are employed to communicate the sensitivities involved.

Along with transparency, a new generation of IAMs could focus our attention in more useful directions, away from short-term marginal changes and instead towards systemic, transformational change. Rather than devising policy to balance central estimates of the social cost of carbon and central estimates of abatement costs, it may be better to seek interventions aimed at two objectives: (i) reducing the probabilities of very bad outcomes to very low levels, even if this involves relatively high cost; and (ii) increasing the probabilities of a positive transformational 'surprise' – for instance a cost breakthrough in clean technology – that could deliver very large social gains.

Determining a central estimate of the SCC does not prevent thinking about transformational change. However, an exclusive focus on the mean SCC tends to direct policy towards a set of interventions involving marginal, incremental changes to the existing system. Given the risks, and the potential benefits of a transition, incremental change is clearly far from enough. Instead, IAMs ought to help decision makers to consider major disruptive change. Far from being 'in the tails of the distribution', disruptive changes to our natural ecosystems and to our industrial ecosystems are now almost inevitable.

23 ETHICS

Among the 'wide range of impacts that are uncertain or difficult to quantify', which Hepburn warns against, and which are hence likely to be omitted from most economic estimates, are many of the systemic risks described in the previous section of this report. As we discussed, these risks include state failure, mass displacement of people, and conflict.

It is worth noting that such events rarely have a noticeable impact on global GDP, even in the worst cases. Both the First World War and the Second World War had a negligible impact on global GDP, despite causing considerable economic damage in some countries.[5] China's great famine of 1958-1962 reduced its own GDP by around 5% per annum,[6] but since China only contributed around 5% of global GDP at that time,[7] the impact on global output was virtually unnoticeable. Naturally, all of these events are remembered not for their impact on GDP, but for the fact that tens of millions of people died.

The point is that the impacts of climate change omitted from economic estimates may not be marginal. They may be, in human terms, very large. Their valuation is, in large part, a question of ethics. We present here a personal perspective on the ethics of climate change from the host of the final meeting that informed this report, Professor Martin Rees.

A personal perspective on the ethics of climate change

Professor Martin Rees, **Astronomer Royal, Former President of the Royal Society, Emeritus Professor of Cosmology and Astrophysics, University of Cambridge**

I am an astronomer. I am mindful that our Earth is 45 million centuries old, but that this century is special. It is the first century when one species – ours – can determine the fate of the biosphere. That is because of anthropogenic stresses to ecosystems, and the unintended downsides of advanced technologies.

Throughout the centuries, we have been vulnerable to natural threats, such as earthquakes and volcanoes. But there is one reassuring thing about these threats: their annual probability is not changing much – it was more or less the same for the Neanderthals (although, of course, their economic consequences are much bigger for us now).

In contrast, we are now deep into the 'anthropocene' – the new period in which human activities have a significant global impact on the Earth's ecosystems. The pressures of a growing human population and economy, on land and on water, are already high. Humans appropriate around 40% of the world's biomass, and that fraction is growing. Extinction rates of plants and animals are rising. On top of this, comes climate change. As the preceding chapters of this report have shown, the risks of climate change are immense. And unlike those natural disasters with which we are familiar, the risks of climate change are growing, and will continue to grow over time.

When scientists conduct investigations into facts, they must be as objective as possible. It is on the basis of this objectivity that their authority rests. But when scientists engage in discussion on the economic, social and ethical aspects of any issue, they speak as citizens and not as experts, and they have no particular authority. It is important that this distinction is clearly made, so that there is no confusion between what is science, and what is opinion. So I wish to be clear that with regard to what follows, I am speaking not as a scientist, but as a concerned citizen.

In my opinion, the present disagreements about climate policy stem less from differences about the science than from differences in ethics – in particular, in the extent to which we should feel obligations towards future generations. Those who value the risks of climate change by applying a standard discount rate to estimates of future costs are in effect writing off whatever happens beyond 2050. There is indeed little risk of catastrophe within that time-horizon, so unsurprisingly such analysis concludes that tackling climate change should be given a low priority compared to other public policy aims.

But a child born this year could quite possibly live beyond the year 2100. The grandchildren of young adults alive today could live through several decades of the twenty-second century. Anyone who cares about those generations, or others further into the future, will deem it worth making an investment now to protect them from the worst-case scenarios. This is the most compelling argument for acting on climate change.

To consider an analogous situation, suppose astronomers had tracked an asteroid, and calculated that it would hit the Earth in 2080, sixty-five years from now – not with certainty, but with, say, 10% probability. Would we relax, saying that this is a problem that can be set on one side for fifty years – as people will by then be richer, and it may turn out that it misses the Earth anyway? I do not think we would. There would surely be a consensus that we should start straight away and do our damndest to find ways to deflect it, or mitigate its effects.

A second ethical issue concerns our obligations to people who are remote not in time but in economic opportunity. It is widely recognized that climate change will hit the hardest those who have contributed the least to its cause. Heat stress will most hurt those without air conditioning; crop failure will most affect those who already struggle to afford food; extreme weather events will most endanger those whose homes are fragile. A decision not to act on climate change is a decision to inflict suffering on a grand scale.

Finally, a third ethical issue concerns the non-human environment. We know that humans are already threatening biodiversity, and that this threat is aggravated by climate change. The level of extinctions could eventually be comparable to the five mass extinction events in the Earth's history, of which we have learned through the fossil record. As some have said, we are destroying the book of life before we have read it. Clearly, in some cases this has a direct effect on our interests: if fish stocks dwindle to extinction, we lose a source of food. There are plants in the rain forest whose genes may be useful for medicine. But for some, this is too anthropocentric a view: biodiversity – life – has a value of its own. To quote the great ecologist E O Wilson, if our despoliation of nature causes mass extinctions, "it is the action that future generations will least forgive us for".

For many people, religious faith is a source of guidance on questions of ethics. As a believer in a constructive dialogue between science and religion, I have attended meetings to discuss climate change with Faith leaders at the Vatican. After one such meeting, a group of religious leaders, political leaders, business leaders and scientists released a statement, declaring that the 'decisive mitigation' of climate change was 'a moral and religious imperative for humanity'.[8] People of many different faiths who have thought about climate change have reached this same conclusion.

For me, being there in the Vatican, seeing through the window the dome of St Peter's Basilica, inspired some further reflections. Europe's great cathedrals still overwhelm us today. But think how they seemed at the time they were built – and the vast enterprise their construction entailed. Most of the builders new little of the world beyond their own villages. Even the most educated knew of essentially nothing beyond Europe. They thought that the world was a few thousand years old - and that it might not last another thousand. But despite these constricted horizons, in both time and space, despite the deprivation and harshness of their lives, despite their primitive technology, they built these huge and glorious buildings - pushing the boundaries of what was possible. Those who conceived these masterpieces, and those who built them, knew they would not live to see them finished. Their legacy still elevates our spirits, centuries later.

What a contrast to so much of our discourse today! Unlike our forebears, we know a great deal about our world - and indeed about what lies beyond. New technologies enrich our lives and our understanding. Many phenomena still make us fearful, but the advance of science spares us from irrational dread. We know that we are stewards of a precious 'pale blue dot' in a vast cosmos - a planet with a future measured in billions of years - whose fate depends on humanity's collective actions in the course of this century.

In today's fast-moving world, we cannot aspire to leave a monument lasting a thousand years, but it is surely shameful to persist in policies that deny future generations a fair inheritance and instead leave them with a depleted and more hazardous world. To design wise policies, we need all the efforts of scientists, economists and technologists, and the best knowledge that the 21st century can offer. But to implement them successfully, we need the full commitment of political leaders and the full support of the voting public. Our responsibility – to our children, to the poorest, and to our stewardship of the diversity and richness of life on Earth – surely demands nothing less.

Our own opinion

On matters of value, no expert, no leader, and no academic discipline has a monopoly of wisdom. It is for all of us to make up our own minds, having reviewed the evidence.

As the lead authors of this report, we have no more authority to judge the value of the risks of climate change than anyone else, but we give our own opinion here for the sake of transparency and for the avoidance of doubt.

We said at the beginning that we assumed our common objectives were human prosperity and security. It is clear to us that the risks posed by climate change to these objectives are very great. We are deeply concerned about what this means for the future of our families, our countries, and our civilization, all of which we care about. At present, our exposure to these risks is far higher than we would wish to tolerate.

We do not believe the situation is hopeless. On the contrary, there is much that we can do. The risks of climate change cannot be entirely eliminated, but they can certainly be reduced. So in the final section of our report, we offer some thoughts on how we can strengthen our efforts towards achieving that goal.

Endnotes

1. Stern, N. (2007). The Economics of Climate Change – The Stern Review. Available at http://www.cambridge.org/us/academic/subjects/earth-and-environmental-science/climatology-and-climate-change/economics-climate-change-stern-review?format=PB
2. Stern, N. (2009). The Global Deal: Climate Change and The Creation of a New Era of Progress and Prosperity. PublicAffairs, New York. p.94
3. 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. Available at http://personal.lse.ac.uk/sternn/128nhs.pdf .
4. Funtowicz, S. O. and Ravetz, J. R. (1994). 'The worth of a songbird: ecological economics as a post-normal science'. Ecological Economics10, 197-207. Available at http://www.nusap.net/downloads/funtowiczandravetz1994.pdf
5. Jaeger, C., Schellnhuber, H.J., and Brovkin, V. (2008). 'Stern's Review and Adam's Fallacy'. Climatic Change. DOI 10.1007/s10584-008-9436-7. Available at http://www.eci.ox.ac.uk/publications/downloads/schellnhuber08-stern-and-adam.pdf
6. Stern N. (2013).
7. See Figure 12 in Keller, W., Li, B. and Shiue, C.H. (2013). 'Changhai's Trade, China's Growth: Continuity, Recovery, and Change since the Opium Wars'. IMF Economic Review 61, 336-378. Available at http://www.palgrave-journals.com/imfer/journal/v61/n2/fig_tab/imfer201310f12.html
8. Vatican Radio (2015). 'Final Declaration on Workshop on Climate Change'. Vatican Radio. Available at http://en.radiovaticana.va/news/2015/04/28/final_declaration_on_workshop_on_climate_change/1140356

RECOMMENDATIONS FOR CONTINUING RISK ASSESSMENT

RECOMMENDATIONS FOR CONTINUING RISK ASSESSMENT

When we began the process of meetings that led to the production of this report, we started out with the sense that there was scope to improve the way that the risks of climate change are assessed, and the way that such assessments are communicated to decision-makers. Our series of meetings reinforced that sense, and provided a few suggestions for how such an improvement might be brought about.

This risk assessment has attempted to give a rough idea of the big picture, but it has certainly not aimed to be comprehensive, and it is far from perfect. We hope that these recommendations may be useful when more comprehensive risk assessments are undertaken in future.

Our first recommendation is that the general principles of risk assessment should be applied to the greatest extent possible. The principles we have attempted to apply were described in detail in the introduction. To summarize them briefly here, they were:

i. **Assess risks in relation to objectives, or interests.** Start from an understanding of what it is that we wish to avoid; then assess its likelihood.

ii. **Identify the biggest risks.** Focus on finding out more about worst-case scenarios in relation to long-term changes, as well as short-term events.

iii. **Consider the full range of probabilities,** bearing in mind that a very low probability may correspond to a very high risk, if the impact is catastrophic.

iv. **Use the best available information, whether this is proven science, or expert judgment.** A best estimate is usually better than no estimate at all.

v. **Take a holistic view. Assess systemic risks, as well as direct risks.** Assess risks across the full range of space and time affected by the relevant decisions.

vi. **Be explicit about value judgments.** Recognize that they are essentially subjective, and present them transparently so that they can be subject to public debate.

As we have argued, an assessment of the risks of climate change must apply these principles to at least three areas: the future pathway of global emissions; the direct risks arising from the climate's response to those emissions; and the risks arising from the interaction of climate change with complex human systems. The last principle listed above applies particularly to the fourth stage: the valuation of risks.

Risk assessments need to be made on a regular and consistent basis, so that in areas of uncertainty, any changes or trends in expert judgment are clearly visible over time. In all three areas mentioned above, this could be facilitated by the identification and use of a consistent set of metrics or indicators. The International Energy Agency has recently suggested a set of 'high-level metrics to track energy sector decarbonisation', including indicators such as public and private investment in low carbon energy research, development and deployment, and the carbon intensity of total transport fuel demand.[1] These and other similar indicators could help inform future assessments of the relative likelihood of different global emissions pathways. Regarding the climate's response to emissions, various such indicators are already in use. Part II of our risk assessment noted that the use of consistent metrics for estimates of future global sea level rise, and for the categories of risk described by the IPCC as 'reasons for concern', made it possible to see that later assessments had estimated the risks to be larger than earlier assessments had. Defining a set of such indicators in relation to systemic risks might be more difficult, but should not be impossible. In all three areas, the use of such indicators could significantly help decision-makers reach their own judgments when confronted by a wide range of differing expert opinions.

Our second recommendation is to broaden participation in the risk assessment process. It follows from our first principle of risk assessment that leaders and decision-makers have a role not only as recipients of a completed risk assessment, but also at the beginning of the process, in defining the objectives and interests against which risks should be assessed. This will enable scientists and other experts to ensure their assessments are as relevant as possible.

Scientists naturally have the lead role in understanding climate change and its direct impacts. At the same time, experts in politics, technology, economics, and other disciplines can provide information relevant to the future of global emissions, and the indirect impacts of climate change as it interacts with human systems.

To ensure that the most relevant information or uncertainties are communicated to decision-makers, it can be helpful to make a distinction between information gathering and risk assessment. Information gathering activities, such as primary scientific research, may be free to collect whatever is useful or interesting. Risk assessment has to interrogate that evidence in relation to defined objectives, and according to a specific set of principles. Separating these tasks may allow both to be carried out more effectively. Such a separation of tasks is often made within intelligence agencies. Climate change risk assessments could benefit from involving not only scientists, but also those for whom risk assessment is a central part of their professional expertise. Qualified individuals could be drawn from fields such as defence, intelligence, insurance, and public health.

Our third recommendation is that a climate change risk assessment should report to the highest decision-making authorities. A risk assessment aims to inform those with the power to reduce or manage the risk. Assessments of specific, local, or sectoral risks of climate change may be directed at those with specific, local or sectoral responsibilities. Assessments of the risk of climate change as a whole should report directly to those with responsibility for governance as a whole. At the national level, this is means the head of government, the cabinet, or the national security council. At the global level, it means institutions where heads of government meet to make decisions.

The aim of improving risk assessment is, of course, to better inform decision-making on risk reduction. Risk reduction – and the question of what might be a proportionate response to the risks of climate change – is the subject of the final part of this report.

Endnote

1. These and other similar indicators could help inform future assessments of the relative likelihood of different global emissions pathways. Regarding the climate's response to emissions, various such indicators are already in use. Part II of our risk assessment noted that the use of consistent metrics for estimates of future global sea level rise, and for the categories of risk described by the IPCC as 'reasons for concern', made it possible to see that later assessments had estimated the risks to be larger than earlier assessments had. Defining a set of such indicators in relation to systemic risks might be more difficult, but should not be impossible. In all three areas, the use of such indicators could significantly help decision-makers reach their own judgments when confronted by a wide range of differing expert opinions.

RISK REDUCTION: ELEMENTS OF A PROPORTIONATE RESPONSE

ST PAUL'S CATHEDRAL, LONDON. BUILT 1675 – 1708. FINANCED BY A TAX ON COAL

Image by Thomas Wesenberg.

RISK REDUCTION: ELEMENTS OF A PROPORTIONATE RESPONSE

A risk assessment is a way to better understand the problems we face; it does not necessarily tell us how to solve them. It may, however, help us think about proportionality – to answer the question: 'what would be a proportionate response to the risk?'

This was the question we discussed in the last of the series of meetings that informed this report, held in London in April 2015. Most of the participants in that meeting had expertise in one of three areas: technology, finance, and politics. Here we present a perspective on the nature of a proportionate response to the risk of climate change in each of those three areas, before ending with some closing thoughts.

24 TECHNOLOGY

Sir David King,[i] Professor Jim Skea,[ii] Professor Tim Green.[iii]

Energy produced without greenhouse gas emissions needs to become less costly than production based on coal, gas or oil. Clean energy must be able to compete directly on cost before a world-wide roll-out can be expected, particularly in the emerging and developing economies. The challenge needs to be a major focus for scientists and engineers. Progress in technology is happening at an impressive rate, but it is not yet fast enough to meet the 2°C target with reasonable probability.

The technologies we need to progress

There is no single magic bullet. We need progress in six major areas. First, there are the three main types of clean energy supply: renewables (especially solar and wind), nuclear power, and coal and gas subject to carbon capture and storage (CCS). All have important roles to play, depending on the country and region in question. In sunny areas like India, Africa and south-east Asia solar can play a central role. In more northern areas, like Japan and Northern Europe, wind and nuclear have an important role, as does CCS in areas rich in coal and natural gas.

There are also three elements that are common to all sources of energy. First is our ability to store the energy cheaply for when it is needed. Then there is our ability to transmit it cheaply to where it is needed. And finally there is our ability to rein in our overall demand for energy through energy efficiency. Storage, for example through batteries, capacitors, and large-scale mechanical methods, is needed at all size scales up to grid-scale, and for a variety of durations from minutes to seasons.

Recent progress

In recent years, the price of solar and wind power installation has fallen dramatically. This has largely been driven by the introduction of feed-in tariffs across the European Union, starting in Germany in 1989. The prices of photovoltaic (PV) panels have been falling by 17% for every doubling of capacity, and the prices of

i. Sir David King, UK Foreign Secretary's Special Representative for Climate Change, former Government Chief Scientific Adviser;
ii. Professor Jim Skea, RCUK Energy Strategy Fellow and Professor of Sustainable Energy Centre for Environmental Policy, Imperial College London
iii. Professor Tim Green, Director, The Energy Future Lab, Imperial College London

PV installation and on-shore wind installation are now comparable with new fossil fuel power installation in many parts of the world. With more research, both plant and installation costs can fall even faster. There is also scope for further progress in developing concentrated solar power, for deployment in desert sites.

However, feed-in tariffs have done nothing for the development of competitively priced energy storage and smart grids. While there has been some significant innovation, particularly in batteries, many of the other storage technologies are immature with uncertain costs, performances and system implications. With smart grids, at-scale demonstration is needed to extract lessons for deployment and to understand behavioural and social implications. This particularly is where a major thrust of publicly-funded research, development and deployment (RD&D) activity is urgently required.[1]

Accelerating progress

We have four key messages relevant to accelerating energy innovation. These are: the scale of investment required; the need for a mission focus that will send signals to the private sector and underpin specific actions; the need to create the right conditions for market entry for novel technologies; and the need for a coordinated international approach.

1. **Scale.** We need to put a much higher priority on the discovery of new, cheaper ways to produce, store and distribute clean energy. In the face of this urgent need it is remarkable to note that there is a declining trend in the fraction of national income devoted to public investment in a cleaner energy future. The public sector has an urgent role to play in addressing this imbalance. The International Energy Agency concludes that our RD&D investment in clean energy technology needs to increase by three to six times in order to hold the global temperature within 2°C above preindustrial levels.[2] The country with the highest proportion of national income devoted to energy RD&D investment is Finland, at 0.13%; the global median level in developed countries (2012) is only 0.035%. In even the best performing segments of the energy sector – such as solar and wind – the ratio of R&D to sales is under 2%. This compares unfavourably with over 5% in consumer electronics, and 15% in pharmaceuticals.[3]

2. **A mission focus.** Most of the energy sector's own RD&D investment focuses on extending the fossil fuel resource base and enabling it to be extracted at lower cost. Public sector RD&D has a unique role to play since it can be deliberately directed at overcoming barriers to the development and adoption of transformational low carbon technologies. The challenge - which brings focus to the mission - is to bring the costs of low carbon technologies down to a level where they can successfully compete with incumbent technologies. If research, development and deployment programmes are directed at achieving this specific goal for each of the key technologies that are essential to a low carbon transition, then resources will be allocated more efficiently, and the desired results will be achieved more quickly.

   A clear RD&D mission focused on low-carbon transformation sends the right signals to the private sector, which will have a key role in bringing these technologies to the market. A parallel can be drawn with the highly successful arrangement for the semiconductor industry, where Moore's law (the number of transistors on a computer chip doubles every two years) has been maintained through a mission-oriented Roadmap driven by a publicly- and industry-funded pre-competitive RD&D programme over the past 30 years (the International Technology Roadmap for Engineers, ITRS).

3. **Creating the right conditions for market entry of clean energy technologies.** Market-pull policies that turn low carbon technologies into attractive commercial propositions are needed to complement RD&D investments. Subsidies for clean energy technologies, and carbon pricing, can both help to create the right market conditions. By increasing demand, and hence the volume of production and the economies of scale, they bring forward the point at which clean energy prices become competitive with mature fossil-fuel based systems.

   This approach has already been seen to work, with simple measures leading to high volume deployment of small-scale technologies – with examples including feed-in tariffs for photovoltaics, efficiency regulations for vehicles, and product standards and labelling for efficient domestic appliances). This approach needs to be replicated further. Support for large-scale technologies – such as offshore wind and nuclear energy, bioenergy, and carbon capture and storage – tailored to technological maturity, is needed so that risks are shared. In particular, market design needs to be adjusted so that it rewards the system benefits of facilitating technologies, such as storage and smart grids.

   Support is also needed to assist new technologies through the 'valley of death' – the period in which a technology may already be ready for market, but not yet able to overcome the advantages of incumbency that benefit existing technologies. Public support can help start-up technology companies survive through this period, when they might otherwise fail.

4. **A coordinated international approach.** The scale of RD&D investment involved calls for a coordinated international approach. Benefits would arise in terms of economies of scale, shared research objectives, the pooling of research findings, the agreement of common RD&D targets and milestones, and the avoidance of duplicated effort. Each country would continue to organise and manage its own programme, but could coordinate its efforts with partners through an overarching technological committee. Such a committee would set out roadmaps for RD&D (as in the semiconductor industry, as mentioned above) which would lead to cost-competitive low carbon technologies. An international approach of this kind is vitally needed to enhance the productivity of RD&D investments, accelerate the diffusion of low carbon energy technologies, encourage the private sector to enter a potentially enormous market, and thereby increase the chance of avoiding dangerous climate change.

25 FINANCE

Rowan Douglas, **Steve Waygood**, **James Cameron**.[iv]

For generations, governments have sought to align the interests of the financial markets and society. Nowhere is this tension more keenly and persistently felt than in the area of climate risks, which is arguably the most significant contemporary market failure. To correct this failure, and respond effectively to the risk of climate change, we need to do better in three areas: disclosing risk; pricing carbon; and incentivising long-term investment.

Disclosing risk

There is a collective call across a wide range of sectors and policy interests to avoid further unreported and unmanaged accumulations of risk. If accumulated risk – whether in the form of short-term bubbles or long-term environmental externalities – is not rationally accounted for and managed at an early stage, then it tends to manifest itself through market shocks, disorder, and system-wide losses at the point when it can no longer be ignored, often with devastating consequences.

Over the last two decades, there has been a revolution in Environmental, Social and Governance reporting and disclosure initiatives. Some of these have improved disclosure of risks to individual enterprises or to society, and this represents valuable progress. However, the proliferation of initiatives can be confusing to investors, and the assessment of many risks – including those associated with climate change – is not yet integrated into the financial system sufficiently for those risks to be effectively managed.

The experience of the insurance industry is instructive. In the late 1980s and early 1990s, traditional risk assessment approaches based on loss experience data were found inadequate to cope with a range of unprecedented, extreme and emerging risks. Since then, the industry has transformed its approach, using science, systems modelling and scenarios to better understand current risk distributions and extremes. The full spectrum of risks is now assessed in estimating three key metrics: i) the annual average loss; ii) the 1 in 20 year annual loss; and c) the 1 in 200 year annual loss. Risk management, based on these metrics, ensures that insurers remain solvent and can fulfil their commitments even in the worst years. This is similar to the practice of 'stress tests' in other sectors. What is distinctive is how the stress test is employed in mainstream financial regulation, credit ratings, equity analysis and annual reporting across the whole insurance and reinsurance sector.

iv. Rowan Douglas is CEO, Capital, Science & Policy Practice and Chairman, Willis Research Network, Willis Group. Steve Waygood is Chief Responsible Investment Officer, Aviva Investors. James Cameron is Chairman of the Overseas Development Institute, and former chairman and founder of Climate Change Capital. With thanks to Bryony Worthington, Mark Campanale, Nick Robins, Paul Dickinson and Ingrid Holmes for additional ideas and input.

As this approach has revealed true levels of risk exposure, it has transformed risk governance within insurance companies and the wider market, making organisations across public, private and mutual[4] sectors far more resilient, transparent and comparable than before. Markets have developed much greater confidence in the insurance sector's ability to underwrite its risks sustainably; uncertainty has been classified and reduced, and capital has remained abundantly available for appropriately risk-adjusted allocation. Valuations and decision-making have been better able to take risks into account and resilience has been rewarded.

Based on the insurance methodology, it would be possible to design a common risk reporting framework that could be applied to all entities (public, private and mutual) including companies, cities and even countries. This would assess risks to each entity's interests under a common template of risk classes, probability thresholds, and periods of time, and translate this into annualised costs, which would be proportionately reduced with greater resilience or reductions in risk. At the company level, this would provide a risk-orientated lens to interpret and formalise much of the work already undertaken in Environmental, Social and Governance reporting. At the national level, it would build on the practice of countries such as the UK in publishing national assessments of civil emergency and security risks. At all levels, it would provide information that would better enable planning and accounting for the future, increasing resilience, and management of emerging risks.

As an example of how this could contribute to the management of climate change risk, consider an energy firm focussed on coal production. The firm may identify a carbon price of US$100 per tonne, or the announcement of an EU target to cut coal consumption by 50%, as one of its extreme loss scenarios. The probability of this may be estimated as '1 in 100' or 1% for the following year, with the contingent liability evaluated, but could rise to high values in future years, in responses to changes in the policy landscape. As the insurance sector has experienced, within a short time, managers and regulators would become familiar with this approach, and leading risk scenarios would become objects for discussion and refinement among practitioners, markets and stakeholders. Markets, benefiting from the increased transparency, robust framework, and tractable numbers produced by this approach, would be better able to discount the value of assets proportionately and ensure that capital was allocated in a way that took into account not only current risks, but also the way in which risks may to change over time.

Of course, some firms may have an incentive to lobby governments not to manage climate risks. While this may be good for the firm's bottom line, it may be antithetical to the broader interests of their shareholders. Shareholders – and society at large – should be able to make up their own minds on this question, but at present it is very difficult for them to see: (i) which trade associations companies are members of; (ii) what these trade bodies are saying about climate change; or (iii) whether this work is in their interests. So in addition to the need to improve disclosure of risks, it should become standard practice that all corporate advocacy relating to climate change is a matter of public record.

Pricing carbon

Governments should recognise that valuing carbon in the real economy is essential. It will be almost impossible to get to grips with greenhouse gas emissions in a complex, dynamic and diverse economy without using carbon pricing in some form. The great virtue of putting a clear price on carbon is that it can engage many, with an interest they can valorise, in the enterprise of achieving a public policy goal in a multitude of ways that no policymaker, however wise, could possibly have determined in advance. At the same time, carbon pricing is not a panacea, and should always been seen as one of a number of price-based and non-price-based policy interventions that can easily co-exist and which will all be necessary to deliver an adequate response.

The vast majority of governments and investors are aligned in wanting a price on carbon in order to rationally and systematically allocate capital away from climate risk, which affects the value of their whole portfolios in ways which are difficult to calculate, and towards better risk-adjusted returns from other, low carbon or resource efficient investments.

There are many ways to implement carbon pricing, and the most appropriate form will vary according to political and legal cultures. However, in any country, a carbon pricing system needs to be simple, enduring and transparent enough for the market to understand and act on. And it needs to cover enough of the economy to make a difference (achieving this is likely to require a portfolio of policies rather than a single one).

But what should the price be? We have learned from our experience so far that even low carbon prices can achieve significant reductions in emissions, while promoting resource efficiency, and without imposing any overall cost on the economy. However, we have also learned that carbon pricing at relatively low levels does not bring about the technological transformation that is required to effectively manage climate risk. Given the inability of economic models to predict such transformations, we have no way of knowing what level of pricing will be effective. A logical approach is therefore to set carbon pricing on a path of rising stringency that keeps pace with revealed information about abatement potential, until we see the desired changes taking place. If this direction of travel is clear to all, then the desired changes will come earlier and at lower cost.

Who should pay the price? To date, governments have mostly placed the burden of change on the consumption end of the carbon life cycle, through carbon pricing and product standards. Carbon prices are paid by fossil fuel consumers. An alternative, potentially additional approach would be for fossil-fuel producers to pay the price. This would have two significant advantages: it is administratively simpler to levy a tax at the point of extraction (or import) than at any other point; and taxing at source will ensure that the price is integrated into the whole economy, not just part of it. A third advantage could be to stimulate investment in carbon capture and storage. This could be achieved by exempting fossil fuel producers from any carbon price to the extent they are able to demonstrate that the carbon they produce remains unburned or equivalent emissions are safely returned to the ground. This would be identical in principle to successful regulations in Europe that have made producers of packaging, automobiles and appliances responsible for dealing with the waste created when those products come to the end of their useful lives.

Who should pocket the proceeds? Any carbon pricing system that is significant enough to be effective will face the opposition of vested interests. Governments may find it easier to overcome this opposition if they have strong public support. This may be achieved by making the system revenue-neutral, giving the proceeds back to the public. An added advantage is that such a system can incorporate a positive feedback: if a price is levied as a fixed tax per tonne of carbon extracted, and if a fixed proportion of total tax revenues are returned to market participants, then action taken to reduce the tax burden by one participant increases the incentive for others to act similarly (since a decrease in total revenues results in an increase in net tax paid). This contrasts with the negative feedback experienced with fixed quantity based carbon pricing policies such as cap-and-trade, where any reduction in carbon consumption by one participant reduces overall demand, and so reduces the incentive for others to follow.

Finally, even more important than any of the specifics discussed above, is the question of credibility. Carbon pricing is effective when investors are confident that the system will endure over time. This requires visible political will and strong institutions. Internationally, further confidence may be generated if major economies agree to implement robust and rising carbon prices together.

Incentivising long-term investment

The International Energy Agency estimates that to limit global warming to 2°C, we will need to invest around $1trn a year in clean energy between now and the middle of the century. Further investment will be needed to reduce emissions in other sectors. This figure may change as our understanding of the severity of the climate risk improves; however, it is already clear that significant sums of money will be required.

Fortunately, with over $50 trillion invested in the global stock markets, and a further $100 trillion held in sovereign and intergovernmental debt, on the face of it, there should be no shortage of capital available. The speed and scale of the growth in sovereign debt that was issued to underpin the global financial system during the financial crisis demonstrates that it is possible to secure financing at the speed and scale implied here. The key is the existence of political will.

Raising and spending this money will need considerable planning, effort and international coordination. If we are to achieve this efficiently, effectively and sustainably, we will need the international community to develop a long-term capital raising plan. The overall direction for such a plan could be set by government leaders in a group such as the G20. The plan would need to consider all forms of large-scale finance. Sovereign debt is one of the asset classes best able to finance investment for the long-term, but its issuance during the financial crisis has already brought a significant number of countries to debt levels that have tested their credit ratings. So the plan must include a new more nuanced approach to evaluating debt-based risk, and also make use of multilateral development banks, infrastructure investment, project finance, corporate debt, foreign direct investment, and equity investment. For all these assets classes, the plan will need to consider which asset owners have the capital available, and, importantly, what incentive structures will allow them to profit from investing sustainably for the long-term. Policies that create 'bankable' projects will be key to this.

A critical weakness of the financial system at present is that almost all its actors are strongly incentivised to focus on the short term – the so-called 'tragedy of the horizons'. Fund managers are assessed on their quarterly performance; investment consultants benefit from switching fund managers; brokers are paid according to trading volumes and so are incentivised to encourage market activity, and so are stock exchanges, whose revenues are linked to the number of transactions that take place. Almost nobody looks more than a year or two ahead. The overwhelming focus on the short term is a problem for the economy as a whole, since it results in misallocation of capital. Company directors are deterred from investing in long-term opportunities, at the same time as markets fail to manage long-term risks, and companies focused on short-term gain can profit at the expense of those seeking to do the right thing over the longer term.

This is not a situation that we are obliged to accept. Governments, stock exchanges, institutional investors and others set the rules of the game by the laws they pass, the regulations they enforce, and the contracts they write. Any of these players can change the rules of the game, and so change behavioural incentives. For example, laws could be amended to explicitly require good stewardship and the assessment of long-term environmental, social and governance (ESG) risk as part of the fiduciary duty of asset managers. In line with this principle, it has been proposed[5] that clauses on responsible investment should be written into fund management contracts, that fund managers' performance should be evaluated on the basis of their long-term ability to beat benchmarks as well as their performance as stewards, and that clients should be able to sue fund managers and investment consultants for negligence if they fail to properly consider the potential for ESG risks and unsustainable development to harm the value of long-term investment portfolios.

In the same spirit, we recommend that governments take a close look at the national financial regulators and their global coordinating bodies, to assess whether their mandates need to be updated in order to ensure that they are attending to the profound, long-term financial risks associated with climate change. If measures are taken to incorporate the assessment of long-term risk into the financial system, we will make much faster progress towards managing risk effectively.

26 POLITICS

Baroness Bryony Worthington, Member of the House of Lords, UK Parliament

In 2008 the UK passed a landmark piece of legislation to address climate risk: The Climate Change Act. It introduced a legal framework committing the UK to an 80% cut in greenhouse gases by 2050 compared to 1990, through a series of consecutive five yearly carbon budgets. The UK was the first country in the world to translate the scientific evidence of climate risk into a long-term legal framework. This was possible due a very strong political consensus that UK could and should act to reduce its contribution to the global climate problem. As was argued at the time, demonstrating leadership in this way subsequently catalysed other countries to follow suit, and now more than 60 countries have passed laws that seek to address their impact on the climate.

The UK's approach to managing the risk of climate change reflects our political situation. The actors and actions contributing to climate change are, for the most part, within the private sector. Political leaders therefore used the rule of law to create a new carbon emissions management system, guiding future policy-making, which includes additional laws and regulations, at an EU and UK level, and influencing company decision-making.

The political context in other countries differs and different responses to climate risk can be expected. For example, in China where there is a higher degree of state involvement in planning the economy, the response to climate change is embodied in the five-year plan. This blueprint sets out a vision with specific targets to achieve it, which in turn provides a framework for the financing of programmes and projects. In the US, with the political deadlock at a Federal level, progress on climate change is being pursued at a State and city level. Some states, such as California, have passed comprehensive legislative packages applying emissions standards and introducing carbon pricing. Elsewhere, in the absence of new laws, the existing Clean Air Act is being used to trigger action, though it is still subject to legal challenge.

There are, however, irrespective of jurisdiction, some common challenges in the politics of tackling greenhouse gas emissions. There are many powerful interest groups whose current business models are incompatible with the changes needed to reduce the risk of climate change. This creates political tension, where efforts to regulate existing activities are met with stiff opposition, resulting in blocking or watering down of proposed interventions. The global nature of the problem, coupled with fears about economic competitiveness, can be a powerful argument against unilateral action. In this context, politicians need to think carefully about helping to manage transition in key sectors of the economy. This may mean providing compensations and targeting incentives towards technologies that can be deployed in the most carbon intensive sectors.

Moves to incentivise new, cleaner, potentially disruptive technologies have proven in many cases politically easier to introduce. However, if they are perceived as too costly, political support can be withdrawn, sometimes abruptly. Increasing the number of voices representing cleaner ways of doing things can create a more balanced political climate, as can well resourced and targeted civil society representations.

The next international climate change agreement will not be a top-down legislative framework based on politically determined carbon budgets. It will instead be a more inclusive, less deterministic document that reflects a shared will to act. The degree of action, however, could easily fall well short of what a risk based assessment of the science would imply is necessary. So we must use the time that remains to build confidence, strengthen political will, and ensure that this agreement represents the best that is possible within this current framework. At the same time, we must think hard about how to increase the effectiveness of our action in the years ahead.

A priority must be to find ways in which international action can increase the momentum that is already apparent in the deployment of cleaner technologies and prevent re-investment in high carbon infrastructure. The Montreal Protocol to phase out ozone-destroying chemicals showed that an international agreement can be remarkably effective when it is focussed on technological standards in a specific economic sector. The same approach can be applied to many of the sources of carbon emissions. For example, the EU, China and the US all have different standards regulating the emissions from power stations and vehicles. If these few large economies agreed to have the same standards, sector participants across the world would be strongly incentivised to meet them; and as technological progress is likely to outpace expectations, governments could agree together to a timetable of progressively tighter standards. In any sector, a critical mass of countries taking a lead will help to incentivise others to follow.

The fight to secure a proportionate response to climate risk will continue, and a deeper, shared understanding of that risk can only help to serve as a spur to action.

Ridding the world of slavery was a hundred year battle. The battle to rid the world of excessive greenhouse gases is already a quarter of a century old and much progress has been made. The human mind is geared for problem solving, and more and more people are applying themselves to the task. Over the next quarter century, the pace of positive change looks set to increase. With sufficient political will, I remain confident that we can and will avert the worst-case climate change scenarios that threaten our very existence.

Endnotes

1. King, D.A., Browne, J., Layard, R., O'Donnell, G, Rees, M., Stern, N. and Turner,A. (2015). A Global Apollo Programme to Combat Climate Change. London School of Economics, in print.
2. International Energy Agency (2013). Tracking Clean Energy Progress 2013: IEA input to the Clean Energy Ministerial. Available at http://www.iea.org/publications/tcep_web.pdf
3. Laleman, R. and Albrecht, J. (2012) Comparing push and pull measures for PV and Wind in Europe, Renewable Energy, 61: 33-37, p.3. See also Grubb, M., with Hourcade, J.-C. and Neuhoff, K. (2014) Planetary Economics,: Energy, Climate Change and the Three Domains of Sustainable Development. Oxford, :Earthscan, Routledge, p.321
4. The 'mutual' sector refers to building societies and credit unions run for the benefit of member investors rather than shareholders or directors
5. By the United Nations Environment Programme Finance Initiative's Asset Management Working Group

27 CLOSING THOUGHTS

As the last of our contributing authors wrote, we have a battle on our hands: a battle to preserve a safe climate for the future. Powerful forces are engaged in this battle, whether we notice them or not. The power of vested interests to resist change, the inertia of infrastructure systems, and the unyielding laws of thermodynamics all seem to be arrayed against us.

To win this battle, we must deploy equally powerful forces in favour of change: the power of human ingenuity, the power of technology, and the power of leadership. We must match the laws of physics with a will and a determination that is equally unyielding.

The greatest risks of climate change arise when thresholds are crossed: what had been gradual becomes sudden; what had been inconvenient becomes intolerable. The greatest reductions in risk will be won in the same way. Gradual, incremental measures will not be enough: we must seek out non-linear, discontinuous, transformational change.

Political leadership can and should be a source of non-linear change. It can move a government from inaction to action, and a society from apathy to engagement. With existing technology, there is already the opportunity for political leadership to dramatically change the trajectory of any country's emissions in the short term.

Technological innovation is a natural source of non-linear change. New technologies can emerge slowly, but then displace old ones rapidly and suddenly when some invisible threshold is crossed. We need to accelerate this pace of change, and bring forward those thresholds, in all the technologies that are needed to win the battle. Above all, we must use both technological progress, and policy measures such as carbon pricing, to cross as soon as possible the threshold at which clean energy becomes cheaper than fossil energy.

In finance, small changes in the rules of the game can produce large changes in results. The right adjustments to regulations and incentives will dramatically alter the flow of money, sending more of it in a direction that serves our long-term economic interests.

The power of non-linear change is not reserved to political leaders, technologists and markets. Social change can also be discontinuous, unpredictable, and dramatic. The battle against slavery (or colonialism) may have taken a century, but when change finally came, it came quickly.

The risks of climate change are amplified by feedbacks: rising temperatures melt ice; sea stripped of ice takes in more heat; and the temperatures rise faster. To win this battle, we must set up our own cycles of positive feedback. Political interventions must change market sentiment, so that the market sends more investment into clean energy technologies, so that this accelerates technological progress, so that new political interventions become possible.

In this battle, every country must contribute according to what it can do best. Those most responsible for the cumulative emissions in the atmosphere must do the most. Countries that are rich in energy from sunlight, wind, rivers, tides, and geothermal heat must push the boundaries of technological innovation in exploiting

those resources, and take the lead in bringing them to the global market. The largest producing and consuming countries must work together to make sure the global market benefits from their economies of scale, bringing down the costs of clean energy for all, at the same time as improving access to energy for the poorest. And while all countries have a role to play in reducing the subsidies given to polluting energy, those that host the hubs of global finance should take the lead in revising the rules of the game.

Just as the risks of climate change are both immediate and long-term, we must act both immediately and with a long-term view. A risk that grows over time will not be managed successfully if our horizons are short-term. Ultimately, the risks of climate change will only be under control when we have reduced global emissions to near zero. So while we must do all in our power to reduce emissions now, we must also follow a path that increases our power to do more in the future.

The risks of climate change may be greater than is commonly realized, but so is our capacity to confront them. An honest assessment of risk is no reason for fatalism. If we counter inertia with ingenuity, match feedback with feedback, and find and cross the thresholds of non-linear change, then the goal of preserving a safe climate for the future need not be beyond our reach.

Many of our parents and grandparents fought for the future of their countries, making greater sacrifices than most of us will ever have to. Never mind what we owe to future generations; it is the least we owe to the past that we should make a decent fight of this battle now.

London, Beijing, Delhi, Cambridge (MA)
14 June 2015

ANNEXES

ANNEX: RISK OF HEAT STRESS TO HUMANS – METHODS AND ADDITIONAL RESULTS

Methods

Relating global temperature rise to local climatic conditions relevant to heat stress
We used the HadGEM2-ES climate model values[1] for temperature and humidity (dew point) to calculate the heat stress index Wet Bulb Globe Temperature (WBGT) for 67,000 global grid cells over land (0.5 x 0.5 degrees), for different time periods (1993, 2025, 2050, 2075 and 2200; each estimated as 25-30-year averages), on the RCP8.5 scenario pathway. This provided approximate data on grid-cell level heat stress change during two centuries.

The heat stress levels were calculated as 30-year averages for each calendar month, so the June values are an average of 900 June days. We calculated the intra-month daily variability of the heat levels and standard deviations (assuming Gaussian distributions), which can be used to identify lower limits for the hottest 10% of calendar month days ('hottest 3 days').

Relating climatic conditions to core body temperatures and heat stress
The WBGT index combines temperature and humidity with estimates of likely air movement over the skin and additional heat from heat radiation to produce a physiologically relevant heat exposure level, which can be used in climate change health impact assessments.[2] The heat stress level also depends on metabolic rate (physical activity level) and clothing.

Details of the WBGT method and its calculation and interpretation can be found in the ClimateCHIP Technical Report 2014:4 at www.ClimateCHIP.org.[3] The mapping of heat stress in relation to work and other physical activities has been described in detail for parts of Asia.[4]

The relationship between WBGT levels and physiological limits was estimated using the de Dear (University of NSW, Australia) formula, which is available as the WWW Thermal Comfort Index Calculator (http://web.arch.usyd.edu.au/~rdedear/) to estimate effects on core body temperature. The WBGT calculations contain the variables that are inserted into the de Dear formulas that then calculate the time trend up to four hours of the core body temperature (70kg person, light clothing).

How uncertainty in the modelled future climate change is addressed.
There is uncertainty as to how much climate will change due to increased emissions of greenhouse gases and consequently how WBGT will change in the future. To address some of this uncertainty, the WBGT for the end of the 21st century was calculated at different levels of global mean temperature change using a pattern scaling technique to derive the local temperature change[5] and assuming the HadGEM2-ES spatial pattern of warming. The different levels of temperature change chosen were based on the distribution of modelled end of the 21st century temperature rise for RCP8.5 from the World Climate Research Programme's (WCRP) Couple Model Inter-comparison Project (phase 5; CMIP5)[6] and presented in the International Panel on Climate Change (IPCC) Fifth Assessment Report.[7] The calculated WBGT values in this work therefore reflect some of the uncertainty in the temperature response to increased climate forcing but do not include the uncertainty in the local response to climate change since only one spatial pattern of warming is used (i.e one model, HadGEM2-ES) or the uncertainty in the future changes to humidity.

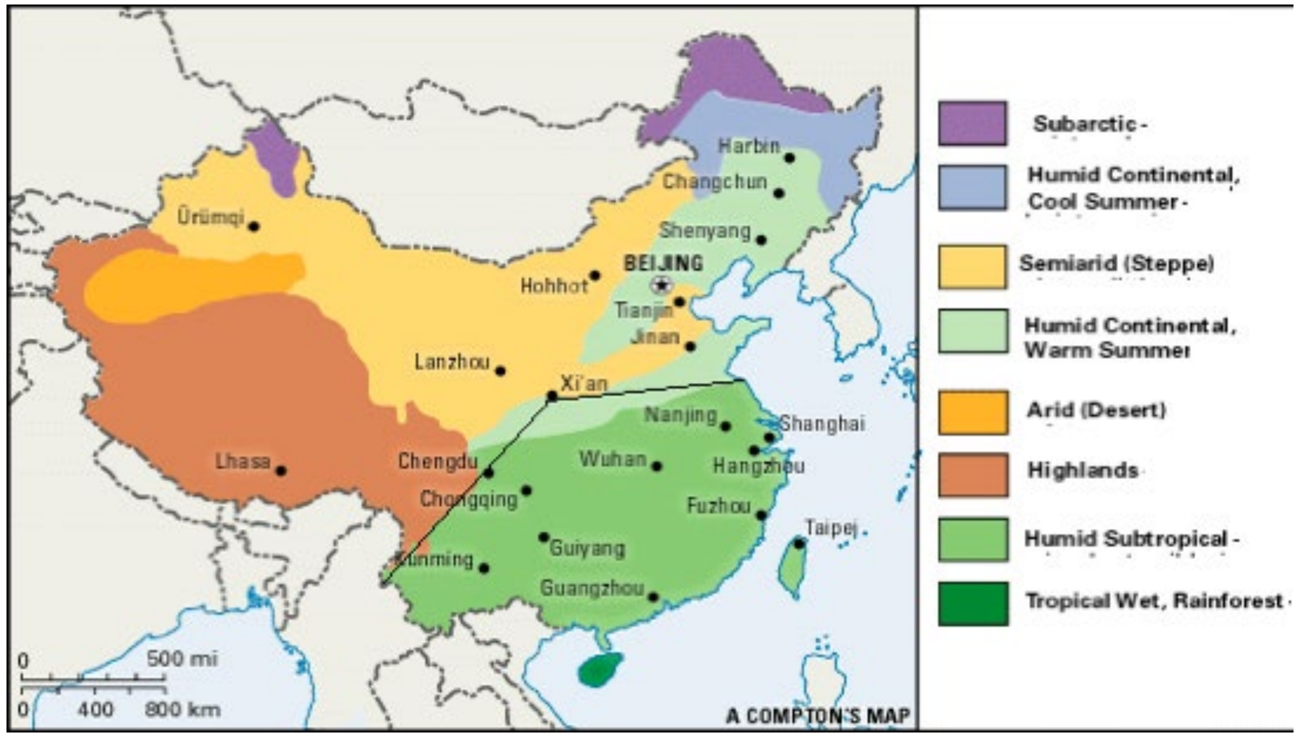
Geographic areas

The three geographic areas in this study were in North India, South-East China and South-East USA. The numbers of grid cells included were 281, 953 and 602 respectively.

N India: Includes Rajastan, Punjab, Haryana, Chandighar, Delhi, Bihar and Uttar Pradesh

SE USA: Louisiana, Mississipi, Alabama, Georgia, Florida, S Carolina, N Carolina, Virginia, W Virginia, Kentucky, Tennessee, Arkansas

SE China: The area below the two straight lines in the map.



Population

For each grid cell we also had estimates of local population numbers in four age groups, and we calculated population-weighted heat exposure probabilities for the adult and elderly population (ages >= 15 years). The population database until 2099 was based on UN Population office estimates (calculations by Briggs, 2014) and after 2099 we used total estimated population changes:

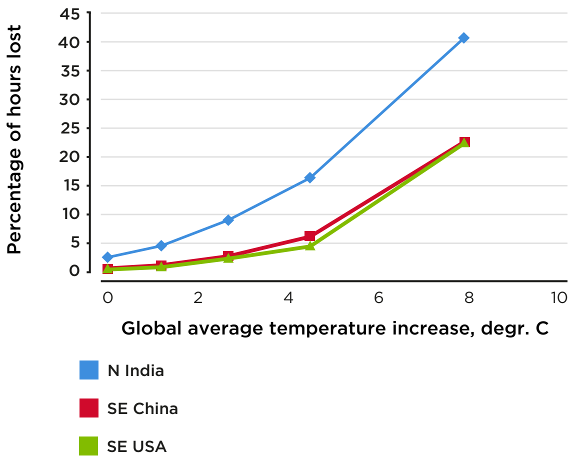
Since our 'probability' estimates for the highest global temperature changes (in 2200) were based on proportion of population, changes in population number between 2085 and 2200 did not need to be taken into account. For simplicity, we assumed that there was no change over time in the relative spatial distribution of population during the second century.

Hours of work lost (see additional results, on the following page)
The risk functions for lost work capacity due to heat were presented in the ClimateCHIP Technical Report 2014:4 at www.ClimateCHIP.org.[8]

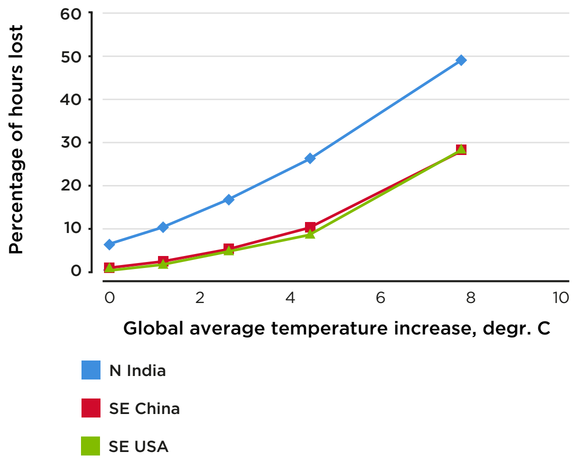
ADDITIONAL RESULTS

This figure displays the results in an alternative way, showing estimates of the proportion of work hours lost in the three study areas due to heat, at different levels of physical activity, in relation to global average temperature increase (0 to +8 degrees C).[i]

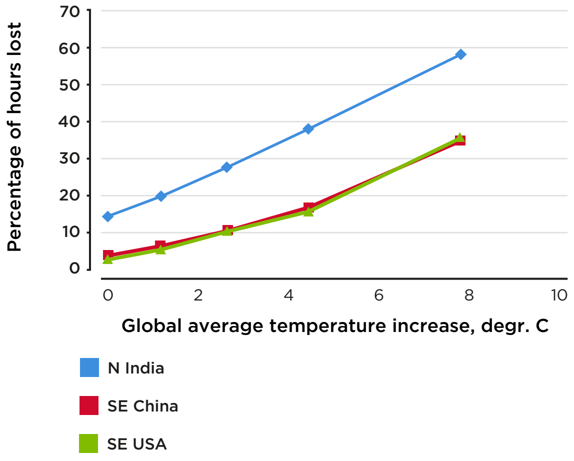
Lost annual daylight work hours (%) for people working hourly at 200W



Lost annual daylight work hours (%) for people working hourly at 300W



Lost annual daylight work hours (%) for people working hourly at 400W



i. Global average temperature increase is shown here as relative to a 'present day' baseline, as defined by the 30-year average centred on 1995 (i.e. from 1980 to 2009). This is about 0.6 degrees C higher than the 'pre-industrial' baseline used in the temperature increase chapter, and referred to generally throughout this report.

Endnotes

1. Downloaded from the ISI-MIP database at Potsdam Institute (Hempel, S., Frieler, K., Warszawski, L., Schewe, J., and Piontek, F. (2013). 'A trend-preserving bias correction – the ISI-MIP approach'. Earth Syst. Dynam., 4, 219-236, doi:10.5194/esd-4-219-2013, 2013.) The climate model data were from the RCP8.5 simulation which assumes a high forcing by the end of the century close to 8.5Wm-2.
2. Kjellstrom T, Holmer I, Lemke B. (2009). 'Workplace heat stress, health and productivity: An increasing challenge for low and middle income countries during climate change'. Global Health Action; 2. doi:10.3402/gha.v2i0.2047.
3. Kjellstrom T, Lemke B, Otto M, Dear K, Hyatt O. (2014) 'Occupational heat stress. Contribution to WHO project on global assessment of the health impacts of climate change, which started in 2009'. Technical Report 2014:4 at www.ClimateCHIP.org.
4. Kjellstrom T, Lemke B, Otto M (2013). 'Mapping occupational heat exposure and effects in South-East Asia: Ongoing time trends 1980-2009 and future estimates to 2050'. Indust Health 51: 56-67.

5. Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner (2013). 'Long-term Climate Change: Projections, Commitments and Irreversibility'. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324.
6. Taylor, K.E., R.J. Stouffer, G.A. Meehl (2012). 'An Overview of CMIP5 and the experiment design.' Bull. Amer. Meteor. Soc., 93, 485-498, doi:10.1175/BAMS-D-11-00094.1, 2012.
7. IPCC (2013). 'Summary for Policymakers'. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker,T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
8. Kjellstrom et al., 2014

ANNEX: **RISK OF WATER STRESS – METHODS**

For a given climate pathway (or emissions scenario), socio-economic scenario and impact indicator, the principal sources of uncertainty which determine the risk that climate change has a specified impact can be classified into three; (i) the overall magnitude of climate change (as indicated by change in global mean temperature, for example), (ii) the spatial and seasonal distribution of changes in relevant climatic variables associated with a given overall magnitude of climate change, and (iii) the translation of these local and regional climate changes into 'impact'. The effects of all these uncertainties on risk and how it changes over time could be assessed by undertaking multiple simulations under all possible plausible conditions, but this is not feasible in practice. The range in potential impacts of climate change through the 21st century is therefore estimated here by combining estimates of the probability distributions of changes in global mean surface temperature – under a given climate pathway - for each year with damage functions relating change in global mean surface temperature to impact.

Changes in temperature through the 21st century were estimated using a probabilistic version[1] of the MAGICC simple climate model,[2] which is run with multiple parameter combinations to produce distributions of temperature change by year.

Damage functions for each impact indicator were constructed by scaling the patterns of climate change as simulated by different climate models to defined changes in global mean temperature and estimating impacts corresponding to each temperature change by combining a spatial impacts model with defined socio-economic scenario.[3] In this application, 21 climate model patterns were used,[4] so there are therefore 21 different damage functions (representing the 21 different patterns of change in climate) for each time period (because the socio-economic characteristics vary over time). Each of the 21 climate model patterns is assumed to be equally plausible. Impacts were assessed under two climate pathways – represented by the RCP2.6 and RCP8.5 scenarios – and under three socio-economic scenarios defining change in population. The socio-economic scenarios represent medium, low and high population growth assumptions, and are taken from the Shared Socio-economic Pathways (SSPs) projections.[5]

Impacts on exposure to water stress and river flooding are based on river flows as simulated using the MacPDM global hydrological model.[6] which operates at a spatial resolution of 0.5x0.5o. The period 1961-1990 is used to define the reference baseline climate. Water resources per capita is calculated for approximately 1300 river basins and islands, and regional and global totals of people in different water stress classes are calculated by summing the numbers of people in watersheds in those classes.[7]

The average annual number of people in major floodplains affected by floods greater than the current 30-year return period flood is estimated by calculating the change in the probability of experiencing the magnitude of the current 30-year flood in the future in each grid cell, and multiplying by the grid cell floodplain population.[8] Basin-scale changes in the annual probability of experiencing a flood exceeding the current 30-year return period flood were estimated by calculating the weighted average of changes in each grid cell within the basin, weighting by floodplain population (so unpopulated grid cells do not contribute to the average).

Impacts on drought frequency are based on changes in the 12-month standardised precipitation index (SPI) calculated from monthly precipitation. A 'drought' is defined as a month with an index of less than -2 as calculated over the climate baseline period (1961-1990). This occurs just under 2% of the time in the baseline period, and can be regarded as an extreme drought. Change in the average annual area of cropland[9] experiencing such a drought is estimated by calculating the change in frequency of this threshold. The UNDP 2009 Global Assessment Report on Disaster Risks[10] uses the SPI (calculated over 6 months) alongside a measure of precipitation variability to characterise drought risks; their assessment uses an SPI threshold of -1, which occurs approximately 15% of the time.

There are, of course, a number of caveats with this assessment. The estimated distribution of potential changes in temperature in a year is based on one simple climate model – MAGICC – with one set of plausible parameters. The spatial patterns of change in climate are estimated from 21 climate models, all of which are assumed equally plausible: a different ensemble of climate models could give a different indication of the range of potential changes in a region. The damage functions are based on scaling patterns of change from these climate models, which basically assumes that climate in a region varies linearly with global mean temperature:[11] this may not be the case, and there may be substantial 'step changes' or non-linearities in specific regions. Only one impact model is used to estimate hydrological changes, and different models can give different responses to the same change in climate.[12] The range in potential impacts is therefore probably underestimated, although the probability of exceeding a threshold is likely to be more robust (there are no indications that the MacPDM model used here is systematically different from other global hydrological models). Finally, there are different potential indicators for change in water stress, flood risk and drought risk, and these may give different indications of the global and regional effect of climate change.

The results should therefore be interpreted as indicative only: the differences between climate pathways and between places are more robust than the actual magnitudes of impact and risk.

Endnotes

1. Lowe, J. A., C. Huntingford, S. C. B. Raper, C. D. Jones, S. K. Liddicoat, and L. K. Gohar (2009). 'How difficult is it to recover from dangerous levels of global warming?' Environmental Research Letters, 4(1),014012 10.1088/1748-9326/4/1/014012.
2. Meinshausen, M., S. C. B. Raper, and T. M. L. Wigley (2011). 'Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6-Part 1: Model description and calibration'. Atmospheric Chemistry and Physics, 11(4), 1417-1456, 10.5194/acp-11-1417-2011.
3. Arnell, N.W., Brown, S., Gosling, S.N., Hinkel, J., Huntingford, C., Lloyd-Hughes, B., Lowe, J.A., Osborn, T., Nicholls, R.J. Zelazowski, P. (2014). 'Global-scale climate impact functions: the relationship between climate forcing and impact'. Climatic Change doi 10.1007/s10584-013-1034-.
4. Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor (2007). 'The WCRP CMIP3 multimodel dataset - A new era in climate change research.' Bulletin of the American Meteorological Society, 88(9), 1383-
5. O'Neill, BC, Kriegler, E., Riahi, K., Ebi KL, Hallegatte, S, Carter, TR, Mathur, R, van Vuuren DP (2014). 'A new scenario framework for climate change research: the concept of shared socio-economic pathways.' Climatic Change 122 387-400. The scenarios are available from https://secure.iiasa.ac.at/web-apps/ene/SspDb/.
6. Gosling, S.N. & Arnell, N.W. (2010). 'Simulating current global river runoff with a global hydrological model: model revisions, validation and sensitivity analysis.' Hydrological Processes 25 (7), 1129-1145. doi:10.1002/hyp.7727.
7. The methodology is the same as in Gosling, S.N. & Arnell, N.W. (2013). 'A global assessment of the impact of climate change on water scarcity.' Climatic Change doi:10.1007/s10584-013-0853-x, but using different socio-economic scenarios.
8. The simulation of flood flows is described in Arnell, N.W. & Gosling, S.N. (2014). 'The impacts of climate change on river flood risk at the global scale.' Climatic Change doi:10.1007/s10584-014-1084-5, although the indicator here is different.
9. Ramankutty N, Evan AT, Monfreda C, Foley JA (2008). 'Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000.' Global Biogeochemical Cycles 22. doi: Gb1003 10.1029/2007gb002952.
10. UNDP (2009) Risk and poverty in a changing climate: 2009 Global Assessment Report on Disaster Risk Reduction. UNDP: New York.
11. Arnell, N.W., Brown, S., Gosling, S.N., Hinkel, J., Huntingford, C., Lloyd-Hughes, B., Lowe, J.A., Osborn, T., Nicholls, R.J. Zelazowski, P. (2014). 'Global-scale climate impact functions: the relationship between climate forcing and impact.' Climatic Change doi 10.1007/s10584-013-1034-.
12. Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N.W., Clark, D.B., Dankers, R., Eisner, S., Fekete, B., Colon-Gonzalez, F.J., Gosling, S.N., Kim, H., Liu, X., Masaki, Y., Portmann, F.T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., Warszawski, L. & Kabat, P. (2014). 'Multi-model assessment of water scarcity under climate change.' Proceedings of the National Academy of Sciences 111, 3245-3250 doi.10.1073/pnas.1222460110.

Hosts of the project workshops

Harvard University Center for the Environment

Tsinghua University

EEW Council on Energy, Environment & Water

Centre for the Study of Existential Risk, University of Cambridge

Sponsors

Foreign & Commonwealth Office

China National Expert Committee on Climate Change

skoll global threats fund

Global Challenges Foundation

Institute and Faculty of Actuaries

Willis