UK-China Cooperation on Climate Change Risk Assessment:

Developing Indicators of Climate Risk

Committee on Climate Change

China Expert Panel on Climate Change

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A report researched and written by a consortium convened by the UK's Committee on Climate Change and the China Expert Panel on Climate Change

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Contents

Foreword

In 2015, under the leadership of Sir David King, experts from the UK, China, India and the USA jointly published a report entitled *Climate Change: A Risk Assessment*. That work evaluated the risks of climate change and put forward a new model for climate change risk assessment, based on principles and best practice used in other fields where significant interests are at stake. One of its recommendations was that climate risks should be monitored on a continuous basis, so that in areas of uncertainty, any changes or trends in expert judgment are clearly visible over time. This would provide an improved scientific basis for decisions aimed at reducing and managing those risks – and this was the motivation for the collaboration and research on which our new report is based.

In July 2015, a delegation of the China Expert Panel on Climate Change visited London to discuss the necessity and possibility of developing a framework for monitoring risks jointly between China and the UK. Later that year, a 2-year 'Bilateral Cooperation Agreement on Climate Change Risk Assessment and Research' was signed between the UK Committee on Climate Change and the China Expert Panel on Climate Change. The agreement focused on three aspects: 1) future global greenhouse gas emissions pathways; 2) direct risks from the climate's response to greenhouse gas emissions globally; and 3) indirect risks generated by the interaction of climate change and complex human systems.

The report you are now reading is the product of that cooperation agreement. The analysis largely follows the outline in our 2015 agreement, and identifies indicators that could be used to consistently monitor climate risk in each of the three categories mentioned above. It has a specific and deliberate focus on high emissions scenarios and potential systemic failures in socio-economic structures and processes. This analysis of a 'worst case scenario' is consistent with best practice in risk assessment as practised in fields such as public health, civil contingencies and national security. Examining the extreme risks allows stakeholders to develop reasonable contingencies for low-probability, high-impact scenarios; and it allows policymakers to consider properly the level of effort required to avoid those scenarios. The report aims to carry out a deeper assessment, providing a strengthened scientific basis to support the actions of climate change decision-makers and an improved information base for the public.

The report is not, however, the only product of this endeavour: the international and interdisciplinary research team and stakeholder group that produced this report has also developed new ideas, understanding and ways of working that would not have happened without this project. This has significant value and will undoubtedly influence the future work of all those involved here.

Whilst our project was being developed, the Paris Agreement was negotiated at COP21. This represented a landmark achievement, obtained thanks to the joint effort of many countries. The agreement is not a destination, but a new start. It opens a new, more positive and practical stage in global action to address climate change, based on national pledges to contribute to emissions reduction, to be ratcheted up over time. It recognises the need to choose green and low-carbon development paths and to avoid unacceptable climate risks. Our report highlights what might be at risk if the Paris goals are not met.

Unfortunately, such a world is a possibility: the signing of the Paris Agreement does not guarantee that its aims will be met. Indeed, the announcement by President Trump that the US would withdraw from the Paris Agreement was undoubtedly negative. Furthermore, global greenhouse gas emissions have continued to rise in recent years. We must not forget, however, that the future is still in our own hands. There is still time to put in place the measures required to avoid the worst impacts of climate change and to prepare for those changes that are unavoidable. So, these negative developments emphasise the need for signatories to the agreement to maintain their resolve, and the new importance of actions at sub-national level, including in the US. It also highlights the continued importance of the international scientific community. More consistent and comparable assessments of climate change risks are required; and positive support and a strengthened evidence base for the actions required to address climate changes on all scales are needed.

Our report shows that the consistent monitoring and assessment of climate change risks is feasible and has significant value. As a result, we recommend that the principle of consistent and comparable climate change risk assessment, using indicators of risk where appropriate, be incorporated deeper into the climate change mitigation and adaptation evidence and policymaking process. With the upcoming international agenda of climate change events – the IPCC Sixth Assessment Report, the 2019 United Nations Secretary-General's Climate Summit, the 2023 UNFCCC Global Stocktake – this is the ideal time to reassess the global climate change risk assessment process.

杜祥琬
Du Xiangwan

Du Xiangwan

Honorary Chairman, China Expert Panel on Climate Change

Deben

Lord Deben

Chairman, Committee on Climate Change

Executive summary

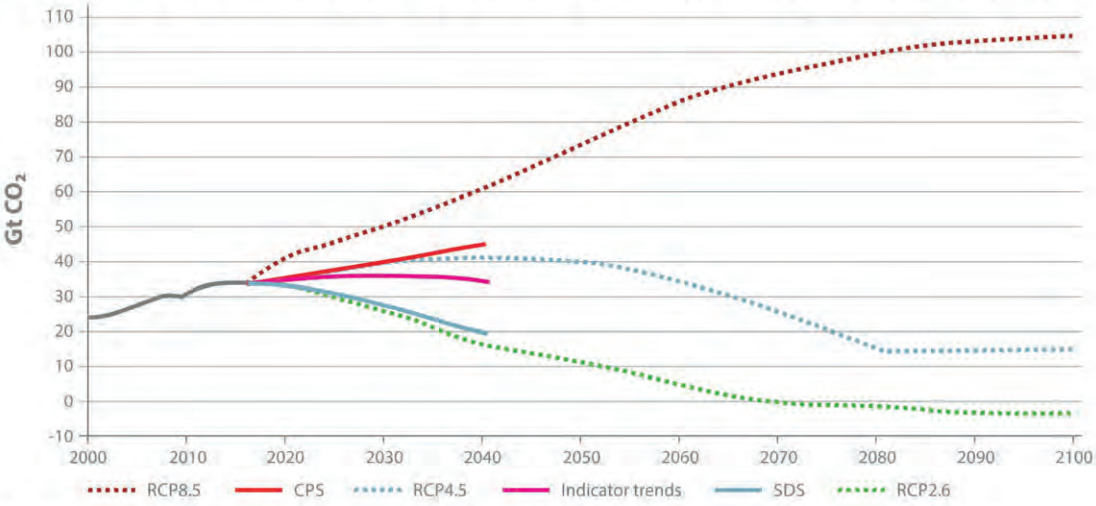
Risk indicators summary

Emissions risks

Energy sector indicators[1]

Sector	Indicator	Unit	Current level 2017	Indicator trends 2040	Sustainable development scenario 2040	Degree on track[2] (%)
Power	Variable renewable electricity capacity	GW	920	5400	6200	80
	Nuclear capacity	GW	419	600	720	40
	CCUS capture capacity	$MtCO_2$ captured/year	30	50	1500	0
Transport	Average passenger car fleet oil consumption	litres per 100 km	8.7	4.5	2.5	45
	Average fuel efficiency of trucks	litres per 100 tonne-km	3.6	2.9	1.5	0
	Biofuel consumption in aviation and shipping	mboe/d	0	0.1	2.6	0
Industry	Energy demand/value added	toe/million USD	175	150	110	0
	CO_2/energy consumption	tCO_2/toe	1.6	1.4	1.2	40
	Zero-carbon fuel share in sector	%	26	28	40	0
Buildings	(Residential) Energy demand/ dwelling	MWh/dwelling	12.1	9.9	7.7	35
	(Services) Energy demand/ value added	kWh/1000 USD	194	140	120	35
	Share of fossil fuels and traditional biomass	%	59	47	37	0

Energy sector indicators in aggregate suggest an emissions pathway of c.35 Gt CO_2 by 2040



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[1] Red indicates that the sector is not on track for the Sustainable Development Scenario. Trends are most in line with the IEA Current Policies Scenario. Amber indicates that there has been some encouraging progress to date, but more efforts needed to satisfy the needs of the IEA Sustainable Development Scenario. Green indicates that trends are most in line with the IEA Sustainable Development Scenario, although continued progress and policy support remain essential.

[2] A value of 100% indicates the indicator is in line with the Sustainable Development Scenario; a value of 0% indicates the indicator is in line (or below) the Current Policies Scenario. Calculated as: (indicator trend value in 2040 – CPS value in 2040)/(CPS value in 2040 – SDS value in 2040).

Direct risks: Hazard indicators *(exposure and potential impact indicators also calculated but not illustrated)*

GLOBAL

Sector	Risk	Indicator	Historical reference level[3]	2100[4]: Low emissions median	2100[4]: High emissions median
Heat extremes	Health impacts	Heatwave (% chance of at least one)	4.7	39	99
	Labour productivity	Days/year with WBGT > 32° C	0	0.05	6.4
Water resources	Periodic water shortage	Hydrological drought (% chance)	5.9	7.9	11
	Persistent water shortage	Area with decrease in runoff (% of area)	0	13.5	35
River flooding	Losses	Flood frequency (% chance of flood > T50)	2	3.4	12.2
Coastal flooding	Losses	Area below the 100-year flood level (10^3 km^2)	641	790	896
Agriculture	Production losses	Agricultural drought (% chance)	9.4	30	70
		Flood frequency (% chance of flood > T30)	3.3	4.8	12.9
		Maize: heat spell frequency (% chance)	4.2	13.8	64
		Maize: reduction in rainfall (% chance)	15	16.6	24
		Maize: decrease in crop duration (% chance)	2.3	34	88
		Maize growing season temperature >23° C (% chance)	46	63	94

CHINA

Sector	Risk	Indicator	Historical reference level[5]	2100[4]: Low emissions median	2100[4]: High emissions median
Heat extremes	Health impacts	Max temperature/year (°C)	31	32.5	36.8
	Labour productivity	Days/year with max temperature >35° C	9	14	34
		Heatwaves/year with 5 or more days >35° C	3	4.8	11
Water resources	Periodic water shortage	Glacier ice storage (% reduction in glacier mass)	0	30	64
	Persistent water shortage	National water resource (billion m^3/year)	3055	3210	3323
Coastal flooding	Losses	Area below the 100-year flood level (10^3 km^2)	84.2		99.2 *(2050)*
Agriculture	Production losses	Agricultural land exposed to drought (10^3 km^2)	345	481	703
		Rice: heat damage (% chance)	19	22	60
		Winter wheat: waterlogging during seedling stage (% chance)	59	45	40
		Winter wheat: waterlogging during heading-filling stage (% chance)	74	70	65

[3] 1981-2010 for global-scale hazard indicators.

[4] Average climate in 2100 for low and high emissions. Each represents an annual average over a 30-year period.

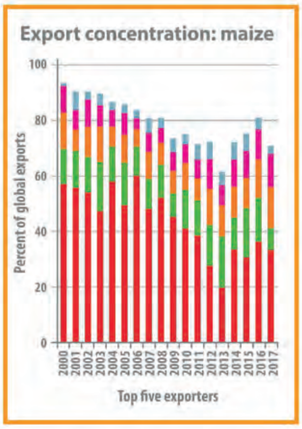
[5] 1986-2005 for China-scale hazard indicators.

Global systemic risks (e.g. to the global food system[6])

Hazard indicators | **Exposure indicators** | **Vulnerability indicators**

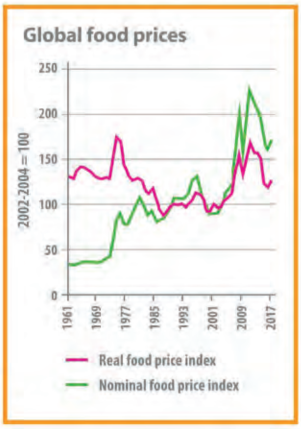
Initial hazard: Climate-driven harvest shock

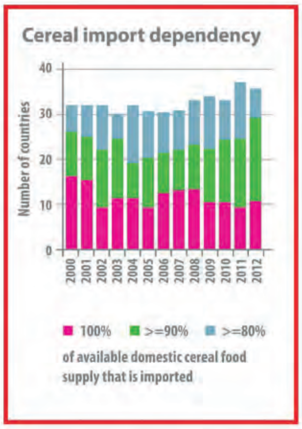

Global production volumes

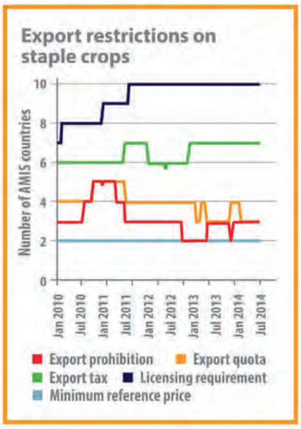

Export concentration: maize


Global stock-to-use ratios

Subsequent hazard 1: International food price spike

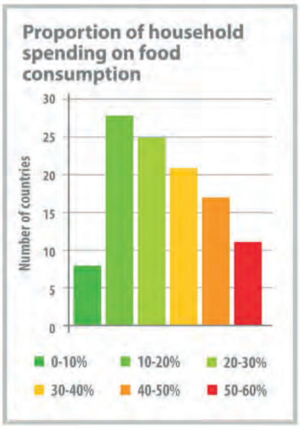

Global food prices

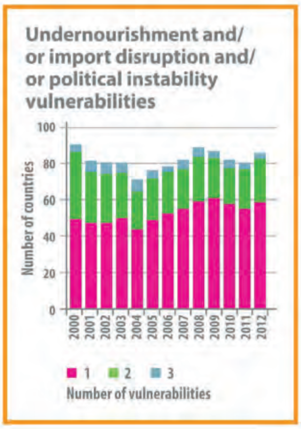

Cereal import dependency


Export restrictions on staple crops

Subsequent hazard 2: National food price spike


National food price trends (e.g. Indonesia: rice national retail average)


Proportion of household spending on food consumption


Undernourishment and/or import disruption and/or political instability vulnerabilities

Subsequent hazard 3

Full risk cascade results in:
Household food crises and national instability

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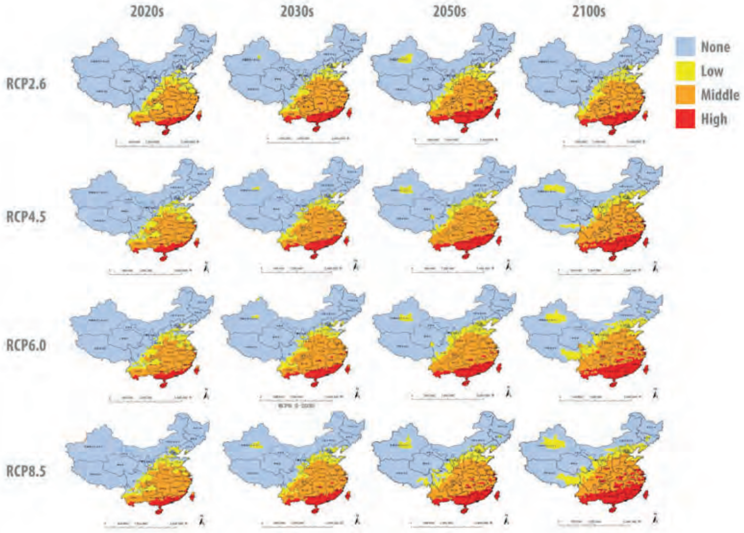
[6] Indicators presented for the food system are illustrative; see Chapter 4 for a fuller set of indicators. The coloured borders for each chart reflect subjective judgements of the level of 'stress' suggested by current indicator data. Green generally denotes stable conditions, or positive trends; amber denotes moderate stress with little temporal change; red denotes unfavourable conditions or negative trends.

Indirect risks in China

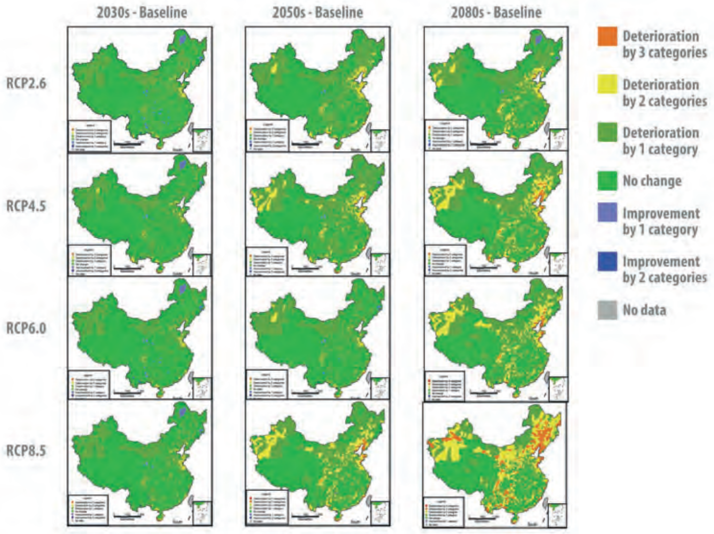
Urban & health risks (illustrated), climate poverty & water risks (not illustrated)

Urban risk example:
Chinese cities' resilience to rainstorms

Health risk examples:
Changes in dengue fever risk areas under different scenarios



Health effects of heatwaves in representative regions of China



Introduction

Warming of the climate is unequivocal, and it is clear that anthropogenic greenhouse gas emissions are the principal driver (IPCC Fifth Assessment Report, Working Group I).[1] Changes to the climate create risks to the natural, social and economic systems upon which societies depend. Extreme weather events such as heatwaves, droughts, intense precipitation and floods can cause humanitarian disasters, destabilise markets, damage critical infrastructure and harm food production. Although of a different nature, the slow onset risks from gradual changes in sea level and average temperatures are no less important and present existential threats to vulnerable populations such as those of low-lying small islands. As global temperatures continue to rise, so too do the risks of passing tipping points in the climate system that could trigger abrupt and disruptive changes that are very difficult to anticipate and adapt to (see Box 1).

Understanding the nature and severity of these risks is fundamental to the urgent tasks of mitigation and adaptation. Decision-makers need information on the full range of risks that climate change poses, including across the spectrum of probabilities, recognising that a low-probability outcome may still correspond to a high risk if the impact is severe – and that what is low probability at one time may become high probability at a later time.

This report responds to this need. It is the result of collaborative research led by the China National Expert Committee on Climate Change and the UK Committee on Climate Change, involving research institutions from both countries alongside the International Energy Agency (IEA). It builds on an earlier collaboration that concluded in 2015 with the report, *Climate Change: A Risk Assessment*[2] and responds in particular to that report's recommendation that '*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. [And] this could be facilitated by the identification and use of a consistent set of metrics or indicators.*' As the 2015 report pointed out, the use of such indicators could significantly help decision-makers reach their own judgments when confronted by a wide range of differing expert opinions. It proposed three categories of risk to assess: the future pathway of global emissions; the direct risks arising from the climate's response to those emissions; and the risks to complex human systems.

This project provides a proof of concept for developing such a set of indicators in each of these categories. The methodologies and results described here provide a first step towards a framework with which policymakers might monitor and assess these dimensions of climate risk over time, allowing them to discern changes in trends and expectations with a view to informing mitigation and adaptation strategies on an ongoing basis. As such, it does not provide a comprehensive set of indicators nor definitive recommendations for climate risk management. Rather, it provides insights for how approaches can be developed, refined and extended in the future to make such an approach possible.

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[1] IPCC (2013) *Climate Change 2013: The Physical Science Basis*, http://www.ipcc.ch/report/ar5/wg1/

[2] King, D., et al. (2015) *Climate Change: A Risk Assessment*, http://www.csap.cam.ac.uk/media/uploads/files/1/climate-change--a-risk-assessment-v9-spreads.pdf

Box 1: Climate risk and tipping points

Rapid changes in the climate system can occur abruptly once certain thresholds, or tipping points, are breached. Examples include a significant slowing or collapse of the Atlantic Meridional Overturning Circulation (AMOC), ice sheet collapse, melting of the arctic permafrost and associated release of carbon, the release of sub-sea methane hydrates, disruption of the monsoon and El Niño Southern Oscillation weather patterns, and dieback of tropical forests. There is considerable uncertainty about when and under what degree of temperature rise these thresholds might be breached. It is thought that the chance of reaching tipping points increases with temperature rise, meaning that the risks become more material on a high emissions pathway.

Taking each in isolation, the likelihood of triggering most tipping elements this century is thought to be small. However, the severity of the potential impacts is enormous. For example, a collapse of the AMOC could alter the climate for Europe, Central America, South America, India and Sub-Saharan Africa with profound implications for food production. These could include a 30% fall in European crop yields, 10% declines in Indian rice yields and the collapse of agriculture in large parts of the Sahel. A collapse of the AMOC could occur over a single decade. This would trigger extreme disruptions to the global food system without historical precedent.[3]

But when tipping points are considered together, there may be a non-trivial risk of tipping elements being triggered, *even on a low emissions pathway*. A recent paper[4] argued that at around 2°C of temperature rise, the risk of triggering certain tipping elements may become material, and that these may then unleash a 'tipping cascade' in which a sequence of tipping elements are triggered as a result of accelerating climate change and feedbacks between them.

Tipping points have not been included in this proof of concept; however, it is recommended that they be integrated into any future climate risk framework – for example, through the development and monitoring of early warning indicators. Given the high degree of uncertainty around the probability of reaching these tipping points, a consistent monitoring of scientists' best estimates of those probabilities would be of high value to policymakers.

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[3] The Global Food Security Programme, UK (2017) *Environmental tipping points and food system dynamics: Main Report*, https://www.foodsecurity.ac.uk/publications/environmental-tipping-points-food-system-dynamics-main-report.pdf

[4] Steffen, W. et al. (2018) Trajectories of the Earth System in the Anthropocene. *PNAS*, 115 (33), 8252-8259, http://www.pnas.org/content/115/33/8252

The international context

Recognition of the common threat posed by climate change enabled governments to agree an unprecedented collective response in 2015, at COP21 in Paris. The Paris Agreement sets the common goal of limiting global average temperature increases to 'well below' 2°C and 'pursuing efforts' to 1.5°C to be achieved through increasingly ambitious national pledges, referred to as nationally determined contributions (NDCs) to reduce greenhouse gas emissions, leading to a balance between sources and sinks of emissions during the second half of the century.

Three years later, the international community has reached a critical juncture. The first opportunity for governments to increase their collective ambition is imminent, as parties prepare to enter into a facilitative dialogue in preparation for the resubmission of their NDCs in 2020. But the United States, the world's largest economy and second biggest emitter of greenhouse gases, has announced its intention to withdraw from the Paris Agreement. And whilst other governments have reaffirmed their commitment to Paris, the task before them is immense. Under current policies, the gap in annual emissions compared to a 2°C least-cost pathway will have reached 14-17.5 $GtCO_2e$ by 2030. Implementing new policies consistent with achieving the NDCs (including that of the United States) would close the gap to 11-13.5 $GtCO_2e$ (UNEP Emissions Gap Report, 2017[5]), still significantly more than the current annual emissions of the United States and European Union combined. Most importantly, current NDC pledges imply global emissions continuing to *increase* throughout the period they cover, whereas for the 2°C Paris goal to be met, they need to begin decreasing as soon as possible.

This raises a number of important questions for governments as they enter into the facilitative dialogue. How are efforts to decarbonise the real economy progressing, and where are the biggest gaps between current policies, pledged ambition and what is actually needed to achieve the Paris goal? What, therefore, is the chance that the world is on a high emissions pathway, and which sectors and subsectors of the real economy require the most urgent policy attention if the risk of a high emissions pathway is to be reduced? What risks do we face on a high emissions pathway and a Paris-compliant pathway?

This project reached three important conclusions which are of direct relevance to these questions. These are further elaborated in the Key findings Box (page 15 below).

First, global efforts to reduce carbon dioxide emissions are dangerously off track: the risk of failing to reduce global emissions onto a 2°C pathway is high and the chance of a high emissions pathway is material. Current progress is not sufficient to limit the temperature rise by 2100 to 2°C. Achieving the 'well below 2°C' Paris goal remains possible but requires a step change in policymaking: nearly all indicators of progress in energy-sector decarbonisation are not in line with the requirements for a 2°C pathway. If policy ambition, technology deployment and investment levels advance at the rates observed in the past, this is likely to lead to 2.7°C of warming by the end of the century (central estimate) and a plausible worst case of 3.5°C (10% chance). Limiting the temperature rise even to these levels assumes that policymakers increase efforts to reduce emissions above existing plans,

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[5] UNEP (2017) *Emissions Gap Report 2017*, https://www.unenvironment.org/resources/emissions-gap-report-2017

which is far from assured. If there is any backsliding or stagnation in policymaking, this could lead to much higher levels of warming, with a plausible worst case of 7°C by the end of the century.

Second, on a high emissions pathway, climate change poses a very high risk to social, economic and environmental systems. The incidence and severity of heatwaves, droughts and floods would increase markedly, with significant direct impacts on human populations and major disruptive risks to complex human systems encompassing food markets, city security, financial markets, infrastructure and health. Moreover, there is a non-trivial risk of passing critical tipping points on a high emissions pathway, some of which could have profound consequences for systemic risks and generate extremely severe societal impacts such as food crises and mass migration.

Third, at the global scale, direct and systemic risks are expected to increase *even on a low emissions pathway*. On a 2°C-compliant pathway, that is, representative concentration pathway (RCP) 2.6, all indicators of direct impact risk increase from current levels. Even if governments are successful in achieving the Paris 'well below 2°C' goal, there will still be a significant degree of residual risk that must be managed. Climate-related impacts will increasingly threaten the stability of complex human systems, particularly if these develop in ways that increase exposure to impacts (for example, through the location of critical infrastructure) or vulnerability to disruption. Managing systemic risks will require new cooperative approaches and governance arrangements. It cannot be assumed that economic growth by itself will allow risk to be reduced.

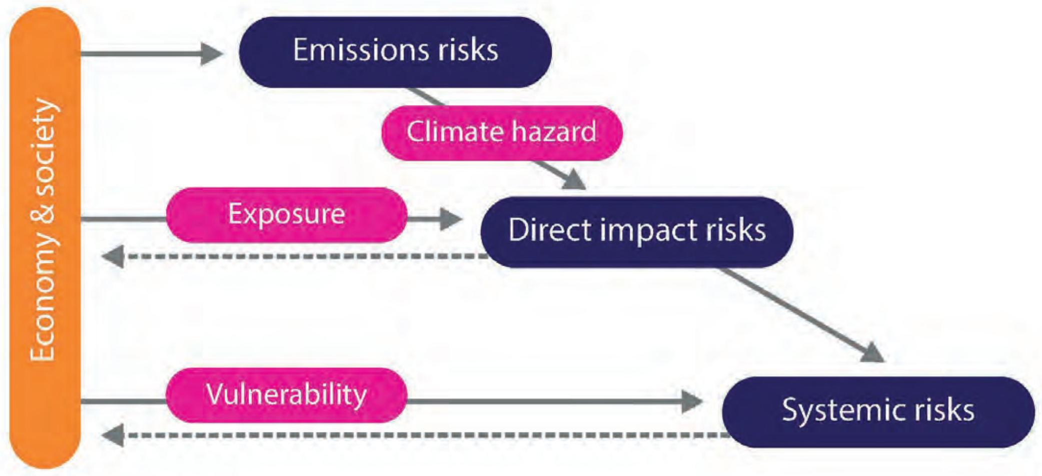
Conceptual framework and methodology

Indicators – summarised on pages 4 –7 – were developed for the three categories of risk (Figure 1) identified in *Climate Change: A Risk Assessment*:

- Emissions risk – specifically the chance that the world is on a high emissions pathway.
- Direct impact risk – relating to climate change impacts on agriculture, water resources, flooding and heat extremes.
- Systemic risk – where direct climate impacts trigger risk cascades that propagate through complex systems such as food markets or financial systems.

For direct impact and systemic risks, indicators were developed at both the global and China scales to demonstrate the applicability of the approach at different levels. At the global level, these three categories of risk are sequentially related: the risk of a high emissions pathway increases the risk of direct climate impacts which can, in turn, trigger cascades of indirect impacts in wider systems. For example, on a high emissions pathway, the (direct impact) risk of serious harvest failures due to extreme weather is expected to increase, in turn increasing the (systemic) risk of wide-ranging disruptions to the global food system.

Figure 1: Simple conceptualisation of categories of climate risk



Emissions risk

As an initial proof of concept, efforts were confined to energy-related carbon dioxide emissions which amount to around two-thirds of global greenhouse gas emissions. A three-tiered approach is adopted to track emissions risk from the energy sector with increasing granularity.

- First, consideration is given to two key drivers of global energy-related CO_2 emissions: energy consumption per unit of GDP and CO_2 emissions per unit of energy consumption. The outcomes of these metrics are presented for various IPCC AR5 scenarios representing business-as-usual (non-mitigation), 550ppm and 450ppm atmospheric concentrations.

- Second, seven energy-sector-wide indicators are considered under the same scenarios, illustrating the proportion of different energy sources in primary energy production, final energy consumption and power generation.
- Third, a set of 12 indicators was selected to assess existing global progress in decarbonising the energy sector. For this final tier, indicators were selected to cover a broad range of emissions sources whilst remaining policy relevant.

Historical time series for each indicator were used to develop trends that could be compared to projected developments under different IEA energy scenarios (current policies, new policies and sustainable development – where only the latter is consistent with achieving the Paris goal) to assess the risks that progress is off track. The individual indicator trends are then aggregated to project energy-sector and industrial-process CO_2 emissions, which are compared to emissions under the IEA energy scenarios and IPCC representative concentration pathways (RCP8.5, 4.5 and 2.6).

Direct impact risk

Indicators of hazard, exposure and impact were developed for eight sub-categories of direct risks relating to heat extremes, water resources, flooding and agriculture. These were forecast to 2100 under a low emissions scenario consistent with the 2°C Paris goal (RCP2.6) and a high emissions scenario (RCP8.5; median temperature increase of around 5°C in 2100), broadly comparable to the sustainable development scenario and the current policies scenario used to assess progress on decarbonising the energy sector. The indicators were compared to quantify the difference in risk between a high and a low emissions scenario. To define a plausible worst case, we took an upper estimate of impacts under the high emissions scenario (see Box 2).

Box 2: Worst case scenarios

Risks are by their nature uncertain and can be presented in different ways. For example, in terms of the likelihood of a particular threshold being exceeded or a particular event occurring; or in terms of the range of possible impacts under particular scenarios. An important concept for decision-makers is that of the worst case scenario. This is the most severe outcome that might plausibly occur. It has obvious utility for planning, for example, when decision-makers may wish to ensure that strategies or investments are viable not simply under expected conditions, but also resilient in more extreme circumstances. Alternatively, they may decide to act to reduce the likelihood of those extreme circumstances arising.

Worst case scenarios have been used to characterise emissions risk and direct impact risk in this study, by defining a plausible worst case outcome from the upper end of an estimated distribution of potential impacts. Therefore, when projecting temperature rises associated with a particular emissions pathway as part of our assessment of emissions risk, these are presented in terms of a central, or expected, estimate and also a plausible worst case estimate. Similarly, for a given emissions pathway, indicators of impact risk are estimated for the expected temperature increase but also for the plausible worst case.

Box 2: Worst case scenarios

For example, under RCP8.5, which approximates the global emissions pathway the world may migrate to should mitigation policies stall, the expected temperature rise by 2100 is around 5°C but the plausible worst case (with a 10% chance) is 7°C. In these scenarios (expected and worst case), sea level rise could be 80cm and 100cm respectively.

It is important to keep in mind that the risks of climate change tend to increase over time. So what is a plausible worst case at one point in time may become the expected case or even highly likely at a later point. For example, under a high emissions pathway (RCP8.5) the probability of a 7°C temperature rise could exceed 50% during the 22nd Century. And even with a sustained global temperature increase of 2°C, we may be committed to a long-term global mean sea level rise of more than a metre[6] – though the timescale over which this will take place is highly uncertain. Consequently the report, *Climate Change: A Risk Assessment* recommended that climate change risks should be assessed by first identifying a threshold of severity of impact of particular concern, and then considering how its likelihood will change over time. We have taken this approach to developing some of the risk indicators in the 'Direct impact risk' section of this report.

Systemic risk

Recognising that the range of possible disruptions to complex, interconnected systems is almost infinite and impossible to model, a narrative approach was used to characterise a systemic disruption as a sequence of cascading indirect impacts initially triggered by a climate impact: from direct impact, to first order indirect impact, to second order indirect impact, and so on. Particular indirect risk transmission points within the system critical to propagation were identified, and indicators of exposure and vulnerability were developed at each. For example, when considering risk transmission from one market to another, indicators were identified to assess the second market's exposure to instability in the first and its vulnerability to instability. Of course, this is an imperfect picture as it is reductionist and inevitably fails to capture the multitude of possible transmissions that could shape a risk cascade. But taken in aggregate, these indicators of indirect risk provide an overall picture of system fragility (see Figure 2 below).

The approach was demonstrated at the global scale for the global food system, with the utility of indicators back-tested against recent instances of system volatility. At the China level, research focused primarily on quantitative analysis of first order indirect risks, illustrating how a number of Chinese regions, populations and economies have been, and could be, impacted by both sudden onset and insidious climatic risks inducing glacial melting, urban insecurity, climate-related poverty and migration, and health impacts. For example, analysis of health impacts found that climate change and extreme weather events have caused, and are expected to continue to cause, the expansion of disease-vector habitats, vector-borne disease risks, and heat-related morbidity and mortality. These factors can result in declines in labour productivity and economic growth, potential

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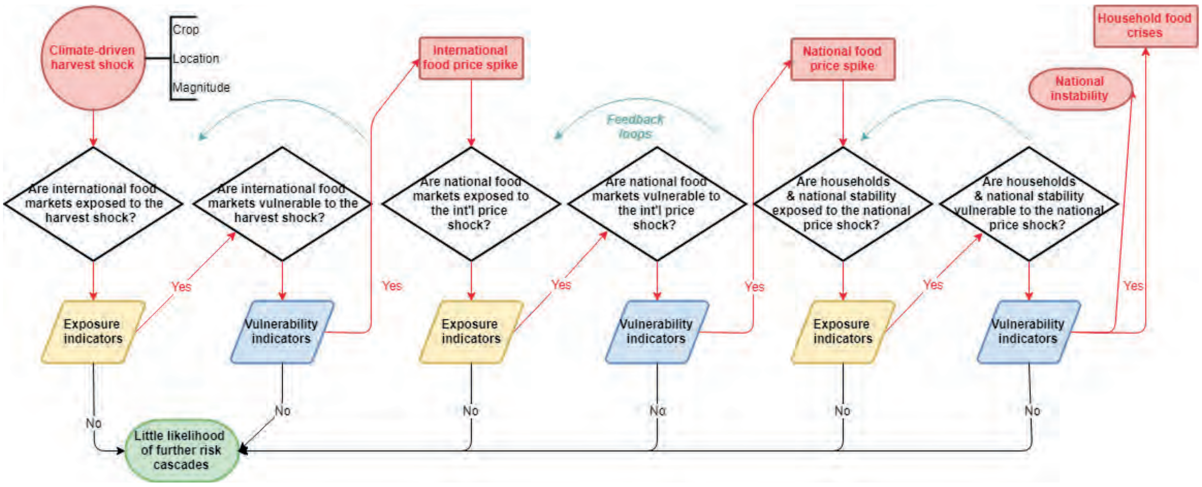
[6] Nicholls, R. et al. (2018) Stabilization of global temperature at 1.5°C and 2.0°C: implications for coastal areas. *Phil Trans A,* 376 (2119), 20160448.

public health crises, interruptions to education systems, migration and border instability, among other systemic risks.

Figure 2: Conceptualisation of a risk cascade



Key findings

1. **Without urgent action to accelerate emissions reduction efforts, there is a significant risk that we will fail to achieve the Paris Agreement's goals.**

Global efforts to reduce carbon dioxide emissions are dangerously off track. Although transformation of the global energy system is underway, progress is too slow and too patchy to achieve a low emissions pathway.

- Of 12 sectoral indicators, only one (deployment of mature renewables such as onshore wind and solar photovoltaics) is on track for a 2°C-compliant emissions pathway.
- Particularly off track, and in need of urgent policy attention, are carbon capture and storage, freight transport, advanced biofuels, industry (efficiency improvements and the share of zero carbon fuels) and the level of zero carbon fuels consumed in buildings.
- Without a step change in policy ambition, the Paris Agreement's goal of limiting global temperature increases to well below 2°C by the end of the century will almost certainly be missed. Existing trends in policy ambition, technology deployment and investment levels point towards a median temperature rise in 2100 of around 2.7°C (worst case 3.5°C). Limiting the temperature rise even to these levels (which means failing to achieve the Paris Agreement's goals) assumes that policymakers increase efforts to reduce emissions above existing plans, which is far from assured.

2. **Continuing with current policies places the world on a high emissions pathway that could lead to a global temperature increase in 2100 of 5°C (central estimate) and a plausible worst case increase of 7°C (10% chance).**

Key findings

At these levels of warming, the direct risks to human and natural systems at the global scale are severe, particularly in a plausible worst case outcome where:

- At the global scale, heatwaves which currently have a less than 5% chance of occurring in a year would occur in almost every year by 2100.
- The risk of flooding increases significantly. One metre of sea level rise by 2100 results in the coastal area exposed to a 1-in-100-year flood increasing by 50%; the incidence of river flooding at the global scale increases by up to 10 times.
- Agriculture is profoundly impacted by a near tenfold increase in the frequency of agricultural drought and higher temperatures that reduce crop yields: temperature extremes that threaten maize production would occur in 80% of years (compared with around 5% currently).
- In China, the number of heatwaves may increase by a factor of three by the end of 21st Century. Rice production may suffer heat damage in 80% of years (compared to around 20% presently), which implies around 20% food production loss in China. Water scarcity in water-stressed regions of western China would increase as glaciers shrink by almost 70%. If considering the impact of extreme events, such as drought, the population under water pressure in the western region would increase by around two times. The maximum population and GDP exposed to the coastal flooding risks in 2050 could exceed 100 million people and more than RMB 32 trillion respectively.

3. **Globally, the risks of direct impacts will increase materially even on a *2°C-compliant emissions pathway.***

At the global scale, direct impact risk increases across all indicators on RCP2.6:

- The global frequency of river flooding increases by a factor of three, and the area affected by coastal flooding increases by 30%.
- The frequency of heatwaves increases, but by less than under higher emissions, and the chance of extremely hot and humid days is greater than at present but considerably less than with high emissions.
- Temperature extremes that challenge maize production would occur in approximately three in ten years.

In China, RCP2.6 could mean that, by the end of the century:

- The average annual number of heatwaves per year may double.
- Glacier mass may reduce by 30%.
- Agricultural land area exposed to drought may increase by more than 40%; rice production may suffer heat damage in around 30% of years (compared with 20% at present).

4. **Increasingly frequent and severe climate impacts threaten the stability of human systems. Disruptions may propagate through complex economic and social systems in ‘risk cascades’ that are hard to anticipate and prepare for and have serious consequences for populations.**

Recent bouts of volatility in international food markets, such as the 2008 global food price crisis and the 2011 wheat price spike, have illustrated the vulnerability of the global food system to

Key findings

extreme weather and demonstrated how risk transmits across borders, potentially contributing to social instability. Other 'at risk' complex systems spanning international, regional and national scales include finance, health and critical infrastructure.

- Increasing direct risks to agricultural production in key export countries could have serious negative consequences for food system stability and lead to significant wider risks to security where food insecure, fragile states are adversely affected.
- In China, the implications of melting glaciers for flooding and water scarcity may increase the risks of poverty and migration in western regions and neighbouring countries, whilst the spread of vector-borne disease could trigger risk cascades into the education system and the tourism sector and create cross-border tensions.

Managing indirect climate risks to complex systems is particularly difficult. Reducing emissions will reduce the risks, but certainly not remove them. Similarly, governments cannot assume that economic growth will simply reduce risk. It may help to reduce vulnerability in some instances (for example, wealthier populations are less vulnerable to food price volatility) but may increase exposure in others (for example, if population and assets accumulate in risky areas, as is happening in China's three major city clusters, and as was witnessed when Hurricane Katrina struck the Gulf Coast of the United States). Moreover, the transboundary nature of indirect systemic risks means that unilateral responses will be insufficient. National adaptation strategies may be unable to fully address risks beyond borders and, in some cases, unilateral responses to reduce exposure and vulnerability to systemic risks may inadvertently *increase* systemic risks if pursued in isolation or in a beggar-thy-neighbour fashion.

Implications for decision-makers

Based on current climate science, this collaborative research endeavour has assessed, and developed indicators for, three categories of climate risk: the future pathway of global energy-sector emissions; the direct risks arising from the climate's response to those emissions; and the risks to complex human systems. The findings regarding these risks have a number of important global implications for decision-makers in government, international organisations and the private sector.

1. Climate change risks need to be addressed with greater importance by all countries

As unconventional security risks, direct and systemic climate change impacts should be included in national and global security risk assessments. Addressing climatic change impacts and implementing low-carbon development should be regarded as significant parts of a strategy for economic and social development. The push for low-carbon economies needs to be approached with greater determination and political courage.

2. Emissions reduction efforts must accelerate if a low emissions pathway is to be achieved and a high emissions pathway avoided

Energy-sector decarbonisation is not progressing at the pace required and a step change in ambition is necessary. Continued policy efforts and technological development in line with historical precedent would still be insufficient to limit temperature increases to well below 2°C by the end of the century. Any stagnation or backsliding of policy risks migration onto a high emissions pathway more consistent with RCP8.5 (median 5°C temperature increase by 2100). The upcoming facilitative dialogue and deadline for governments to resubmit their NDCs presents a critical opportunity for collective action to manage global emissions risk.

3. Future risks cannot be eliminated and will increase in both low and high emissions scenarios

Decision-makers must prepare for a future of increasing direct and systemic risks in all emissions scenarios. Increasing exposure of human populations and assets to direct and indirect impacts is likely to be an important driver of direct and systemic risks. Increasing frequency and severity of direct impacts at the global scale will increase the risk of trigger events for systemic disruptions. Increasing complexity, due to more extensive global supply chains and increasingly interconnected technologies and systems, for example, is likely to exacerbate systemic risks.

4. New governance arrangements are needed to manage systemic risks

Overcoming the particular challenges of coordination and extra-territoriality inherent in systemic risk management will require new governance approaches at international, regional and national levels and tailoring to the particular systems in question. As national and international security concerns arise from many systemic climate risks, these concerns and existing security-sector organisations should both be factored into future governance arrangements. Given the long lead times involved in building new institutions and developing existing ones, efforts should begin immediately to understand more fully the nature of different climate-induced systemic risks (e.g. for financial markets, the global food system, health systems, critical infrastructure systems, etc.) and develop risk management frameworks and identify data requirements for collective risk monitoring.

5. The omission of tipping points from this analysis means that worst case impacts may be underestimated

The chance of passing climate system tipping points during the course of this century is thought to increase with temperature rise. Therefore, on a high emissions pathway there is a significant risk of critical thresholds being exceeded, particularly with a plausible worst case temperature rise of 7°C by the end of the century. There is also a non-trivial risk of tipping points on lower emissions pathways, as argued in a recent paper.[7] Certain thresholds may be reached at lower levels of temperature increase – possibly around 2°C – and trigger a cascade of tipping elements that could accelerate climate change and generate catastrophic direct and indirect impacts. For example, accelerated melting of the Greenland ice sheet could lead to more rapid sea level rise and slow the Atlantic overturning circulation with profound implications for weather patterns, and also contribute to melting of Antarctic ice. Consequences of these changes could include dieback of the Amazon rainforest, leading to higher levels of atmospheric carbon, and a catastrophic drop in agricultural output.

6. Decision-making should take a long-term perspective on future climate risks

The deteriorating outlook for direct and systemic risks has implications for decisions with long-term outcomes and investments with long lifetimes. For example, infrastructure built today might still be operational by the end of the century when risks will be considerably more severe; the effectiveness of long-term carbon sequestration by reforestation or afforestation will depend on future climate change in the areas concerned. It is therefore important that decision-makers consider the full range of future climate risks over the coming century, including the possibility of a high emissions pathway and the associated plausible worst case outcomes for direct and systemic risks, to ensure that their decisions are resilient to climate change in the long run.

7. Integrating analyses of climate risk and resilience into decision-making can have wider economic benefits

Economies with resilient infrastructure and strong risk management practices are likely to enjoy lower costs of capital and attract higher rates of investment, all other things being equal. Nonetheless, the primary financial incentives for investing in resilience are protecting people, avoiding future costs and protecting cash flows in the wake of a shock. As such, short-term interest in financial rewards can result in inefficient capital allocations to resilient infrastructure, and real demand for such investments is hampered. For example, governments are discouraged by additional upfront capital costs and political opportunity costs; investors lack relevant benchmarks and tools to guide their capital allocations; and multilateral development banks struggle to assess and report the resiliency of their operations. It is therefore paramount that investment appraisal methods provide

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[7] Steffen, W. et al. (2018) Trajectories of the Earth System in the Anthropocene. *PNAS*, 115 (33), 8252-8259, http://www.pnas.org/content/115/33/8252

better pricings of physical climate risks so net present values reflect improvements in resilience; that capital market instruments are devised to direct capital to resilient infrastructure projects by integrating insurance risks; and that credit rating methodologies are adjusted to improve their assessments of resilience and provide resilient projects with improved capital costs.

8. The prospects of future climate resilience are improved by accelerating current mitigation efforts

Whilst future risks cannot be eliminated, the best prospects for minimising climate hazards and avoiding reaching adaptation limits are offered by expediting and increasing the ambition of current mitigation actions. Delays in action will constrain future development options, whilst ambitious economic, social, technological and political transformations enacted now may maximise the prospects of resiliency to future climatic risks.

Implications for risk assessment and monitoring

A key conclusion of this project is that a common framework for the regular and consistent assessment and monitoring of climate risk is a feasible proposition.

The 2015 report, *Climate Change: A Risk Assessment*, demonstrated how general principles of risk assessment could be applied in relation to climate change. These include: assessing risks in relation to objectives; identifying the largest risks; considering the full range of probabilities; using the best available information; taking a holistic view; and being explicit about value judgments.

In this new project, we have demonstrated proof of concept of a framework for the regular and consistent assessment and monitoring of emissions risk, direct impact risks and systemic risks, based on a set of indicators. The methodologies developed here can certainly be further refined and improved, but they are tractable and generate results that can inform decision-making. They are based on data that can be readily and regularly compiled.

Emissions risk indicators can be updated on a consistent basis using information from the IEA database. Regular updating of these indicators (e.g. on an annual basis) will show whether the rates of deployment of clean technologies are converging towards the trends required for consistency with the 'well below 2°C' goal, or diverging further from them.

Over a longer time period, the mixture of technologies assumed in the 2°C consistent scenario is itself likely to change, and this will in turn influence the indicators. The effect of any changes in assumptions should be reported explicitly, and the trend of such changes monitored over time, as this will give decision-makers useful information on the direction of change in expert judgment regarding the relative importance of different clean energy technologies.

Direct impact risk indicators can be updated to reflect material changes in scientific knowledge and expert judgment regarding climate sensitivity and the relationships between general climate variables (such as temperature or sea level rise) and the probability of specific impacts and extreme events. Such material changes may not be frequent, but over a long time period the trend in these indicators will provide decision-makers with useful information on which to judge whether the scientific community has tended to underestimate or overestimate the risks. In each case, it will be important to provide analysis of the reasons for any change in indicators, so as to distinguish between the effects of, for example, changes in the real world and changes in modelling assumptions.

In addition, direct impact risk indicators can be updated to reflect changes in the exposure and vulnerability of human populations. Over time, these trends will show whether adaptation challenges are increasing or decreasing, which may inform development priorities and investment decisions.

Systemic risk indicators can be updated using publicly available data from relevant sources. For example, official statistics from the Food and Agriculture Organization of the United Nations (FAO) and the Agricultural Market Information System (AMIS) were used to develop indicators of global food system risk. At any point, comparing the current indicator to historical averages or past extremes may provide information on the stability or fragility of the system of concern. Over time, the trends in these indicators will provide some insight into whether the system is moving towards greater stability (or resilience) or towards instability and/or fragility. This should help decision-makers judge the need for systemic reforms and other measures to manage risk and avoid system failures.

Given the urgent need to accelerate the pace of emissions reduction, as well as the pressing need to build greater resilience to climate change, we suggest that organisations with a responsibility for assessing any of the risks of climate change should consider how to update their assessments on a regular and consistent basis, allowing for comparability across time, and giving decision-makers the benefits of the insights described above.

In particular, organisations with expertise and responsibility that mean they are well placed to contribute to the development of this proof of concept of risk indicators into a full risk monitoring framework include:

- The IEA for data related to energy emissions risk.
- The IPCC for data and expert judgments related to direct impact risks.
- The FAO and AMIS for data related to indicators of food system risk; the FAO for data related to agricultural and land-use emissions risk.
- The Bank of International Settlements for data related to financial system risk.
- The WHO for data related to health systems risk.
- The World Bank and other multilateral development banks for data related to critical infrastructure risk.

Since all governments would benefit from a holistic view of the risks of climate change and of the trends in relevant risk indicators, it could be valuable for one international body to take the lead in compiling indicators from different sources (such as the organisations listed above) into a single set. The UN Secretary General's office, for example, could be a candidate for overseeing this process, given its position at the apex of the UN system and links to the UN General Assembly and Security Council.

This would facilitate the use of the indicators to inform other relevant processes, such as updates to national risk registers, the regular international stock-take of progress towards global emissions reduction targets and the five-yearly submission of increasingly ambitious NDCs at the UNFCCC.

Chapter 1: Introduction

1.1 Background

Warming of the climate is unequivocal, and it is clear that manmade greenhouse gas (GHG) emissions are the principal driver (IPCC, 2013). Changes to the climate create risks to the natural, social and economic systems upon which societies depend. Climate change may also amplify pre-existing risks. Understanding how climate change is affecting the myriad risks faced by human societies is critical for governments to prioritise action on climate change and to effectively manage risks. This, in turn, requires information on current risks, on their direction of travel, and on the risks that might arise if action were not taken to reduce emissions of GHGs. Information is needed across the full spectrum of probabilities, recognising that a low-probability outcome may still correspond to a high risk if the impact is severe – and that what is low probability at one time may become high probability at a later time. Such information is also important for other actors that must respond to the changing risk landscape, such as international organisations, businesses and NGOs.

The 2015 report, *Climate Change: A Risk Assessment* (King et al., 2015), identified these needs and demonstrated the importance of the full range of climate risk rather than just central expectations. It proposed three categories of risk to assess: the future pathway of global emissions; the direct risks arising from the climate's response to those emissions; and the risks to complex human systems. The report recommended that:

> *'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. [And] this could be facilitated by the identification and use of a consistent set of metrics or indicators in each of the three areas of risk.'*

This report responds to this recommendation. It is the result of collaborative research led by the China National Expert Committee on Climate Change and the UK Committee on Climate Change, involving research institutions from both countries alongside the International Energy Agency. It builds on the earlier collaboration that resulted in *Climate Change: A Risk Assessment*.

1.2 Risk assessment and risk monitoring

Periodic risk assessments are commonly used in governments, international organisations and businesses to advise leaders about the risk landscape and to provide policymakers and managers with information to support decisions on aspects of risk management such as risk mitigation and preparedness measures. In the specific case of climate change, periodic risk assessments of this kind can help inform decisions about emissions reduction and adaptation to changing future risks. Risk is here broadly defined as 'the potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or community'.[8]

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[8] This is a paraphrase of the UNISDR definition.

Box 1: Worst case scenarios

Risks are by their nature uncertain and can be presented in different ways. For example, in terms of the likelihood of a particular threshold being exceeded or a particular event occurring; or in terms of the range of possible impacts under particular scenarios. An important concept for decision-makers is that of the worst case scenario. This is the most severe outcome that might plausibly occur. It has obvious utility for planning, for example, when decision-makers may wish to ensure that strategies or investments are viable not simply under expected conditions, but also resilient in more extreme circumstances. Alternatively, they may decide to act to reduce the likelihood of those extreme circumstances arising.

Climate Change: A Risk Assessment (King et al., 2015) highlighted the importance of information related to changes in the likelihood of lower-probability but higher-impact risks, such as shocks to food supply, major health risks, impacts on economic growth or security threats. An impartial assessment of how these risks might change in the future may be particularly important for policymakers seeking to decide on whether (and by how much) future emissions should be reduced. A distinction can be drawn between ‘direct’ risks, such as changes in the number of heatwaves or crop productivity, and ‘systemic risks’ which threaten an entire system, such as challenges to food security or community-wide health emergencies. Systemic risks may be triggered by concurrent or sequential direct risks, and can be propagated across time and space where human systems and responses to a trigger amplify rather than dampen risks. Somewhat inevitably, the inherent complexity of systemic risks makes them harder to quantify in the same way as can be done for direct risks.

Risk assessment is the process of identifying the potential magnitude and likelihood of risks. A particular variant of risk assessment focuses on ‘extreme’ risks. This considers not only high-impact events such as catastrophic impacts on food supply and systemic crises (see Box 1) but also impacts in scenarios that might occur under high future emissions. For example, a ‘worst case’ risk assessment would consider impacts under high future emissions of GHGs and compare these to impacts under lower future emissions.

Risk monitoring is the process of tracking the level of risk. It contributes to risk assessment by (i) tracking the state of the system and comparing it with what is expected (‘diagnostic monitoring’) and (ii) helping to identify emerging trends (‘prognostic monitoring’). Conventionally, monitoring is based on observations (or a combination of observations and model assessments). In the context of climate change, it is possible to monitor emissions and concentrations of GHGs, the current state of the energy supply system, the current state of the climate system and the occurrence of climate-related impacts. However, there are four main challenges to diagnostic and prognostic monitoring of the risks posed by climate change.

First, the characteristics of the climate system and climate impacts vary considerably from year to year, and different characteristics vary at different rates. Differences from year to year or even decade to decade are therefore not necessarily indicative of longer-term trends or changes in system state. This is particularly important where features of the climate system, such as El Niño, introduce longer-term periodic variations and influence variability from one year to another. This effect is apparent with global average temperature, and is even more obvious in some regions where the amount of rainfall can depend very much on the state of the climate system.

Second, variability in impact and risk from year to year can be strongly influenced by non-climatic factors. This is particularly important for impacts where changes in exposure will affect the consequences of weather events (e.g. rising numbers of people in areas at risk of flooding). Variations in emissions from year to year also largely reflect fluctuations in levels of economic activity rather than the effects of policy interventions (Le Quéré et al., 2017).

Third, future risks are dependent on the pathways of future emissions, but for the next few years there is little difference across the range of plausible emissions pathways. Recent observations in themselves provide no guidance on the likely future direction of emissions over the long term.

Fourth, many of the factors which affect vulnerability to high-impact systemic risks are challenging to quantify and to project forward. These factors include the characteristics of economic and population growth, but also drivers related to governance and institutional structures and practices.

This report presents a *risk assessment*, focusing on high-impact risks under high emissions, and proposes a framework for *risk monitoring* which seeks to assess the likelihood that emissions are on a pathway that would lead to large changes in climate. As such, it provides a proof of concept of the recommendation from *Climate Change: A Risk Assessment* that regular risk assessments for each of the three areas of climate risk be undertaken using a consistent set of indicators.

1.3 A climate risk monitoring framework

An effective climate risk monitoring framework has two components that, together, provide an assessment of (i) potential risks of future climate change and (ii) the likelihood that the world is on a pathway which will generate the highest risks. Central to the framework is the use of a small discrete number of plausible emissions pathways.

As a first step, the likelihood that future climate follows different potential climate pathways must be assessed. These could include a ‘high emissions’ world, and a world which meets the Paris Agreement’s ‘well below 2.0°C’ temperature target. It does this through characterising future emissions of GHGs which result in the pathways.

Second, future policy-relevant impacts and risks under these different pathways must be characterised. Direct impacts can typically be quantified using impact models, whilst systemic risks are much more influenced by qualitative attributes such as access to resources and power, governance and institutional arrangements. More generally, direct impacts are conceptualised as a function of change in *physical hazard*, change in *exposure* and change in *vulnerability*. Changes in physical hazard include changes in temperature, rainfall, river flows, sea level and crop productivity. Exposure describes the people, activities and assets which may be affected by a physical hazard, such as numbers of people living in floodplains or the location and timing of crop production, and potential impact is a function of hazard and exposure. Vulnerability describes the propensity of what is exposed to hazard to suffer harm or loss, and is more difficult to quantify than hazard or exposure. It includes the ability and capacity to adapt to impact. Systemic risks are influenced by the direct impacts of climate change and by changes in vulnerability.

Both steps combine modelled projections into the future with observations of the current drivers of emissions, hazard, exposure and vulnerability. The selection of indicators is critical, and a distinction is drawn between *diagnostic* and *prognostic* indicators. Diagnostic indicators characterise relevant aspects of emissions, impact and risk, but do not in themselves allow inferences about direction of change. The comparison of observations and projections for these indicators provides a context for future impacts, and provides a check on the plausibility of projections. Prognostic indicators allow the identification of emerging trends. They are either indicators which show a clear signal, or indicators which are highly predictive of changes in the future ('leading indicators').

Future climate change (as characterised by change in emissions and global mean temperature) is determined by characteristics of future economies and societies. Changes in physical hazard are driven by changes in climate, and changes in exposure and vulnerability are driven by changes in society. Changes in exposure can be expressed in quantitative terms, but changes in vulnerability are better expressed in a narrative form. Together, changes in physical hazard, exposure and vulnerability influence direct risks, and the combination of changes in direct risk and vulnerability affect future systemic risks. In a final feedback, the occurrence of major systemic risks could impact upon economies and societies to such an extent that emissions and exposure to risk are subsequently altered.

1.4 Structure of the report

This report presents a 'proof of concept' risk assessment of the three areas which correspond to those originally identified in *Climate Change: A Risk Assessment* (King et al, 2015) – see Figure 1. At the global level, the three areas of risk are sequentially related: a high emissions pathway increases the risk of direct climate impacts which can, in turn, trigger systemic impacts. For example, on a high emissions pathway, the risk of serious harvest failures due to extreme weather is expected to increase, in turn increasing the risk of disruptions to the global food system.

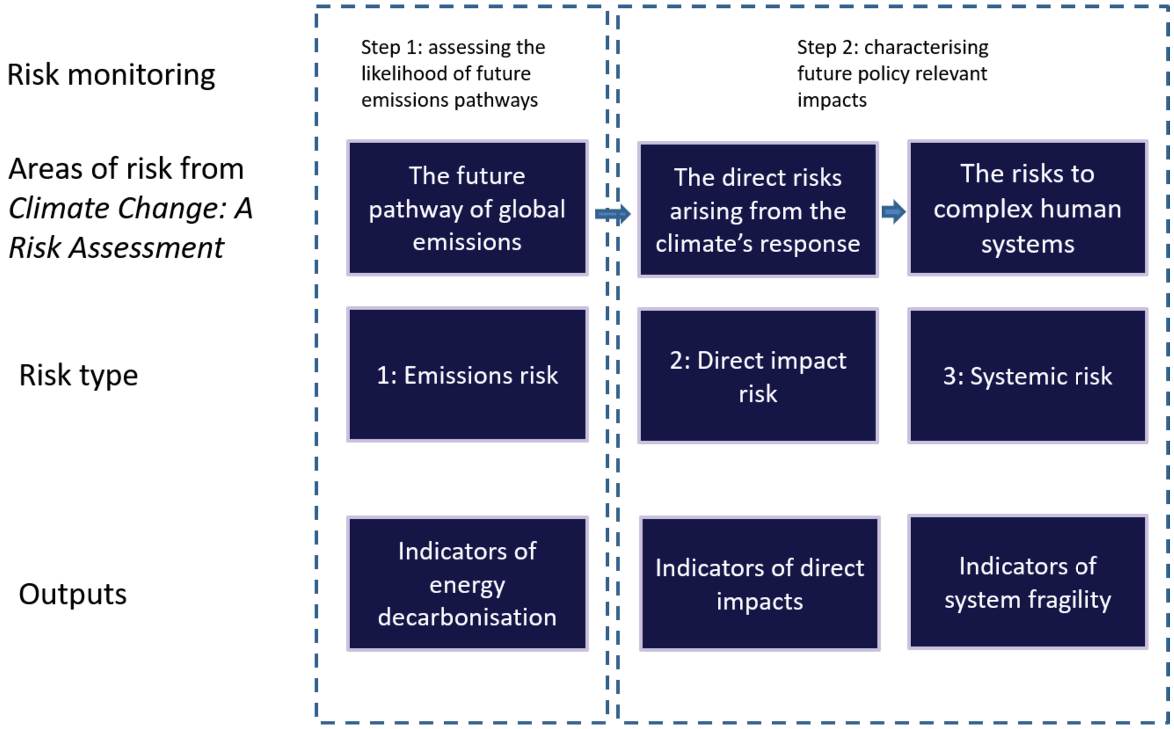
Chapter 2: Energy-sector emissions risk focuses on future emissions of GHGs, and in particular looks at the characteristics of the economy and society which influence future emissions. As per the first step of risk monitoring above, it considers the likelihood of different future emissions pathways by developing indicators to track progress on decarbonising the energy sector and examining the implications for future emissions. This corresponds to the first area of risk identified in *Climate Change: A Risk Assessment.*

Chapter 3: The direct risks of climate change focuses on the direct impacts of climate change using a number of indicators to characterise risks under high and low emissions pathways. This forms part of the second step of risk monitoring described above. Part of this takes a global perspective, whilst part focuses on direct impacts in China. This corresponds to the second area of risk identified in *Climate Change: A Risk Assessment.*

Chapter 4: Systemic risk in the context of climate change is concerned with the potential systemic risks posed by climate change. Recognising that the range of possible disruptions to complex, interconnected systems is almost infinite and impossible to model, a narrative approach was used to characterise a systemic disruption of the global food system and to develop indicators of system fragility. At the China level, analysis examined the potential consequences of climate impacts for local populations. This also forms part of the second step of risk monitoring, concerned with characterising future policy-relevant impacts, and corresponds to the third area of risk identified in *Climate Change: A Risk Assessment.*

The final chapter draws general conclusions from the proof of concept, and makes recommendations for the development of an operational procedure for monitoring risks and using indicators to identify changes in risk in the future.

Figure 1: Areas of climate risk



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Chapter 2: Energy-sector emissions risk

2.1 Background and introduction

Emissions of anthropogenic greenhouse gases (GHG) have risen dramatically since the industrial revolution, with particularly rapid growth since the second half of the 20th century. This has led to concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in the atmosphere substantially higher than at any time in at least the last 800,000 years (IPCC, 2013). The latest science suggests that human activity is extremely likely to have been the dominant cause of the increase in average surface temperatures observed over the second half of the 20th century, which corresponds to a large fraction of the observed warming since pre-industrial times.

Multiple lines of evidence indicate a strong linear relationship between cumulative CO_2 emissions and global temperature changes (IPCC, 2013). This relationship has resulted in the concept of a remaining global 'CO_2 budget' (the cumulative amount of CO_2 that may be emitted in the future) commensurate with an estimated probability of remaining below a chosen temperature target. Limiting global mean surface warming in 2100 to less than 2°C relative to the pre-industrial period (1861–1880) with a probability greater than 66% requires cumulative CO_2 emissions from all anthropogenic sources since 1870 to remain within a range of 2550 to 3150 billion tonnes (Gt) CO_2 (IPCC, 2013; IPCC, 2014). Around 2000 $GtCO_2$ was emitted between 1870 and 2015, meaning that the remaining CO_2 budget from 2015 for a 66% chance of limiting the surface temperature rise to 2°C lies between around 550 and 1150 Gt.

Future pathways for global GHG emissions will depend critically on factors such as global population, rates of economic development, lifestyle choices, and the evolution of energy technologies and energy policies. Another crucial factor is climate policy. Only by increasing climate policy ambition around the world can global GHG emissions be reduced to the levels needed to limit the rise in global mean surface temperature.

This chapter aims to provide policymakers with a high-level overview of progress towards addressing GHG emissions using two complementary approaches. First, we examine a small number of high-level drivers of future GHG emissions to provide an overview of recent developments in energy consumption and the changes needed in the energy sector to reduce GHG emissions. Second, we examine a larger number of more detailed indicators to provide a more focused look at trends within sectors. The detailed indicators are then used to develop a plausible pathway for future emissions. We finish the chapter by estimating the impacts of different future global emission pathways on the probabilities of achieving different warming targets.

Indicators are selected to compare emissions, energy consumption, and deployment trends observed historically (including recent market developments) with the trends for these variables under a variety of future emissions scenarios. We initially concentrate on the energy sector as it is responsible for around two-thirds of current GHG emissions. The first stage of the work (examining high-level drivers) relies on the energy and emissions trends from the large dataset of scenarios included as part of the Third Working Group (WGIII) of the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5). The second stage (examining the development of sectoral and sub-sectoral level elements within the energy sector) uses a smaller number of discrete scenarios provided in the World Energy Outlook (WEO) of the International Energy Agency (IEA, 2017). The combination of the global multi-model scenario database with closer examination of the IEA scenarios provides a rounded risk assessment around the selected indicators.

This chapter is structured as follows: after an introduction to risk assessment methods (Section 2.2), the IPCC AR5 scenarios are used to provide an overview of future projections of global CO_2 emissions and the key socio-economic and technological drivers of these projections (Section 2.3). Section 2.4 uses these scenarios to investigate energy consumption and emissions projections from the energy sector. Section 2.4.4 then narrows the focus to provide insights into the development of sectoral and sub-sectoral level elements within the energy sector. These are used to build up a comprehensive picture of overall trends for the energy sector and thus develop a future projection for global energy-sector CO_2 emissions. The impacts of different emission pathways on the probability of different levels of global warming are considered in Section 2.6; Section 2.7 concludes.

2.2 An approach to risk assessment in energy-sector emissions

There is an extremely broad range of possible indicators that could be used to help understand possible future global emissions pathways. These could span different causes or sources of emissions, provide varying degrees of detail, and cover a wide range of possible time periods. To provide a logical process for selecting the most relevant indicators, it is therefore helpful first to develop an overarching conceptual framework and examine a variety of issues that should be taken into consideration.

There are a number of existing hierarchies of emissions indicators. These have generally been developed to help countries better understand the opportunities for emissions reduction (and associated benefits) and to help advance the decarbonisation of countries' economies in a targeted manner. While our focus is different – to enable a holistic or integrated view of future trends in global emissions – these conceptual structures remain useful.

One method for understanding the drivers of global GHG emissions is the Kaya identity (Kaya, 1990). This decomposes changes in total GHG emissions into a number of subsets:

$$\text{GHG emissions} = \text{Population} \times \frac{\text{GDP}}{\text{Population}} \times \frac{\text{Energy}}{\text{GDP}} \times \frac{\text{GHG}}{\text{Energy}}$$

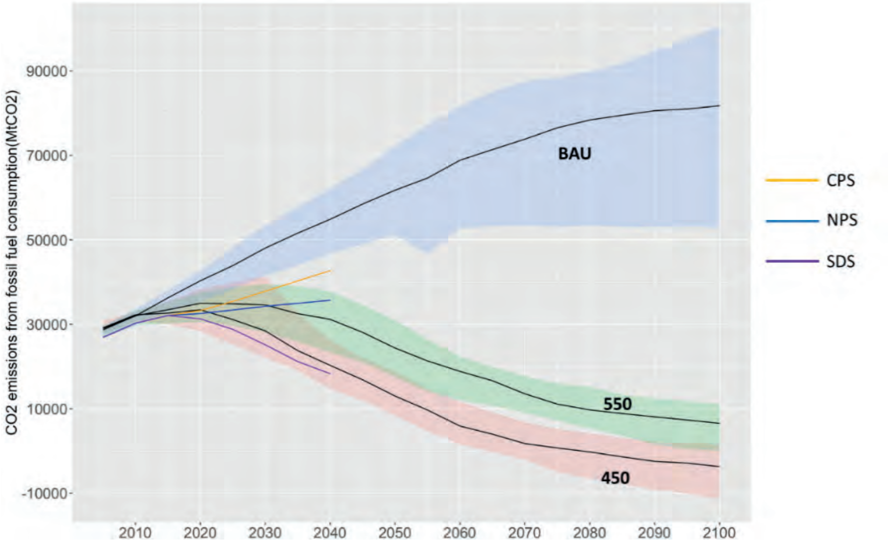
The consumption and production of energy is currently responsible for around two-thirds of current anthropogenic GHG emissions and transformation of countries' energy sectors was at the heart of many of the nationally determined contributions (NDCs) made as part of the Paris Agreement. We therefore focus initially on understanding current and future global emission levels from the energy sector. Developing indicators at the national level would be a useful extension (as emphasised in previous IEA work [IEA, 2014; IEA, 2016]), although in many countries this is not yet straightforward as there is a need first to collect the nationally representative data to develop such indicators. The majority of indicators also focus on CO_2 emissions since this is the largest source of GHG emissions.

In the first stage of this work, a small number of indicators are examined. For each selected indicator we examine overall emissions and energy trends from scenarios contained in the IPCC AR5 WGIII

Scenario Database. We then compare how these indicators evolve over time across different groups of scenarios. The scenarios in the IPCC AR5 database cover a wide range of possible futures: some have a strong focus on low-carbon transformation, others achieve the NDCs pledged as part of the Paris Agreement but fail to achieve the long-term temperature goals included in the Paris Agreement, while others reflect a reversal in countries' decarbonisation ambitions leading to significantly higher emissions in coming years. We therefore group the scenarios according to their long-term temperature outcome to generate a distribution for each selected indicator. The distribution for each indicator is regarded as an uncertainty range that the specific indicator must fall within to achieve the long-term temperature outcome.

The IPCC AR5 WGIII Scenario Database contains 1,184 scenarios produced by 31 different energy-economy or integrated assessment models. All scenarios are published in the peer-reviewed literature, include a minimum level of variable and scenario documentation, represent (at least) the global energy system, and provide data out to at least 2030. We categorise these scenarios into three groups: non-mitigation scenarios that lead to a median temperature rise of over 3°C in 2100 (also sometimes referred to as 'business as usual' [BAU] scenarios); scenarios that lead to an atmospheric concentration of around 550ppm CO_2-eq in 2100 (which lead to a median temperature rise of between approximately 2.2°C and 2.6°C in 2100); and scenarios that lead to an atmospheric concentration of around 450ppm CO_2-eq in 2100 (which lead to a median temperature rise of less than 2°C in 2100). Variables available from the scenario database include energy-related variables such as sectoral end-use energy consumption, emission-related variables such as CO_2 emissions, and economic and social variables, such as population and gross domestic product (GDP). Figure 2 shows CO_2 emissions from fossil fuel consumption across these three groups of scenarios. In the non-mitigation scenarios, global CO_2 emissions grow substantially above today's levels and in 2100 range from around 50 Gt to 100 Gt. In the 550ppm CO_2-eq scenarios, global CO_2 emissions peak around 2030, and by 2100 the 15th to 85th percentile range of emissions is from around 0 Gt to 10 Gt. In the 450ppm CO_2-eq scenarios, global CO_2 emissions tend to peak in the 2020s (although some scenarios do not peak until 2030), with near zero or net negative emission levels in 2100 in most scenarios.

Figure 2: Emissions in the business as usual (BAU), 550ppm CO_2-eq and 450ppm CO_2-eq scenarios in the IPCC AR5 Scenario Database



Note: The upper and lower limits for each strip chart represent the 15th percentile and 85th percentile of emissions in the scenarios and the black line, the median of emissions. CPS = IEA Current Policies Scenario; NPS = IEA New Policies Scenario; SDS = IEA Sustainable Development Scenario.

In the second stage of this work, a larger dashboard of indicators is developed to provide a more granular examination of developments in the energy sector and provide a broader risk assessment of emissions trends. Historical trends and recent developments are examined for each of these indicators (which aim to cover the key emissions sources from across the energy sector) with a particular focus on how these trends compare with the projected trajectories in the IEA's WEO scenarios. This element of the work relies upon three pre-existing scenarios published as part of the IEA World Energy Outlook 2017 (IEA, 2017), which have the following characteristics:

- The **Current Policies Scenario** depicts a path for the global energy system shorn of the implementation of any new policies or measures beyond those already supported by specific implementing measures in place. Energy-related CO_2 emissions in this scenario rise from 32 Gt today to around 42 Gt in 2040.
- The **New Policies Scenario** reflects the way that governments currently see their energy sectors developing over the coming decades. It contains both energy-sector policies and measures that are already in place, and the aims, targets and intentions of policies that have been announced, even if these have yet to be enacted or the means for their implementation are still taking shape. In this scenario, emissions from the global energy-sector CO_2 grow to just under 36 Gt in 2040.
- The **Sustainable Development Scenario** incorporates three key elements. It describes a pathway to the achievement of universal access to modern energy services by 2030; it contains a large reduction in other energy-related pollutants; and it paints a picture to 2040 that is consistent with the direction needed to achieve the objectives of the Paris Agreement (most notably a peak in emissions being reached as soon as possible followed by rapid emissions reductions thereafter).

The comparison of historical trends to the projected trends across these three scenarios is used to provide a ‘traffic-light’ dashboard to highlight whether the specific indicator appears to be on track with the Current Policies Scenario (red), the Sustainable Development Scenario (green) emissions pathways or lies somewhere in between (amber). The selected indicators are then used to generate a plausible pathway for future CO_2 emissions from the energy sector. For this, we first assess the importance of a selected indicator to overall emissions reductions and then use the traffic-light dashboard to estimate the projected pathway for that indicator. The projected pathway is based on an extrapolation of historical time series data into the future, is assumed to be linear, polynomial or exponential, and takes into account recent investment decisions, announced policy, regulatory, and business aims and strategies from around the world, and progress in research, development and deployment. While the assumed functional form of the future trend is somewhat subjective, and alternative choices could be equally valid, the aim is to be informed by as broad an array of information as possible. These elements also inform the length of the historical time series used for the extrapolation to ensure that data from before any trend break are excluded.

By assessing the progress to date for each indicator and weighting the importance of each to overall emissions trends for the energy sector, we build up a plausible emissions trend for the energy sector from the sectoral or sub-sectoral level.

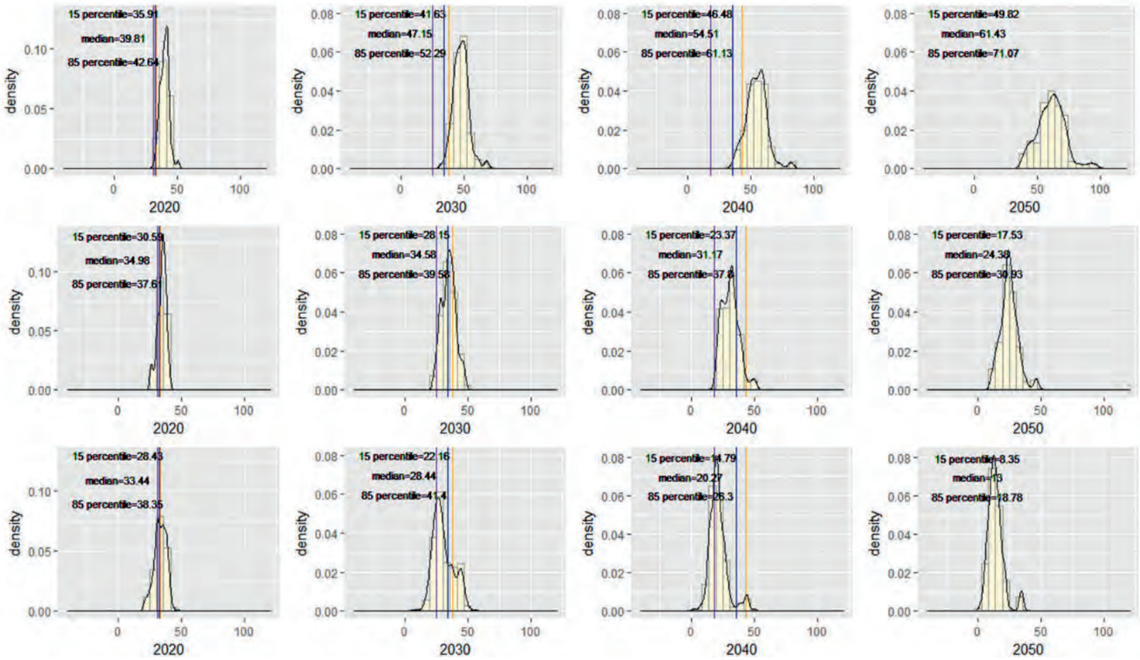
2.3 Historical and projected changes in global energy-related CO_2 emissions

The first energy-wide indicator is simply total CO_2 emissions from the entire energy sector (Figure 3). Since 1990, CO_2 emissions have risen by around 650 million tonnes on average every year. There has been a slight slowdown in this rate of growth in recent years: between 2014 and 2016, CO_2 emissions were broadly flat; however, 2017 once again showed an increase. Global energy-related CO_2 emissions is clearly the most important risk indicator as it reflects the combined effects of dynamic changes in the underlying indicators.

- In the non-mitigation AR5 scenarios, global CO_2 emissions gradually increase from 35 $GtCO_2$ in 2016 to around 40 $GtCO_2$ in 2020 (range of 36 to 42.5 $GtCO_2$), 47 $GtCO_2$ in 2030 (range of 41.5 to 52 $GtCO_2$), and 61.5 $GtCO_2$ in 2050 (range of 50 to 71 $GtCO_2$). This translates into average annual growth rates of around 1.7%, 1.5% and 1.2% for the three decades between 2020 and 2050 respectively. Emission levels in 2050 are around 70% greater than 2016 levels.
- In the 550ppm CO_2-eq scenarios, global CO_2 emissions peak at around 35 $GtCO_2$ by around 2030 and then gradually fall to 31 $GtCO_2$ in 2040 (range of 23.5 to 38 $GtCO_2$) and to 23 $GtCO_2$ in 2050 (range of 17.5 to 31 $GtCO_2$). Emission levels decline at an average annual rate of about 1% during the 2030s and 2.4% during the 2040s; by 2050 emissions are around one-third below 2016 levels.

- In the 450ppm CO_2-eq scenarios, global CO_2 emissions peak at around 33 $GtCO_2$ in the 2020s (range of 28.4 to 38.3 $GtCO_2$), but then fall rapidly to 28.5 $GtCO_2$ in 2030 (range of 22 to 41.5 $GtCO_2$) and 13 $GtCO_2$ in 2050 (range of 8.5 to 19 $GtCO_2$). The average annual rate of decline is around 1.6%, 3.3% and 4.4% for the three decades between 2020 and 2050 respectively. Emission levels in 2050 are around 65% lower than 2016 levels.

Figure 3: Energy-related CO_2 emissions in the non-mitigation scenarios (top row), the 550ppm CO_2-eq scenarios (middle row) and the 450ppm CO_2-eq scenarios (bottom row)



As highlighted by the Kaya identity, global energy-related CO_2 emissions reflect the combined effects of changes in four overarching indicators: population, GDP per capita, energy consumption per unit of GDP, and emissions per unit of energy consumption. There is limited variation in the rate of population growth and GDP per capita between the scenarios. The global population increases from around 7.3 billion in 2015 to 7.6 billion in 2020, 8.3 billion in 2030 and 9.3 billion in 2050 while global GDP grows by around 3.5% to 2030 and by around 2.7% after 2030. The differences and distributions of the remaining two drivers are considered below.

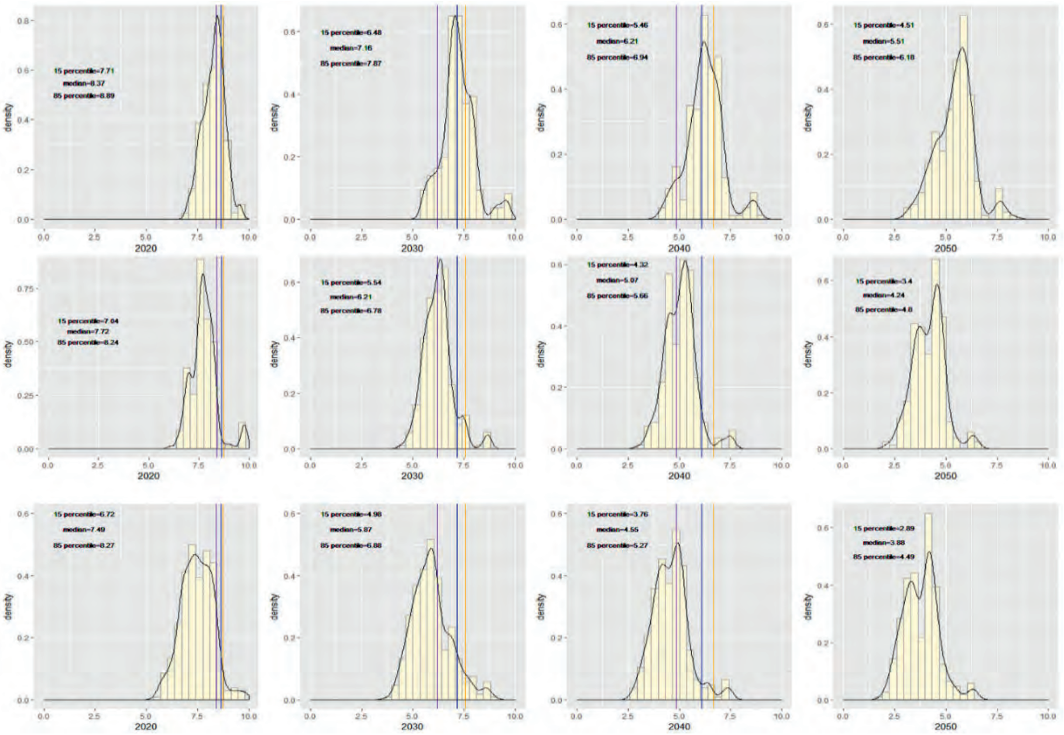
2.3.1 Energy consumption per unit of GDP

Changes in energy consumption per unit of GDP reflects changes in global energy efficiency (Figure 4).

- In the non-mitigation scenarios, global energy consumption per unit of GDP falls from 8.2 MJ/USD in 2020 to 6.9 MJ/USD in 2030 and 5.2 MJ/USD in 2050, representing an annual average decline of around 1.5% per year (broadly in line with the rate of improvement observed historically). Despite this improvement in efficiency, global energy consumption grows from around 570 EJ in 2015 to about 700 EJ in 2030 and 900 EJ in 2050. This is because the annual rate of global GDP growth (averaging around 3% between 2020 and 2040 and slightly slower thereafter) exceeds the rate of efficiency improvement.

- In the 550ppm CO_2-eq scenarios, energy consumption per unit of GDP declines sharply: the average annual rate of decline is around 2.4% during the 2020s, 2.2% during the 2030s, and 1.6% during the 2040s. This improvement nevertheless fails to offset fully GDP growth and so global energy consumption grows to 680 EJ in 2050.
- In the 450ppm CO_2-eq scenarios, the annual rate of decline in energy consumption per unit of GDP is only about 0.1% greater than that in the 550ppm CO_2-eq group of scenarios. Global energy consumption therefore still grows slowly to around 650 EJ in 2050.

Figure 4: Energy consumption per unit of GDP (MJ/USD) in the non-mitigation scenarios (top row), the 550ppm CO_2-eq scenarios (middle row) and the 450ppm CO_2-eq scenarios (bottom row)



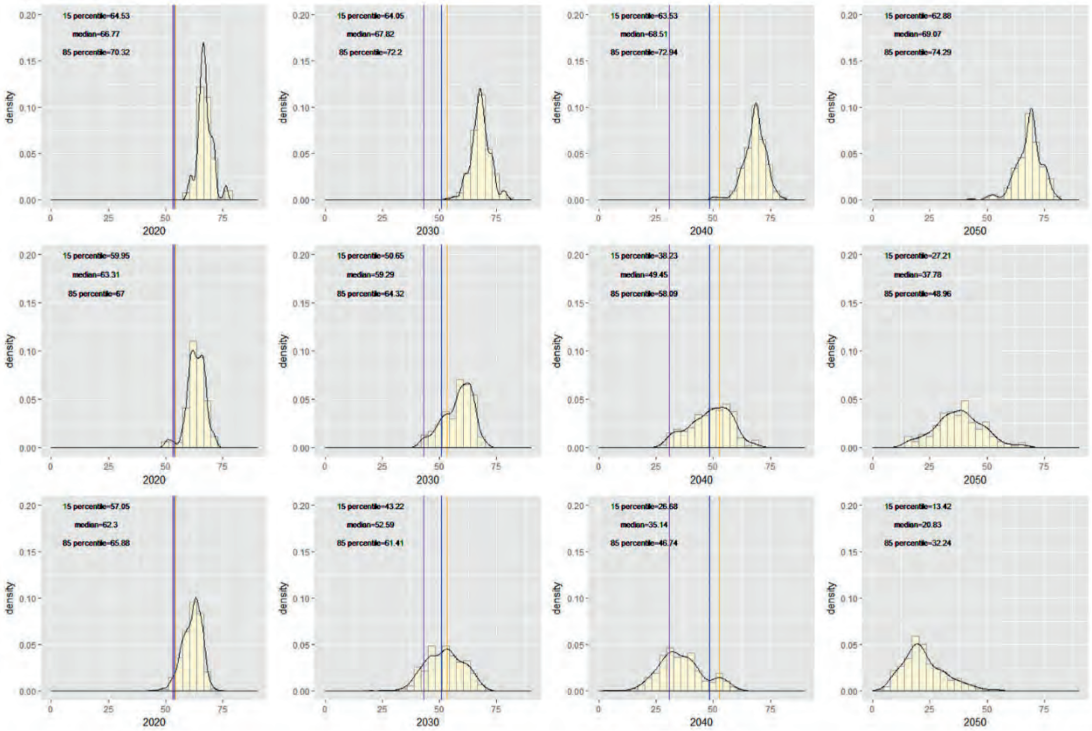
2.3.2 CO_2 emissions per unit of energy consumption

Changes in the level of emissions per unit of energy consumption is an important indicator for the evaluation of the energy sector and the types of fuel consumed (Figure 5).

- In the non-mitigation scenarios, global CO_2 emissions per unit of energy consumption remain at around today's level of 66 $kgCO_2$/GJ, with little change over the period from 2020 to 2050.
- In the 550ppm CO_2-eq scenarios, the energy sector has much lower emissions. CO_2 emissions per unit of energy consumption fall to 58 $kgCO_2$/GJ in 2030 and 36 $kgCO_2$/GJ in 2050. The average annual rate of reduction is around 0.9%, 1.5% and 3.2% in the 2020s, 2030s and 2040s respectively. There is also a steady decrease in CO_2 emissions per unit of GDP (which falls at annual rates of between 3.3% and 4.7%). The decline in emissions per unit of GDP before 2030 is driven mainly by the decline in energy consumption per unit of GDP, but after 2030, by the decline in emissions per unit of energy consumption.

- In the 450ppm CO_2-eq scenarios, CO_2 emissions per unit of energy consumption fall from 62 $kgCO_2/GJ$ in 2020 to 50 $kgCO_2/GJ$ in 2030 and to around 20 $kgCO_2/GJ$ in 2050. The average annual rate of decline is therefore around 2.2%, 3.8% and 5.2% during the 2020s, 2030s and 2040s respectively. Again, there is also a steady decrease in CO_2 emissions per unit of GDP (which fall at average annual rates of between 4.7% and 6.6%). The reduction in CO_2 emissions per unit of energy consumption contributes around 50%, 65% and 80% of the decline in emissions per unit of GDP across the three decades respectively, and so is the key factor reducing emission levels.

Figure 5: CO_2 emissions per unit of energy consumption in the non-mitigation scenarios (top row), the 550ppm CO_2-eq scenarios (middle row) and the 450ppm CO_2-eq scenarios (bottom row)



2.4 Energy-sector-wide indicators

While the high-level indicators above provide useful context for understanding emissions trends in the energy sector, they do not provide the full picture of recent developments. They also cannot be used by themselves to generate a particularly robust plausible future emissions trajectory. It is therefore necessary to look at a more sectoral or sub-sectoral level.

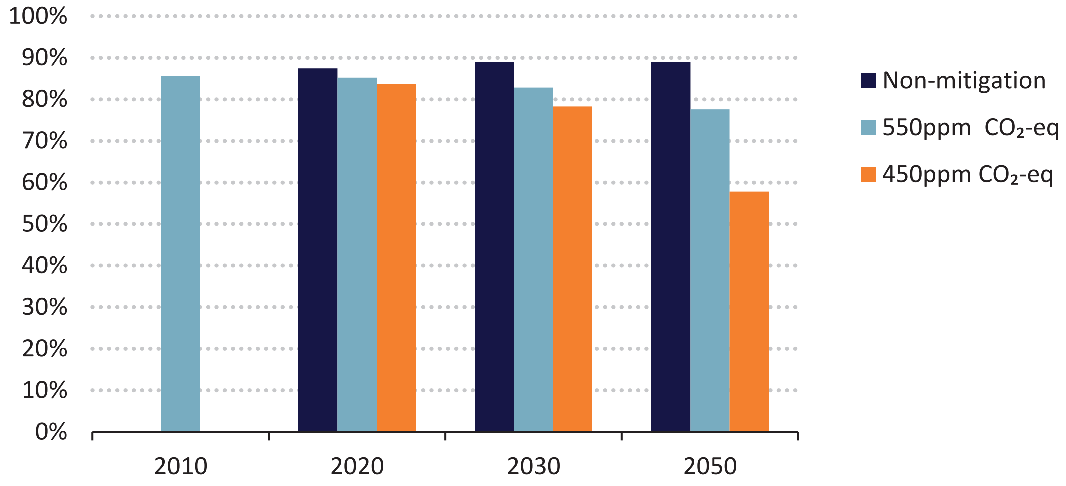
In the low emission scenarios, reductions in CO_2 emissions per unit of energy consumption are largely responsible for the fall in emissions. To explore this in more detail, the following technical indicators are considered based on the available data in the IPCC AR5 WGIII Scenario Database:

- Proportion of fossil energy in primary energy.
- Proportion of coal in primary energy.
- Proportion of electricity in final energy consumption.
- Proportion of fossil energy in power generation.

2.4.1 Proportion of fossil energy in primary energy

Fossil energy accounted for more than 85% of primary energy in 2010, a share which rises marginally in the non-mitigation scenarios (Figure 6). In the 550ppm CO_2-eq scenarios, the proportion of fossil energy in primary energy remains just over 85% to 2020 but then gradually drops to 78% in 2050, marking an average annual decline of around 0.25 percentage points. In the 450ppm CO_2-eq scenarios, the proportion falls by about 1 percentage point annually after 2030 to just under 60% in 2050.

Figure 6: Proportion of fossil energy in primary energy

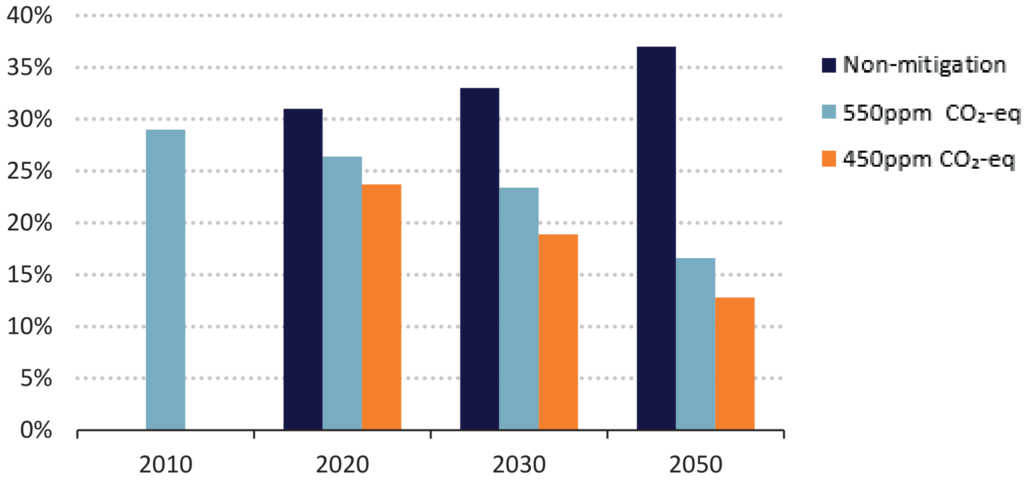


2.4.2 Proportion of coal in primary energy

In the non-mitigation scenarios, the proportion of coal in primary energy increases from less than 30% in 2010 to around 37% in 2050 (Figure 7). In the 550ppm CO_2-eq scenarios, the proportion falls by approximately 0.3 percentage points annually between 2010 and 2050, to 23% in 2030 and 17% in 2050. In the 450ppm CO_2-eq scenarios, the percentage declines rapidly to 19% in 2030 and 13% in

2050, with an average annual rate of decline of 0.5 percentage points between 2010 and 2030 and 0.3 percentage points between 2030 and 2050.

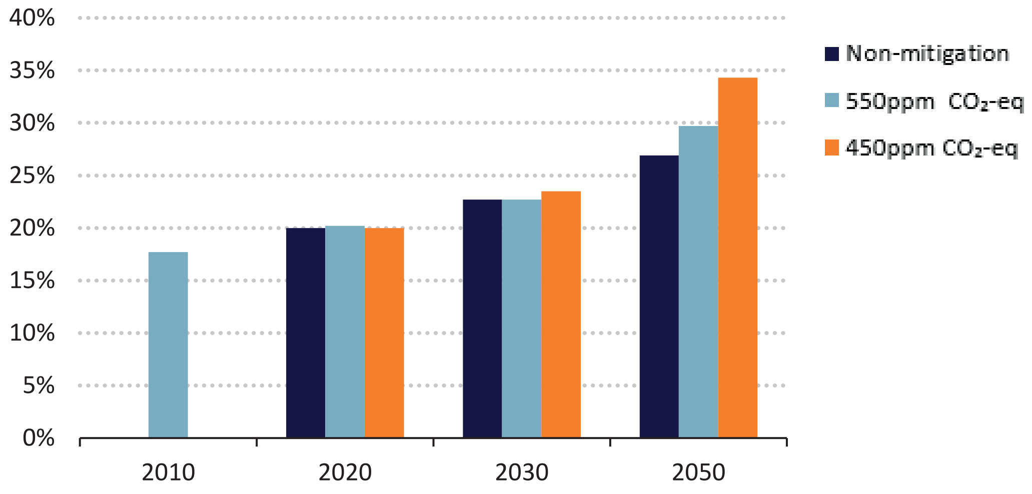
Figure 7: Proportion of coal in primary energy



2.4.3 Proportion of electricity in final energy consumption

Final energy demand is increasingly electrified in all scenarios, but the extent of this electrification is much more pronounced in the low-carbon pathways, particularly after 2030 (Figure 8). In the non-mitigation scenarios, the proportion of electricity in final energy increases gradually from 18% today to 23% in 2030 and 27% in 2050. In the mitigation scenarios the proportion grows further. In the 550ppm CO_2-eq scenarios, the proportion reaches 30% in 2050 while in the 450ppm CO_2-eq scenarios it climbs to nearly 35% in 2050.

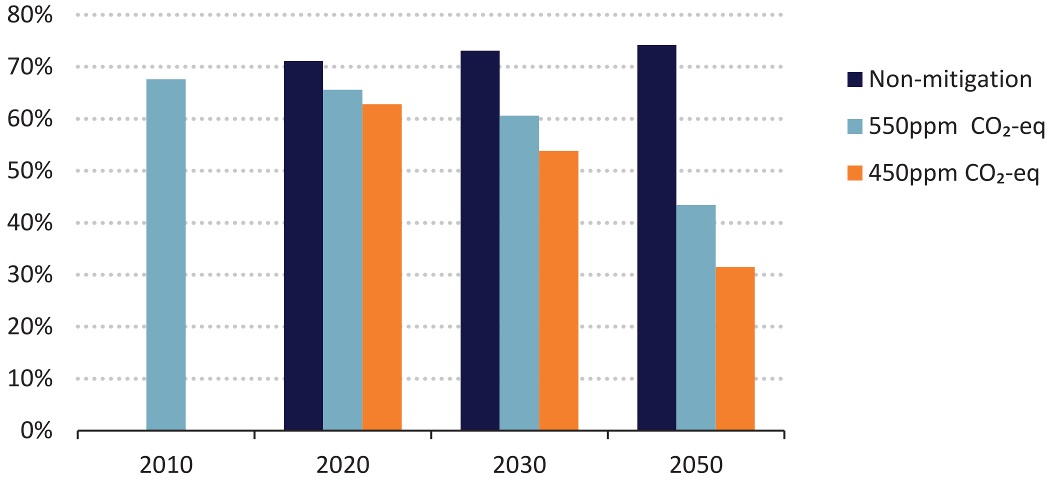
Figure 8: Proportion of electricity in final energy consumption



2.4.4 Proportion of fossil energy in power generation

In the 450ppm CO_2-eq scenarios, the proportion of fossil energy in power generation falls from just under 70% today to just over 30% in 2050 (Figure 9). The average annual rate of decline in these scenarios is around 1 percentage point after 2030.

Figure 9: Proportion of fossil energy in power generation



2.5 Sub-sector indicators

In this section we look in more detail at the underlying dynamics driving the overall trends described above. We explore trends within the power sector, transport, industry, and residential and commercial buildings, first by examining high-level data that is provided through our examination of the AR5 scenarios, and then by exploring trends in more detail using the WEO scenarios. The insights from this consideration are then used to build up a picture of the emission trends that could be expected for the energy sector (based on the approach outlined in Section 2.2).

2.5.1 Power sector

The power sector today generates around 25,000 TWh electricity and accounts for over 40% of energy-sector CO_2 emissions. After decades of steady growth, annual power-sector emissions have remained just above 14 Gt since 2011; the global average emission intensity of electricity generation today is therefore around 550 gCO_2/kWh. A flattening of coal power generation and an increasing share of renewable power generation have supported this stabilisation of emissions. In 2016, renewable technologies provided around 24% of global electricity generation, up from 20% in 2011; the share of coal has meanwhile dropped from 41% in 2011 to just below 38% in 2016.

2.5.1.1 Trends in the AR5 scenarios

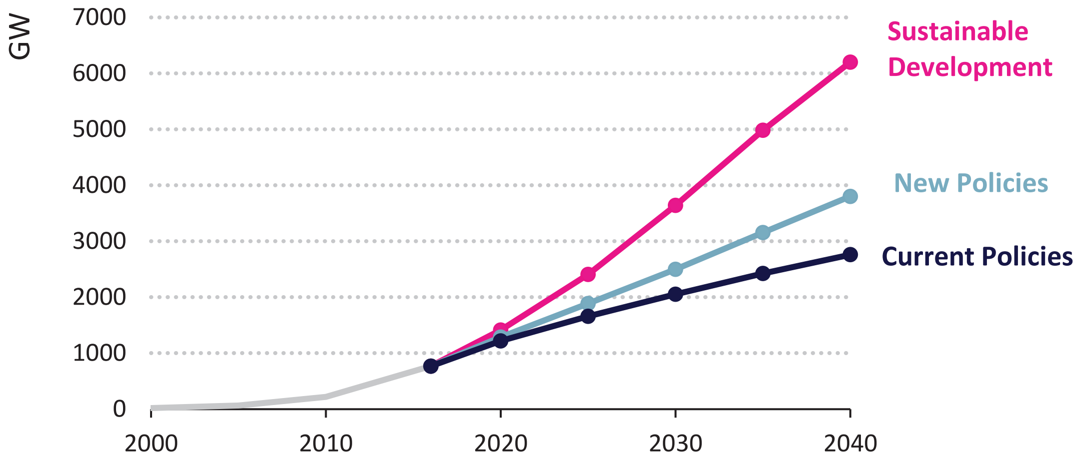
- In the non-mitigation scenarios, few efficiency measures are deployed and generation grows on average by around 2% each year to 2050 (to around 42,000 TWh in 2050). The CO_2 emission intensity of electricity generation grows initially (to around 640 $kgCO_2/kWh$ in 2020) but then falls back to around today's level in 2050.
- In the 550ppm CO_2-eq scenarios, with a greater level of end-use energy efficiency measures deployed, global power generation is initially much lower than the non-mitigation scenarios to 2030. Thereafter there is an increasing level of electrification to help reduce end-use sector CO_2 emissions (in transport and heat for buildings) and so by 2050 electricity generation is broadly similar to the non-mitigation scenarios.
- In the 450ppm CO_2-eq scenarios, efficiency and electrification are accelerated and augmented: efficiency initially moderates the level of growth of electricity and so generation in 2030 is nearly 10% lower than in the non-mitigation scenarios. After 2030 there is a strong growth in electrification and by 2050 total electricity generation is nearly 45,000 TWh (greater than the level seen in either of the other two scenario groupings). The global average emissions intensity falls rapidly to 330 $kgCO_2/kWh$ in 2030 and to close to 0 $kgCO_2/kWh$ in 2050.

2.5.1.2 Installed variable renewable electricity capacity (Figure 10)

The rate of installation of new variable renewable electricity capacity (onshore wind, offshore wind, solar photovoltaics [PV] and concentrated solar power [CSP]) has been accelerating at an impressive rate in recent years: a total of 127 GW renewable power capacity was installed in 2016 (excluding large-scale hydropower), marking another record year for renewable capacity additions. Solar PV accounted for over half of this (an increase of 74 GW), with the next largest addition from onshore wind (52 GW). China is leading the way in terms of new capacity, installing almost 35 GW of solar PV and 20 GW of onshore wind capacity in 2016. In total there was nearly 800 GW renewable electricity capacity in place globally in 2016.

These recent positive trends are expected to continue, China installed nearly 45 GW of new solar PV capacity in 2017 and there were global capacity additions of nearly 100 GW. Annual investment in renewable electricity capacity has been growing rapidly in recent years: investment stood at USD 297 billion in 2016 (excluding large-scale hydropower) and constituted the largest source of spending in the power sector. In inflation-adjusted terms this is slightly down from 2011, but with lower unit costs the scale of capacity additions was 50% higher. Solar PV and onshore wind represent the bulk of investments – around USD 120 billion and USD 80 billion respectively. Looking forward, solar PV and onshore wind capacity installations are expected to remain at high levels. While continued progress and policy support remain essential, trends are developing positively compared to the levels seen in the Sustainable Development Scenario.

Figure 10: Installed capacity of variable renewable electricity capacity technologies globally



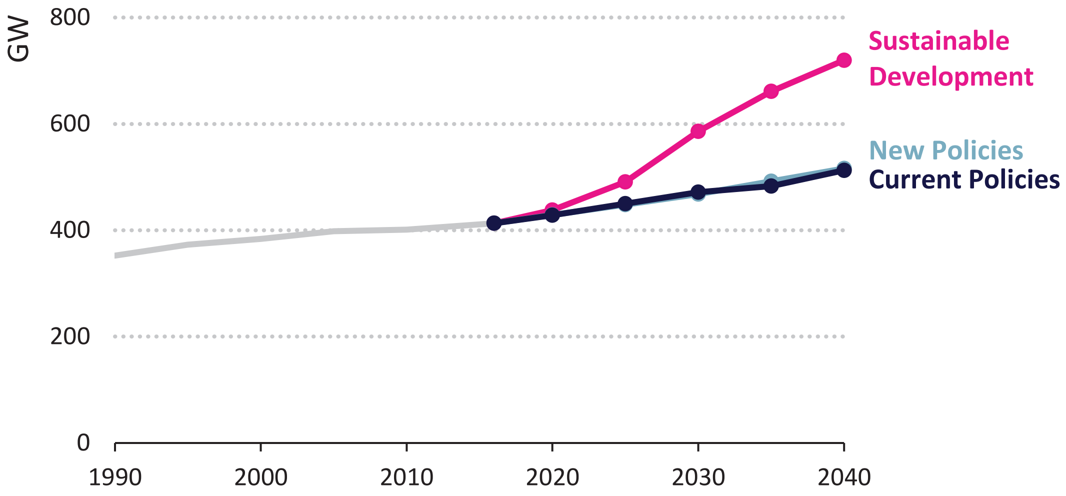
Source: WEO 2017 (IEA, 2017).

2.5.1.3 Installed nuclear capacity (Figure 11)

Around 10 GW new nuclear capacity was added in 2016, the highest level of increase since 1990. The majority of this was installed in China. The project pipeline for new nuclear facilities is less promising, however: in 2016 construction started on only 3.2 GW new capacity, compared with an average of 8.5 GW over the past ten years. High construction and financing costs of nuclear capacity as well as a generally unsupportive policy climate are seen as major challenges to increasing the level of new capacity additions. Capacity retirements are also set to increase due to an ageing nuclear power plant fleet globally, as well as the planned premature closure of operational nuclear power plants in a number of countries. Nevertheless, nuclear power continue to enjoy some policy support in a number of key regions: China, India and Russia are due to make decisions over the next few years on whether or not to continue to expand nuclear fleets.

Overall, this suggests levels of net capacity additions below what is required for the Sustainable Development Scenario, with trends that tend to be more in line with the New Policies Scenario.

Figure 11: Installed nuclear capacity

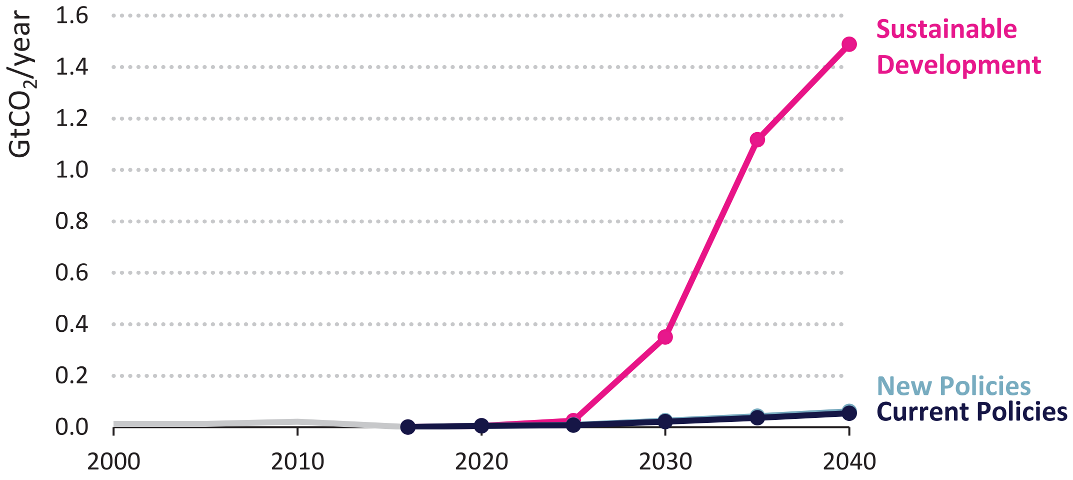


Source: WEO 2017 (IEA, 2017).

2.5.1.4 Installed carbon capture utilisation and storage (CCUS) capacity in the power sector (Figure 12)

There are currently only two operational large-scale CCUS power stations globally, both of which are installed on coal-fired power plants. The first facility was installed at the Boundary Dam power plant in Canada in 2014 with a capture capacity of 1 Mt CO_2 per year. The second facility was PetraNova in the United States, opened in January 2017, with an annual capacity of 1.4 Mt CO_2. There are around seven projects in early development stages (with a combined capture capacity of 11 Mt CO_2 per year); however, there are currently no other power-sector CCS facilities under construction or in the late stages of development. Further, even if all announced CCS projects were to be completed by the mid-2020s this would only bring capacity to about half the level projected in the Sustainable Development Scenario. Progress to date is much more in line with the Current Policies Scenario.

Figure 12: Installed power-sector CCUS capacity



Source: WEO 2017 (IEA, 2017).

2.5.2 Transport sector

The transportation sector is responsible for almost a quarter of energy-sector CO_2 emissions (7.7 Gt in 2015) and consumes just over 110 EJ energy. Over the past five years, emissions have grown on average by around 2.0% each year. Three-quarters of the sector's emissions come from road transport. Cars account for approximately half of road transport CO_2 emissions, road freight 40%, and the remainder are from buses and two/three wheelers.

2.5.2.1 Trends in the AR5 scenarios

- In the non-mitigation AR5 scenarios, both energy consumption and CO_2 emissions grow at an average annual rate of around 1.5% to 2050. Energy consumption grows to over 175 EJ in 2050 while direct emissions increase to nearly 12 $GtCO_2$. There is no real improvement in CO_2 emissions per unit of energy consumption.
- In the 550ppm CO_2-eq AR5 scenarios, energy consumption in 2050 is around 25% lower than in the non-mitigation sectors (135 EJ).
- In the 450ppm CO_2-eq AR5 scenarios, energy consumption is broadly similar to the 550ppm CO_2-eq scenarios, but the CO_2 emissions intensity of energy consumption falls each year by between 0.5% and 1% to 2050. Direct emissions therefore drop to around 6 $GtCO_2$ in 2050.

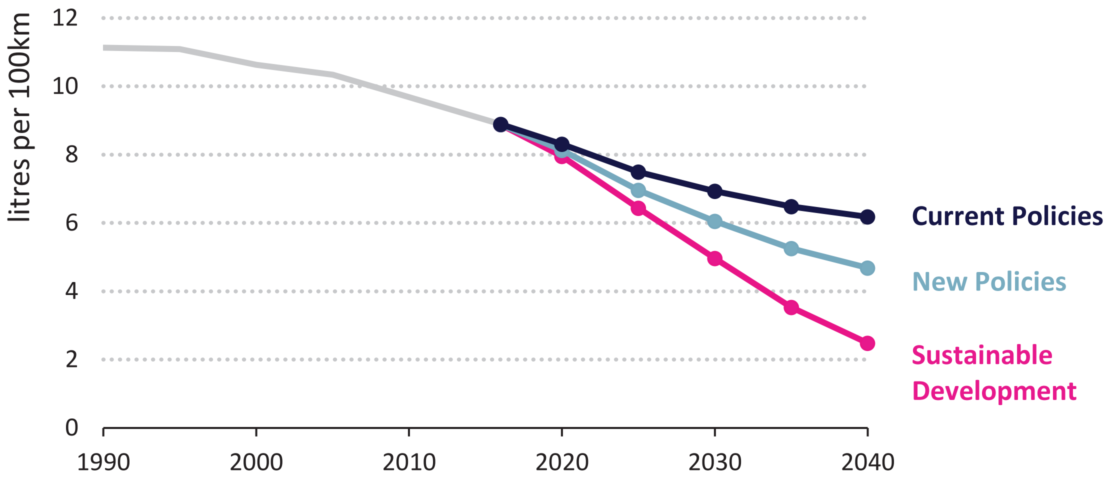
2.5.2.2 Average passenger car fleet oil consumption (Figure 13)

The average level of oil consumed per kilometre by the global passenger car fleet has fallen in recent years. However, increases in road activity (incorporating both the number of cars on the road and the amount that these are driven) has outweighed this improvement, leading to an overall increase in total oil consumption and CO_2 emissions. Low oil prices over the past few years have shifted preferences towards larger and less fuel efficient cars in some countries, most notably the United States.

Nevertheless, there have been positive trends in the electrification of passenger car fleets. Sales of electric cars continue to increase with the light-duty electric car market growing by 50% in 2016, reaching 750,000 sales worldwide. The global electric car stock surpassed 3 million vehicles in 2017 after having crossed the 1 million mark in 2015. Until 2015, the largest electric car stock could be found in the United States, but in 2016 China became the country with the highest number of electric cars. Nevertheless, electric cars still currently correspond to less than 0.3% of the total number of passenger light-duty vehicles, and their share of new car sales globally is only marginally above 1%. The impact of electrification on average passenger car fleet oil consumption has therefore been limited to date; it will take time before rising levels of electrification translates into lower car fleet oil consumption. Fuel efficiency standards and consumer preferences are therefore critical.

In total, this indicator exhibits some positive developments towards the Sustainable Development Scenario trajectory, but is generally more in line with the New Policies Scenario.

Figure 13: Average passenger car fleet oil consumption

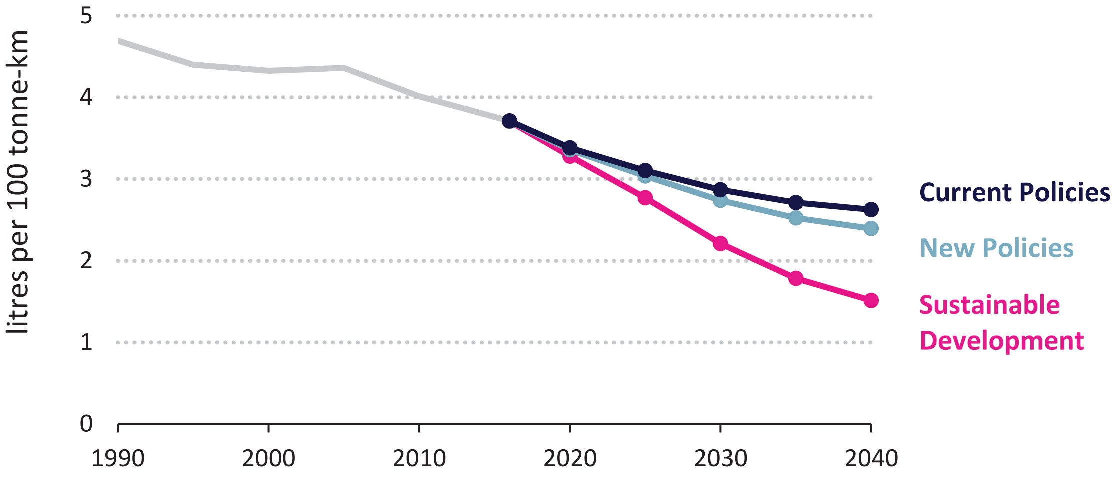


Source: WEO 2017 (IEA, 2017).

2.5.2.3 Average fuel consumption by trucks (Figure 14)

There have been some improvements in the fuel efficiency performance of road freight vehicles (trucks) in the past few years but at a slower pace than for passenger cars. To date Canada, China, the European Union, India, Japan and the United States have proposed or implemented freight vehicle efficiency standards. Electrification has yet to reach road freight in any significant manner. The majority of road freight vehicle manufacturers have announced that they are working on electric vehicles but have not launched models on a commercial scale: it is too early to tell whether this will be successful. This indicator is therefore most in line with the Current Policies Scenario.

Figure 14: Fuel efficiency of trucks



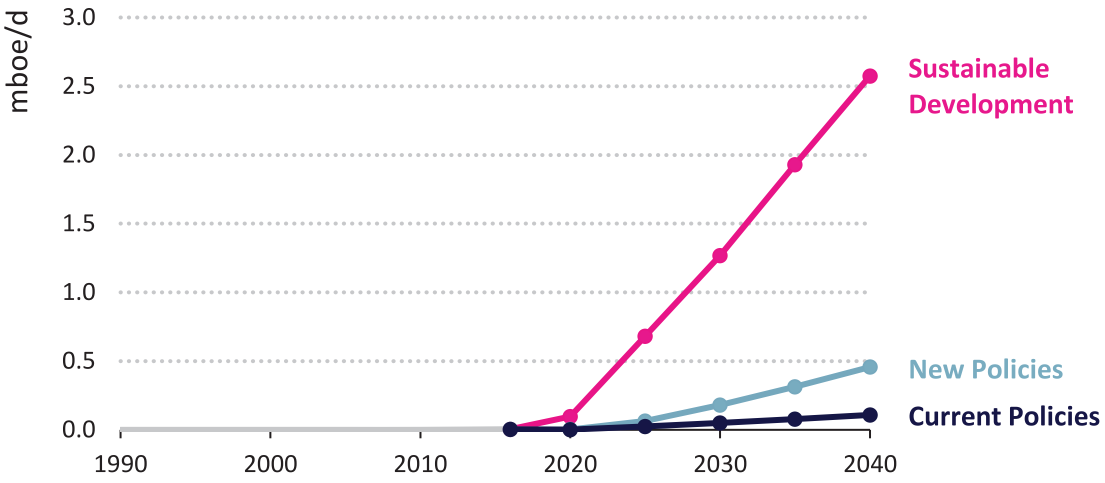
Source: WEO 2017 (IEA, 2017).

2.5.2.4 Total biofuel consumption in aviation and shipping (Figure 15)

Currently there are only minor volumes of biofuel consumed in aviation and shipping. In order to meet the Sustainable Development Scenario trajectory, the use of biofuel would need to start ramping up at a rapid pace in the next few years and reach over 1 million barrels of oil equivalent per day (mboe/d) by the late 2020s. Several actors in the aviation industry (including the International Civil Aviation Authority) have announced voluntary, aspirational targets to achieve carbon neutral growth by 2020 and a 50% reduction in GHG emissions by 2050 relative to 2005 levels. Biofuels for aviation are seen as one of the key measures in order to reach these targets. Yet the high cost of bio-jet fuel is one of the main factors prohibiting more widespread use. Sourcing suitable feedstock is another. Advanced bio-jet fuels based on lignocellulosic feedstocks or using algae are still at a demonstration phase and are not yet commercially viable. Similarly, there has been little progress in the shipping sector towards increased biofuel use.

In summary, current developments provide little indication of positive momentum in biofuel consumption in aviation and shipping towards the levels in the Sustainable Development Scenario.

Figure 15: Total biofuel consumption in aviation and shipping



Source: WEO 2017 (IEA, 2017).

2.5.3 Industry

The industry sector consumed just over 110 EJ energy in 2015 and was responsible for around 20% of energy-sector CO_2 emissions (just under 7 $GtCO_2$). Industrial energy consumption has grown by around 1.7% each year on average over the last five years but a changing energy mix has enabled CO_2 emissions to stay broadly flat. Coal consumption has declined while gas and electricity have increased. There is also around 2.1 $GtCO_2$ emitted from industrial processes, the majority of which stems from cement manufacture. Total industry CO_2 emissions from both energy and processes are therefore around 8 Gt today.

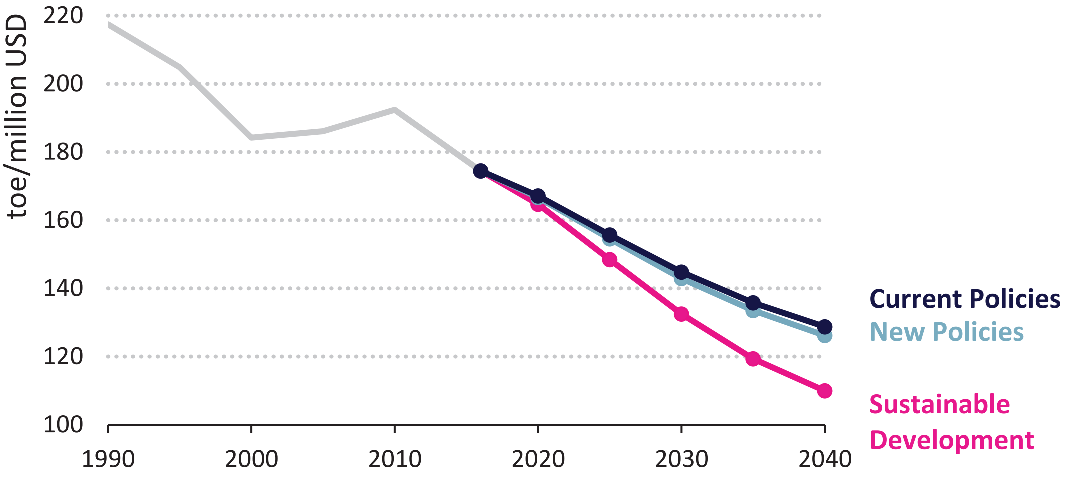
2.5.3.1 Trends in the AR5 scenarios

- In the non-mitigation AR5 scenarios, final energy consumption grows by between 1% and 1.3% each year to 2050. There is no significant improvement in the emission intensity of energy consumption in the industry sector between 2020 and 2050 and so direct CO_2 emissions from industry grows to above 14 $GtCO_2$ by 2040.
- In the 550ppm CO_2-eq AR5 scenarios, energy consumption in 2050 is around 30% lower than in the non-mitigation scenarios, but emissions are marginally higher than today.
- In the 450ppm CO_2-eq AR5 scenarios, final energy consumption is again broadly similar to the 550ppm CO_2-eq scenarios, but the CO_2 emissions intensity of energy consumption falls each year by between 1.5% and 2.8% to 2050. Emissions therefore fall to around 5.3 $GtCO_2$ in 2050.

2.5.3.2 Energy demand per unit of value added in the industry sector (Figure 16)

The ratio of energy demand to value added in industry improved by around 10% over the past five years. Heavy industries have seen the greatest slowdown in energy consumption growth while lighter (and more value adding) industries have continued in line with longer-term trends from the past. Despite these improvements, energy efficiency policies and efforts need to be strengthened for this indicator to develop in line with the Sustainable Development Scenario.

Figure 16: Energy demand per unit of value added in the industry sector



Source: WEO 2017 (IEA, 2017).

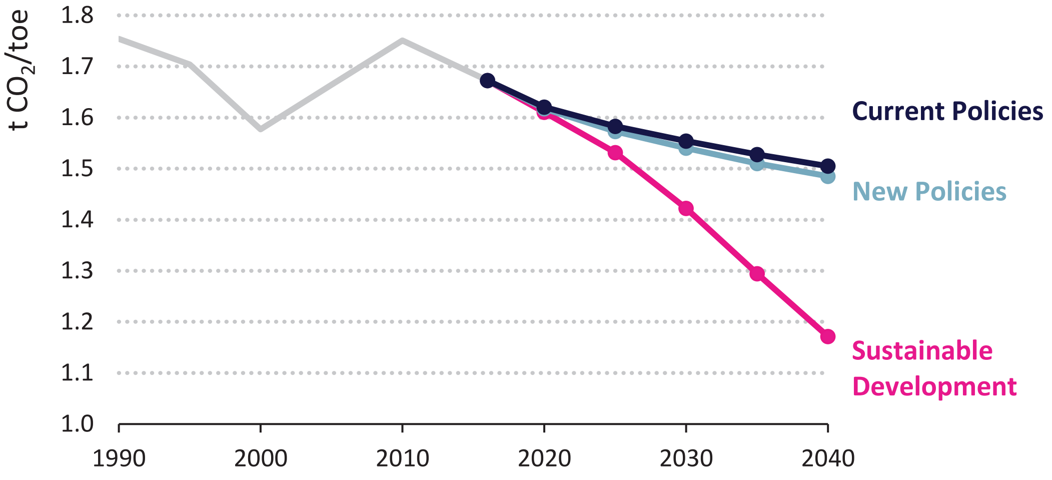
2.5.3.3 CO_2 per unit of energy consumption in the industry sector (Figure 17)

The CO_2 intensity of the industrial sector has improved in recent years given the flat level of CO_2 emissions while energy consumption has increased. Most of the improvements, however, have come outside of the heavy industries, which have not seen any substantial change in their energy mix. Between 2010 and 2014, global steel production in electric arc furnaces increased by only 1 percentage point to 30%. The iron and steel industry will need to step up efforts to increase the share of electric arc furnaces, which would help improve energy efficiency and lower its CO_2 intensity. The chemicals industry has made better progress towards reducing CO_2 emissions in recent years.

There has been some progress in the use of CCUS in industry: there are 13 industrial projects operational that have a combined capture capacity of around 25 $MtCO_2$ per year. The majority of these are related to natural gas processing but there are also a few that are used in industrial processes such as the production of fertilisers. The world's first steel CCS project started operation in 2016. There are also four facilities under construction and another six in advanced development stages.

The New Policies Scenario and Current Policies Scenario do not project drastic improvements in this indicator, so recent trends suggest a rate of improvement that exceeds the level required in these two scenarios. However, much more effort will be needed to reach the trajectory of the Sustainable Development Scenario.

Figure 17: CO_2 per unit of energy consumption in the industry sector

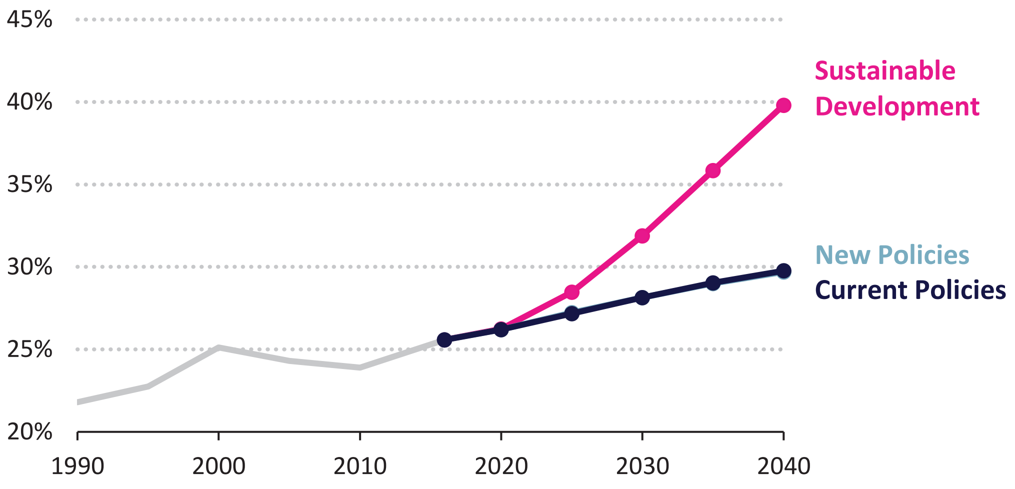


Source: WEO 2017 (IEA, 2017).

2.5.3.4 Zero carbon fuel share in the industry sector (Figure 18)

The use of zero carbon fuels (bioenergy, other renewables and electricity) has increased in recent years, mainly as a result of an increase in electricity consumption. However, improvements are slow and are behind the levels projected in the Current Policies Scenario and the New Policies Scenario.

Figure 18: Zero carbon fuel share in the industry sector



Source: WEO 2017 (IEA, 2107).

2.5.4 Buildings

Buildings account for just under 10% of direct energy-sector CO_2 emissions (3.5 $GtCO_2$), a share that has been broadly constant over the past five years. Residential buildings are responsible for around two-thirds and service sector the remaining one-third of emissions. Energy consumption from buildings has increased by around 1% each year since 2010.

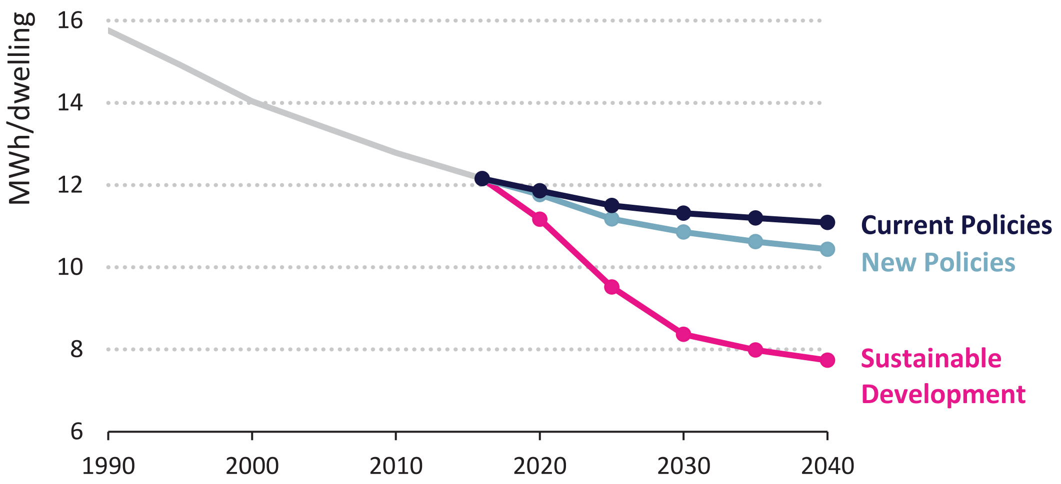
2.5.4.1 Trends in the AR5 scenarios

- In the non-mitigation AR5 scenarios, there is no major growth in final energy consumption to 2050. However, direct CO_2 emissions from the sector grow by around 0.6% each year on average as there is a change in the types of fuels that are consumed (most notably away from the traditional use of biomass towards liquefied petroleum gases [LPG] and natural gas): direct emissions therefore increase to around 4.4 $GtCO_2$ in year 2050.
- In the 550ppm CO_2-eq AR5 scenarios, energy consumption in 2050 is around 20% lower than in the non-mitigation sectors with no significant improvement in the emission intensity per unit of energy consumption.
- In the 450ppm CO_2-eq AR5 scenarios, final energy consumption is again broadly similar to the 550ppm CO_2-eq scenarios. The rate of decline in the CO_2 emissions intensity of energy consumption is more modest than that seen in other sectors (falling by between 0.3% and 0.5% each year to 2050) but emissions still fall to less than 2 $GtCO_2$ in 2050.

2.5.4.2 Energy demand per dwelling in residential buildings (Figure 19)

The total number of households globally increased by 150 million to more than 2 billion between 2011 and 2016 (an 8% increase). At the same time energy demand increased by around 5%, and so there has been a drop in overall energy demand per dwelling globally. The Sustainable Development Scenario requires a rapid improvement in this indicator meaning that the deployment of energy efficiency measures and low-carbon building technologies would need to increase at a much faster pace than currently observed, particularly in advanced economies. The indicator points to developments most in line with the New Policies Scenario.

Figure 19: Energy demand per dwelling in residential buildings

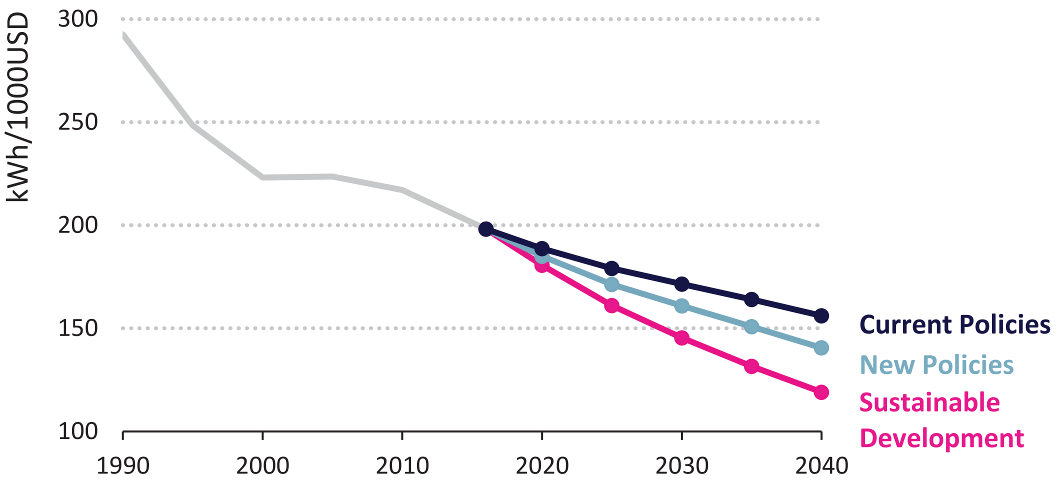


Source: WEO 2017 (IEA, 2017).

2.5.4.3 Energy demand per unit of value added in services (Figure 20)

The value added by services has increased markedly in recent years while energy demand has grown by just over 1% (led by increased consumption of electricity and natural gas). As in the residential sector this indicator is most in line with the New Policies Scenario.

Figure 20: Energy demand per unit of value added in services

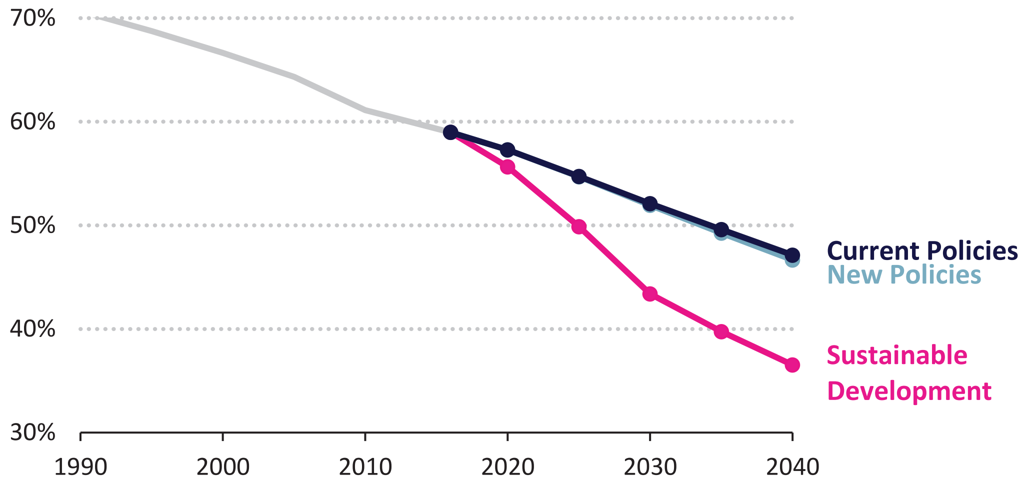


Source: WEO 2017 (IEA, 2017).

2.5.4.4 Share of fossil fuels and traditional biomass in the buildings sector (Figure 21)

The share of fossil fuels and traditional biomass in total energy use in buildings has dropped steadily since 1990, and currently stands at just under 60%. Over the past ten years, the consumption of fossil fuels and traditional biomass has been relatively flat in absolute terms, as increases in energy demand have been met by electricity. Nevertheless, traditional biomass is today still the single largest fuel used in buildings (with a share of about 23%) followed by natural gas (at 21%). Despite these improvements, this indicator it is not on track to meet the Sustainable Development Scenario, which requires a step change in the rate of decrease.

Figure 21: Share of fossil fuels and traditional biomass in the buildings sector



Source: WEO 2017 (IEA, 2017).

2.5.5 Summary

A ‘traffic-light’ categorisation is used here to summarise how the recent trends for the indicators compare with the projected trends in the different scenarios. As discussed in Section 2.2, the extrapolation of the historical time series data for each indicator into the future takes into account recent investment decisions, announced policy, regulatory, and business aims and strategies from around the world, and progress in research, development and deployment. The ‘Degree on Track’ in Table 1 is calculated as the 2040 value for the indicator trends minus the 2040 value in the Current Policies Scenario divided by the difference between the 2040 values in the Current Policies and Sustainable Development Scenarios. A value of 100% would indicate that the indicator is fully in line with the Sustainable Development Scenario while a value of 0% would indicate the indicator is in line the Current Policies Scenario. These are then allocated to a ‘traffic-light’ colour:

- Red indicates that the sector is not on track for the Sustainable Development Scenario. Trends are most in line with the Current Policies Scenario.
- Amber indicates that there has been some encouraging progress to date, but more efforts are needed to satisfy the needs of the Sustainable Development Scenario. Trends lie between the Current Policies and Sustainable Development Scenarios.
- Green indicates that trends are most in line with the Sustainable Development Scenario, although continued progress and policy support remain essential.

Table 1: Traffic-light dashboard of energy-sector indicators

Sector	Indicator	Unit	Current level	Indicator trends	Sustainable Development Scenario	Degree on track*
			2017	**2040**	**2040**	
Power	Variable renewable electricity capacity	GW	920	5400	6200	80%
	Nuclear capacity	GW	419	600	720	40%
	CCUS capture capacity	$MtCO_2$ captured/year	30	50	1500	0%
Transport	Average passenger car fleet oil consumption	litres per 100 km	8.7	4.5	2.5	45%
	Average fuel efficiency of trucks	litres per 100 tonne-km	3.6	2.9	1.5	0%
	Biofuel consumption in aviation + shipping	mboe/d	0	0.1	2.6	0%
Industry	Energy demand/value added	toe/million USD	175	150	110	0%
	CO_2/energy consumption	tCO_2/toe	1.6	1.4	1.2	40%
	Zero carbon fuel share in sector	%	26%	28%	40%	0%
Buildings	(Residential) Energy demand/dwelling	MWh/dwelling	12.1	9.9	7.7	35%
	(Services) Energy demand/value added	kWh/1000 USD	194	140	120	35%
	Share of fossil fuels + traditional biomass	%	59%	47%	37%	0%

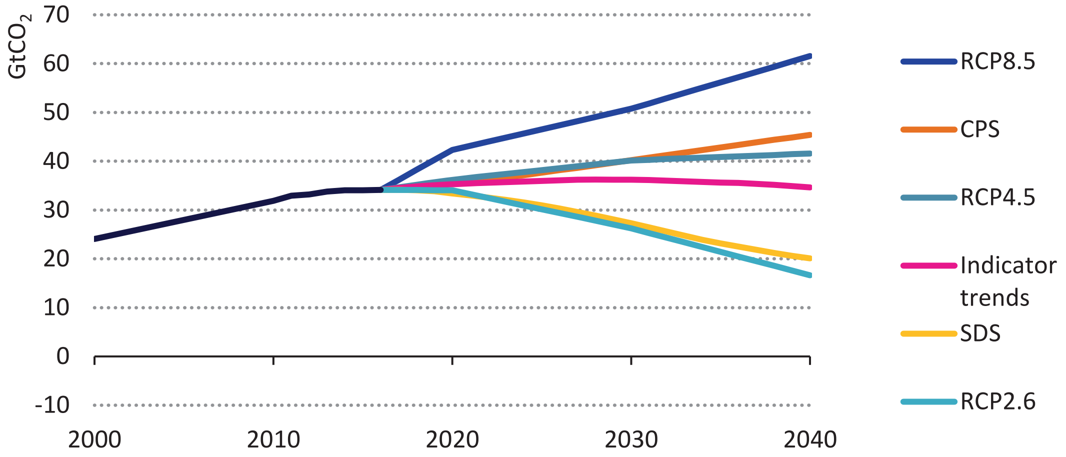
Note: *A value of 100% indicates the indicator is in line with the Sustainable Development Scenario; a value of 0% indicates the indicator is in line with (or below) the Current Policies Scenario; CCUS = carbon capture utilisation and storage.

Our final step is to develop an outlook for future emissions from the energy sector. This is based on the status of these 12 sector-specific indicators and the contributions that each makes to emissions reductions in the Sustainable Development Scenario relative to the Current Policies Scenario (the New Policies Scenario is not used for this).

The trend for emissions from that sector or sub-sector are based on where the indicator lies between the projections from the Current Policies and Sustainable Development Scenarios (i.e. its ’degree-on-track’). Some of the indicators generated at the sub-sectoral level do not necessarily cover every specific emissions source from the sector as a whole. In the transport sector for example, emissions from the three indicators cover around 90% of current sectoral emissions (emissions from buses and trains are not captured). In this case, the weighted trend of the three chosen indicators is assumed to be representative of the emissions trend for the entire sector. After generating a composite emissions trend from each of the three indicators, this is extrapolated to cover total emissions from the sector.

The resultant level of energy-sector CO_2 emissions (including industry process emissions) based on this extrapolation of indicator trends is shown in Figure 22. Emissions continue to rise slowly until the late 2020s, and then fall very gradually to around 35 Gt in 2040 (3 Gt higher than today). This can be compared with the Representative Concentration Pathways (RCPs) generated as part of the IPCC AR5. The outlook for emissions based on these indicator trends most closely tracks RCP4.5. This is significantly below the trend in RCP8.5, which grows to over 60 $GtCO_2$ by 2040, but also far above the trajectory seen in the Sustainable Development Scenario, which is broadly similar to the trend seen in RCP2.6.

Figure 22: Energy-sector and industrial process CO_2 emissions based on indicator trends



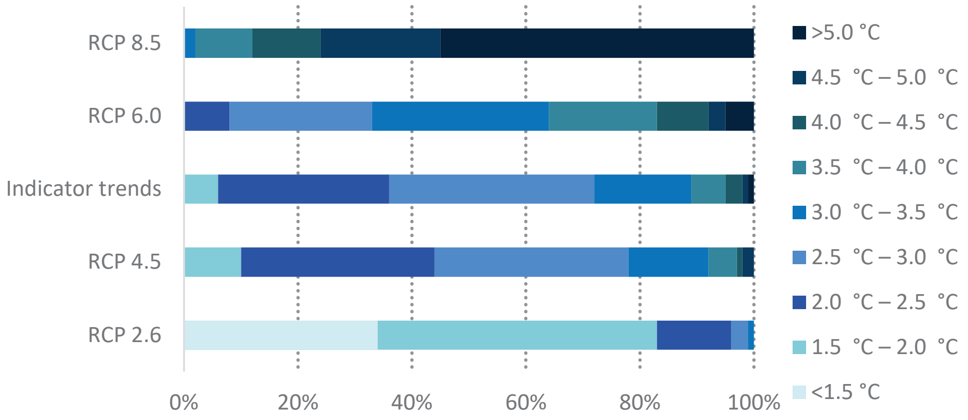
Notes: CPS = Current Policies Scenario; SDS = Sustainable Development Scenario; RCP = Representative Concentration Pathway.

2.6 Impacts of emission pathways on temperature rise

The final stage here is to covert the emissions trends into temperature rises. The warming probability of different emission pathways, calculated using the climate model MAGICC (Meinshausen et al., 2011), is shown in Figure 23. These pathways include both the RCPs (van Vuuren et al., 2011) and the outlook based on indicator trends as shown in Figure 22. The RCP2.6 pathway approximately corresponds to the Sustainable Development Scenario and the 450ppm CO_2-eq AR5 scenario grouping discussed above, while the RCP4.5 pathway is most similar to the 550ppm CO_2-eq AR5 scenario grouping. The probability of achieving different temperature rises in 2100 across these different scenarios is summarised in Figure 23.

Under RCP2.6, the median temperature rise in 2100 is around 1.65°C; there is around a 33% chance that the temperature rise will be below 1.5°C, and less than a 5% chance that it will exceed 3°C. The outlook based on indicator trends has a median 2100 temperature rise of around 2.7°C with less than a 5% chance that it will be below 2°C and around a 25% chance that it will exceed 3°C. As expected, given the similar emissions trajectories shown in Figure 22, the temperature outcome from the outlook based on indicator trends is broadly similar to RCP4.5. It should be remembered, that even the outlook based on indictor trends relies on a continued acceleration in policy ambition (albeit not at the pace necessary to realise emission mitigation in line with the Sustainable Development Scenario). This means that emissions fall very gradually over time to just under 25 $GtCO_2$ in 2100. Without these, the GHG emissions trend will not flatten and could continue to rise in line with the Current Policies Scenario or even RCP8.5. Under RCP8.5, there is a near 90% chance that the temperature rise in 2100 will exceed 4°C, with the median temperature rise in 2100 exceeding 5°C.

Figure 23: Warming probability in different scenarios



2.7 Conclusions

The long-term average global surface temperature rise is a function of cumulative emissions. The energy sector is responsible for around two-thirds of GHG emissions today. As the world's population and economy continues to grow, the energy sector will be a critical determinant of the future emissions levels.

Although countries have already taken some positive actions to reduce GHG emissions, pledges made as part of the Paris Agreement goal are insufficient to achieve the stated goal of 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C'. Much more rapid post-2030 emissions mitigation would be required than modelled under cost-effective pathways if the pre-2030 pledges are not significantly improved.

Since 2000, the amount of energy consumed per unit of GDP has fallen by around 1% each year; to achieve the temperature objectives of the Paris Agreement, this rate of decline needs to increase to over 2.5%. The level of CO_2 emissions emitted per unit of energy consumed also needs to fall in parallel: despite recent policy efforts, this has risen marginally since 2000.

The pace of transition to achieve a high-efficiency, low-carbon energy system therefore needs to accelerate rapidly. To examine this in more detail, we have identified 12 sub-sectoral indicators across the energy system to provide insights on the state of the energy transition today and to investigate how CO_2 emissions from the energy sector could develop in the future. Only one of the 12 selected indicators is on track with the pace required to realise the sustainable energy transition; no others are progressing at the necessary rate.

Based on these trends, energy-sector CO_2 emissions would continue to rise until the late 2020s, and then fall very gradually to around 35 Gt in 2040 (3 Gt higher than today). Extrapolating this trend to 2100 would lead to a median temperature rise in 2100 of around 2.7°C (with a 10–90% range of 2.1–3.5°C), which is broadly consistent with estimates of the impacts on emissions trends of the pledges made as part of the Paris Agreement. Limiting the temperature rise even to this level would require a ramp up from existing policy efforts; without these measures, the temperature rise in 2100 will very likely exceed 4°C (with a 50% chance that it will exceed 5°C). Ultimately, in all cases, net-zero CO_2 emissions are necessary to stop a continued increase in the average global temperature.

Of the 12 selected indicators, only mature variable renewables (such as onshore wind and solar PV) are on track. Yet even for these technologies, accelerated policy support and technological progress remain essential, especially to address the challenges that can arise with large-scale renewable-based electricity systems.

Insufficient progress is being delivered in all other sub-sectors. Five out of 12 indicators have shown some recent improvements but require much greater policy efforts. These cover progress in: passenger transport, the emissions intensity of fuels consumed in the industry sector, efficiency in residential and service buildings, and the deployment of nuclear capacity.

In passenger transport, policies are needed to increase the costs of owning and operating cars with high emissions intensities while incentivising the purchase of more efficient and zero carbon options. Investment is also needed in energy-efficient modes of public transport, regulations need to be introduced that mandate ambitious vehicle efficiency improvements, and measures implemented that encourage the adoption and development of low-carbon fuels.

In the industry sector, the near-term focus should be on implementing best available technologies and continuing to improve energy efficiency. Longer-term emissions cuts will require policy support to incentivise innovation at both pilot and commercial scale as well as collaboration across companies, sectors and national borders.

In buildings, much greater effort is needed to make end-use appliances as efficient as possible and ensure that buildings are near zero-energy when they are constructed, deep retrofits are undertaken on the existing building stock, and heating in buildings is increasingly provided through zero carbon sources. Greater access to finance is critical to stimulate the necessary investments.

Finally, while there are positive developments in the level of nuclear capacity being developed and planned in some countries, in many other cases progress is increasingly lagging. Clear and consistent policy support is necessary for both existing capacity and to encourage new capacity. This includes efforts to reduce the investment risk arising during the licensing and siting stage and therefore minimise the level of capital expenditure required prior to receiving a final approval or decision.

Six indicators are significantly off track and require renewed policy focus. These include progress in carbon capture and storage, freight transport, levels of advanced biofuel produced and consumed, efficiency improvements and the share of zero carbon fuels in industry, and the level of zero carbon fuels consumed in buildings.

Carbon capture utilisation and storage (CCUS) is critical for the decarbonisation of both the power and industry sectors. While the global portfolio of large-scale CCUS projects has expanded in recent years, the current absence of adequate policy support is severely impeding necessary progress.

Advanced biofuels are vital for the decarbonisation of many transport sectors (particularly aviation), but current rates of deployment are severely off track. Widespread mandates are essential to accelerate their uptake, which should be complemented by financial de-risking measures (including tax incentives) to facilitate technological innovation and commercialisation, particularly during the period when costs remain high.

In all cases, robust scaling-up of public and private clean energy research, demonstration and development investment is essential to deliver a sustained, affordable and secure energy-sector transformation.

The approach used in this report to track changes and provide projections for specific indicators within the energy sector provides a quick and accessible overview of efforts to tackle GHG emissions. By updating these indicators on a regular basis, it would be possible to track whether new developments have improved or worsened the long-term trajectory for overall emissions. As well as helping to assess the impacts of recent policy decisions, this would also indicate where policies are proceeding at the rate required and where they are needed to accelerate action. One effort in this regard is the IEA's 'Tracking Clean Energy Progress',[9] which provides a rigorous assessment of progress in specific energy technologies and sectors that are needed to realise the clean energy transition.

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[9] See http://www.iea.org/tcep/

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Chapter 3: The direct risks of climate change

3.1 Introduction

The aim of this chapter is to assess the direct risks of different levels of climate change, focusing on high rates of change and comparing them with impacts at low rates of change. It characterises risks by a range of indicators which describe future impacts associated with climate extremes, water resources stress, river and coastal flooding, drought and agriculture. This chapter builds on Chapter 2 which considers future emissions pathways, and provides a foundation for the analysis of systemic risks in Chapter 4.

The United Nations International Strategy for Disaster Reduction (UNISDR) defines risk as the 'potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time' (UNISDR, 2009). Risk is conceptualised as a function of the *physical hazard*, *exposure* to hazard, and *vulnerability* to loss (IPCC, 2012). The physical hazard describes climatically induced events such as heatwaves, floods and droughts. Exposure describes the people, activities and assets which may be affected by a physical hazard, such as the number of people living in flood-prone areas or the location and timing of crop production. Vulnerability describes the propensity of what is exposed to hazard to suffer harm or loss. This is strongly determined by drivers such as access to resources, governance and capacity to anticipate or adapt.

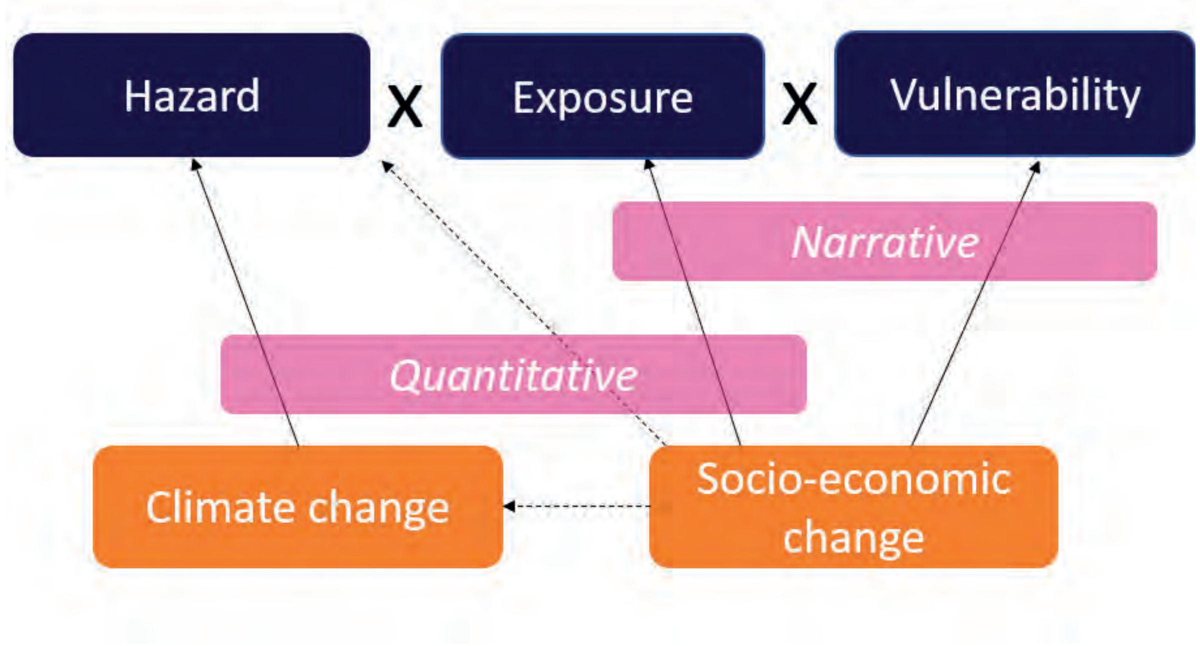
Climate change will alter the physical hazard, and socio-economic change will alter exposure and vulnerability (Figure 24). The key characteristics of the physical hazard and exposure can be quantified, and quantitative projections can be made based on climate and socio-economic scenarios. However, future changes in the drivers of vulnerability are much more challenging to express in quantitative terms, and can best be characterised through narrative storylines. This chapter focuses on quantitative indicators of physical hazard and exposure, and produces projections of potential risk which combine hazard and exposure. It does not consider vulnerability and, therefore, does not make projections of the actual impacts that may be experienced.

The approach adopted here is to estimate risks through the 21st century for a range of indicators, under *two emissions scenarios* and associated *climate scenarios*, and *five socio-economic scenarios*. The two emissions scenarios characterise low and high emissions, and the climate scenarios describe variations between regions and through the year in the changes in relevant climate variables (such as precipitation). There is some variability in the projected changes in climate between different climate models, and we use ensembles of models to characterise this uncertainty. Together, the emissions and climate scenarios are used to estimate changes in physical hazard. The changes in physical hazard are then combined with changes in exposure under the five socio-economic scenarios to estimate potential changes in the human dimensions of risk.

Risks are assessed at the global and the Chinese scales, using the same emissions and socio-economic scenarios and consistent sets of indicators.

The project as a whole is concerned not only with projecting future risks, but also with monitoring how risks and their drivers are evolving. However, monitoring the occurrence of physical hazards does not give useful insights into potential future risks because of the high year-to-year variability and the effect of internal climatic variability (such as El Niño) on differences from year to year. It is difficult to identify trends, and more specifically impossible to project future risks by extrapolating from recent experience. Monitoring current physical hazards is therefore most useful for providing a historical context for future scenario-based projections of hazard risks, and particularly for comparing year-to-year variability with longer-term trends. However, exposure varies more slowly, so trends in current exposure are potentially more indicative of future trends in impact and risk. Observed trends in the quantitative and qualitative drivers of vulnerability may also give useful insights into future vulnerability, and these are discussed in Chapter 4. Monitoring current actual impacts (for example numbers of people flooded) does not give useful information about future trends, partly because of the high year-to-year variability in hazard occurrence and partly because exposure changes over time.

Figure 24: Risk as a function of hazard, exposure and vulnerability, and the drivers of change in risk



This chapter presents an assessment of future climate risk across a number of indicators spanning different sectors. No attempt is made to evaluate the relative importance of different risks in different sectors, for three reasons. First, the indicators by necessity characterise impact using different metrics, which may not be directly comparable. Second, the relative ranking of different indicators will be influenced by decision-makers' priorities, and these of course vary between decision-makers and purposes. Third, the assessment concentrates on indicators that have already been defined and calculated: not all sectors are covered (the effects of tropical storms, for example, are not considered explicitly).

Projections of the impacts of climate change are uncertain, due to uncertainty in the rate of change in emissions, the response of the climate system to the increase in emissions, change in exposure to hazard, and the imperfect representation of processes within climate and impact models. For a given emissions and socio-economic scenario, published impact assessments tend to concentrate on the central estimate of impact and represent uncertainty by a range around this central value. We follow this approach whilst presenting the impact results, but at the end of the chapter we focus on the 'high-end' impacts at the top of the plausible range of impacts under the high emissions scenario. We do this because this assessment follows the call in King et al. (2015) for an increased focus on the 'worst case' climate change impact (Chapter 1).

3.2 Methodology

3.2.1 Introduction: hazard, exposure and vulnerability

The overall approach adopted in this chapter is to use a suite of impact models with climate, sea level and socio-economic scenarios to estimate the direct ('first-order') impacts of climate change at the global and Chinese scales. These models first simulate the current and future physical hazard (for example heatwave frequency) and then combine this with projected exposure (for example number of people aged over 65) to produce projections of indicators of potential impact (for example number of people exposed to heatwaves). The hazard and potential impact indicators are calculated for four impact areas, namely heat extremes, water resources, river and coastal flooding, and agriculture. Vulnerability is a function of social and institutional systems and behaviours, and is not included here: vulnerability determines how potential direct impacts translate into actual impacts, and how they develop into the systemic risks described in Chapter 4.

There are many different definitions of indicators for each hazard and impact, partly because different aspects of these hazards are relevant for different exposures and impact areas, and partly because different thresholds or critical values are relevant in different places. For example, different temperature thresholds or durations can be used to define a 'heatwave', depending on the characteristics of the exposed population and the health risks that are of concern. The specific indicators used at the global and Chinese scales are described in Sections 3.3 and 3.4.

Hazards and potential impacts are calculated for two emissions scenarios, representing low and high rates of emissions, for a range of plausible geographical patterns of change in climate associated with low and high emissions, and for a range of plausible socio-economic scenarios. These are discussed below.

3.2.2 Emissions scenarios and change in global mean temperature and sea level

Risks are calculated using two emissions scenarios. One of the emissions scenarios represents a future with high emissions, and we use Representative Concentration Pathway (RCP)8.5 (van Vuuren et al., 2011) to describe this world (note that this is not a forecast, but a plausible projection). As shown in Chapter 2, this emissions scenario has higher emissions than either the 'indicator trends' or 'Current Policies Scenario', and we use it primarily because it has been used in previous studies which we incorporate here. The other emissions scenario represents a world with much lower emissions, and is used so that we can compare risks under different rates of change in emissions. We use RCP2.6 (van Vuuren et al., 2011) to describe this world, which is broadly consistent with the goal of the Paris Agreement to limit the increase in global mean temperature to well below 2°C. RCP2.6 produces similar changes in temperature to the 'Sustainable Development Scenario' presented in Chapter 2.

Figure 25: Change in global average temperature under the two emissions scenarios. The temperature plot shows the median change plus the 10th and 90th percentiles. Observed data (black line) from HadCRUT4 to 2016.

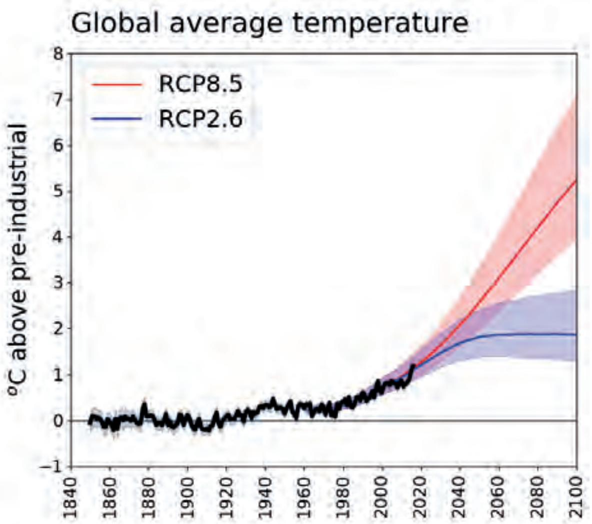
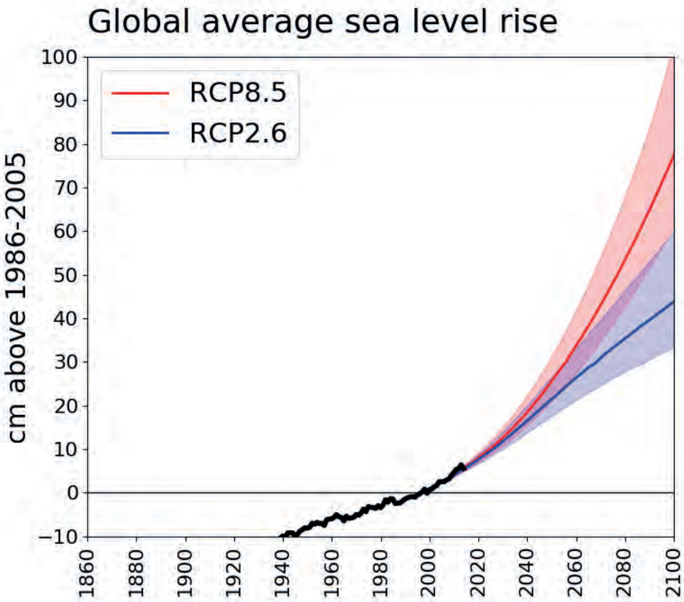


Figure 25 shows the change in global mean temperature under the two emissions scenarios, together with the observed change in global mean temperature. For each pathway, the probability distribution of future change in global mean temperature is estimated using a probabilistic version of the MAGICC climate model (Wigley & Raper, 2001; Lowe et al., 2009). The probability distribution accounts for uncertainty in climate sensitivity, the strength of the carbon cycle feedback, and the exchange of heat between atmosphere and ocean, and shows the median estimate of change in global average surface temperature along with the 10th and 90th percentiles. The observed trend is consistent with the projected future global mean temperature, but does not enable an assessment of the rate of future change.

The coastal zone impacts depend on sea level rise, primarily due to the thermal expansion of sea water as it warms and the melting of land-based glaciers and ice sheets. Figure 26 shows the projected change in global average sea level rise under the two emissions scenarios, again with observed change. The projected sea level rise is estimated from the increase in global mean temperature (see Annex 1). Sea level rise varies across the globe due to changes in ocean currents, the geographic distribution of thermal expansion, and the gravitational distribution of melting ice, but this is not represented in the scenarios used here. Sea level rise along the coastal zone also depends on vertical land movement due to, for example, glacial isostatic adjustment, tectonic change or subsidence (where the latter can be caused by the extraction of groundwater), and this is included. This can be particularly noticeable in susceptible areas where population is concentrated, and locally could be more important than sea level rise.

Figure 26: Change in global average sea level under the two emissions scenarios. The plot shows a middle estimate together with 'low' and 'high' projections for each emissions scenario. Observed data (black line) from Church & White (2011), updated to 2015.



3.2.3 Changes in regional and local climate

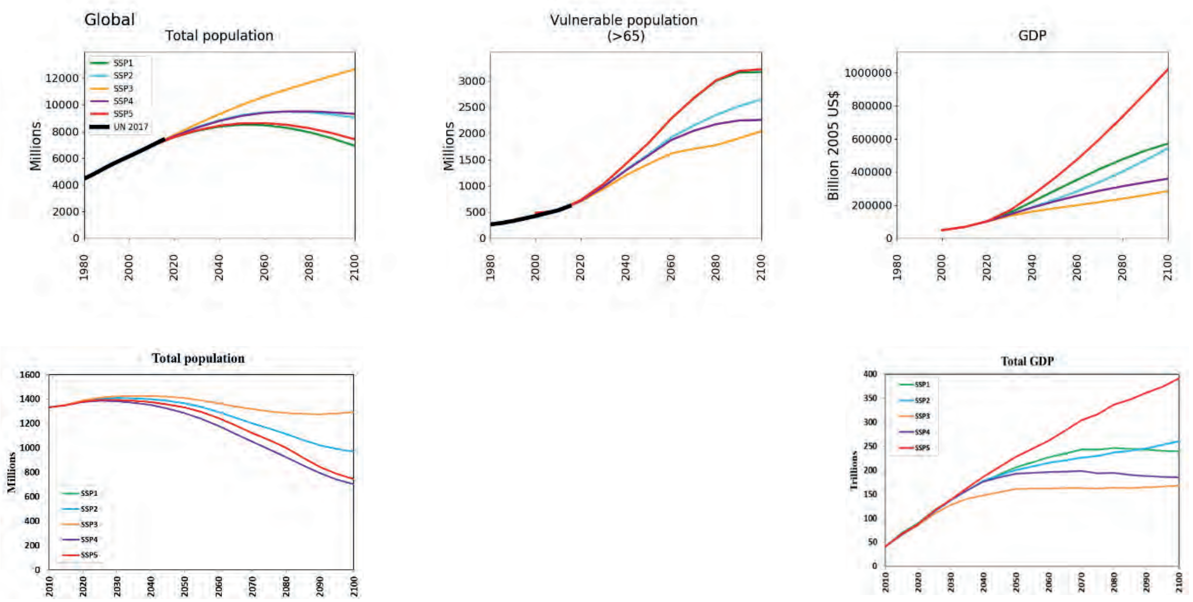
Changes in the hazard indicators are dependent not only on the change in emissions and the increase in global average temperature, but also – and more directly – on local changes in temperature, precipitation and other relevant climate variables. Scenarios describing plausible changes in local climate are based on the output of global climate models. Whilst different climate models tend to produce broadly similar large-scale patterns of change in climate (wet regions get wetter, dry regions get drier and temperature increases are greater at high latitudes), the estimated magnitudes of change can vary considerably and the direction of change may differ through the year. This assessment therefore uses ensembles of climate models to characterise the effects of uncertainty in the spatial distribution of change. These ensembles are all based on climate models used in the Coupled Model Intercomparison Project Phase 5 (CMIP5) intercomparison exercise (Taylor et al., 2012) and assessed in the IPCC Fifth Assessment Report (IPCC, 2013).

3.2.4 Socio-economic scenarios

Changes in exposure are defined by five Shared Socio-economic Pathways (SSPs; O'Neill et al., 2017). These socio-economic scenarios include both quantitative projections of potential changes in population and economic growth and narrative characterisations of changes in national and international governance and policy. In this chapter we just use the quantitative population and economic growth projections. The population projections in the SSPs are slightly different to those made by the United Nations Population Division: like the emissions scenarios, they are to be interpreted as plausible futures not specific predictions.

Figure 27 shows the global total population, ‘vulnerable’ population (over 65 years old) and total gross domestic product (GDP) under the five SSPs, together with the total projected population and total GDP in China. Note that all the Chinese population scenarios show a slight increase to the 2040s, and a reduction thereafter.

Figure 27: Projected global (top) and Chinese (bottom) population and GDP under the five SSP scenarios. The global data are taken from the IIASA SSP database http://tntcat.iiasa.ac.at/SspDb, and the Chinese data from Jiang et al. (2017, 2018)



3.2.5 Other relevant studies

There have been very many studies into the potential impacts of climate change at the local and regional scale (as reviewed for example in the IPCC Fifth Assessment Report; IPCC, 2014). However, there have been relatively few studies concerned with socio-economic impacts and risks at the global scale. Most of these global-scale studies have been undertaken as part of coordinated multi-sectoral studies using consistent climate and socio-economic scenarios. Examples include the QUEST-GSI project (Arnell et al., 2016a), which used older SRES climate and socio-economic scenarios, the ISI-MIP initiative (Warszawski et al., 2014), which used a subset of the CMIP5 climate scenarios, BRACE (O’Neill et al., 2018), which used multiple ensembles from a single climate model, and the HELIX project, which uses CMIP5 and later climate models. The BRACE project and published HELIX papers (Betts et al., 2018) have concentrated on the impacts avoided if specific climate policy targets are achieved, rather than impacts under high rates of climate change.

King et al. (2015) presented an initial assessment of global direct climate risks across a number of sectors (heat stress to people, crop production, water stress, drought, and coastal and river flooding), concentrating on impacts under high rates of change and attempting to estimate ‘worst case’ impacts for some of the sectors. The analysis was based on a combination of reviews of existing studies and new research with CMIP5 scenarios. The global-scale assessment in this report builds on the King et al. (2015) assessment by considering a wider range of indicators and sectors, and using a consistent approach based on the same climate and socio-economic scenarios.

3.3 Direct risks at the global scale

3.3.1 Introduction

This section presents an overview of the direct risks posed by climate change at the global scale. It presents changes in physical hazard and the combined effects of changes in hazard and exposure, and also presents information in terms of both the magnitude of risks and the likelihood that risks exceed specific thresholds.

3.3.2 Indicators

The indicators are summarised in Table 2 and described in detail in Annex 1.

Table 2: Risk indicators calculated at the global scale

Impact area	Risk	Indicator of hazard	Indicator of exposure	Indicator of potential impact
Heat extremes	Health impacts	Annual likelihood of at least one heatwave (at least 4 days with temperature >99th percentile of warm season temperature)	Number of people over 65	Average annual number of vulnerable people exposed to heatwaves
	Labour productivity	Average annual number of days with WBGT >32°C	Number of people between 20 and 65	Average annual proportion of working age population exposed to unworkable conditions (at least 30 days with WBGT >36°C)
Water resources	Persistent water shortage	Proportion of land area with a reduction in runoff	Number of people	Number of people living in water-stressed watersheds
	Periodic water shortage	Annual likelihood of experiencing a drought (12-month SRI less than −1.5, for at least 6 months)	Number of people	Average annual number of people exposed to drought (6+ months)
River flooding	River flood loss	Annual likelihood of the reference period 50-year flood	Number of people in river floodplains	Average annual number of people exposed to river flooding, assuming no protection
Coastal flooding	Coastal flood loss	Area potentially affected by the 100-year flood	Number of people in coastal floodplains	Average annual number of people flooded, assuming no increase in level of protection

Table 2: Risk indicators calculated at the global scale

Agriculture	Loss of production (general)	Annual likelihood of experiencing a drought (6-month SPEI less than −1.5, for at least 3 months)	Area of cropland	Average annual area of cropland exposed to drought
		Annual likelihood of the reference period 30-year flood	Area of cropland	Average annual area of cropland exposed to flood
	Loss of production (maize)	Annual likelihood of a hot spell during the growing season (5+ days >36°C)	Area of maize cropland	Average annual area of maize cropland exposed to hot spells
		Annual likelihood of rainfall during maize reproductive season being more than one standard deviation below the mean	Area of maize cropland	Average annual area of cropland with rainfall more than one standard deviation below the mean
		Annual likelihood that crop duration decreases by more than 10 days	Area of maize cropland	Average annual area of cropland with reduction of crop duration of at least 10 days
		Annual likelihood that average growing season temperature is greater than 23°C	Area of maize cropland	Average annual area of cropland with average temperature >23°C

Notes: SPEI = standardised precipitation evapotranspiration index; SRI = standardised runoff index; WBGT = wet bulb globe temperature.

3.3.3 Overview of the methodology for assessing global-scale impacts

The coastal hazard and impact indicators depend on sea level rise (including the effects of subsidence and isostatic adjustment) and socio-economic change, and were estimated using the DIVA modelling framework (Hinkel, 2005; Vafeidis et al., 2008). Changes in the other indicators are dependent not only on the change in global mean temperature, but also on local changes in temperature, precipitation and other relevant climate variables. These indicators were estimated by combining the probability distribution of global mean temperature change in a given year (from Figure 25) with damage functions (updated from Arnell et al., 2016b) describing the relationship between global mean temperature change and risk. There is a separate damage function for each of

23 patterns of local change in climate, based on 23 CMIP5 climate models (Osborn et al., 2016). The damage functions were constructed in two stages, repeated for each of the 23 model patterns. The first was to construct climate scenarios corresponding to defined increases in global mean temperature by rescaling patterns showing change per degree global temperature change (Osborn et al., 2016). The second was to use gridded hazard and impact models to estimate hazards and impacts for each of these scenarios, and to build a damage function relating hazard and impact to global mean temperature change. The hazard damage functions are independent of time, but the impact functions are calculated separately for different time periods because exposure changes over time. The impacts on the population of a 2°C increase in temperature will be different in 2020 and 2080, for example.

The resulting estimated hazards and impacts therefore take into account uncertainty in the amount of global average temperature change for a given emissions pathway and the changes in regional climate associated with a given global average temperature change. This uncertainty is represented by showing the median estimate together with ‘low’ and ‘high’ estimates: the low and high estimates are actually the 10th and 90th percentiles from the distribution of estimates, but these should not be taken too literally because the distribution does not necessarily incorporate all the potential sources of uncertainty.

For each indicator, the period 1981–2010 is assumed to represent baseline climatic conditions (Harris et al., 2014). The indicators characterise hazard and impact averaged over a 30-year period, and there will be variability in the actual occurrence of events around this average from year to year.

Impacts in each sector are described in two figures. The first shows, for each indicator, the evolution of the hazard through the 21st century under low and high emissions, the risk through the century that the hazard exceeds some defined level, and the impact in 2100 by emissions scenario and socio-economic scenario. The hazard plots also show the observed hazard occurrence from 1960 to 2016 (based on the CRU TS4.01 global gridded climatology; Harris et al., 2014). The impact plots also show the estimated impacts with the 1981-2010 climate and 2010 population and GDP.

The second figure shows the spatial distribution of hazard for each indicator, showing hazard occurrence over the baseline period 1981–2010 and occurrence in 2050 under high emissions, for two illustrative climate model scenarios. These two were selected from the 23 CMIP5 patterns, and are intended to illustrate both the spatial variability in change in hazard and the variability across climate models.

Table 3 summarises the hazard indicators in 2100 under low and high emissions.

Table 3: Global-scale hazard indicators with the 1981–2010 reference climate, and average 2100 climates for low and high emissions. Each represents an annual average over a 30-year period

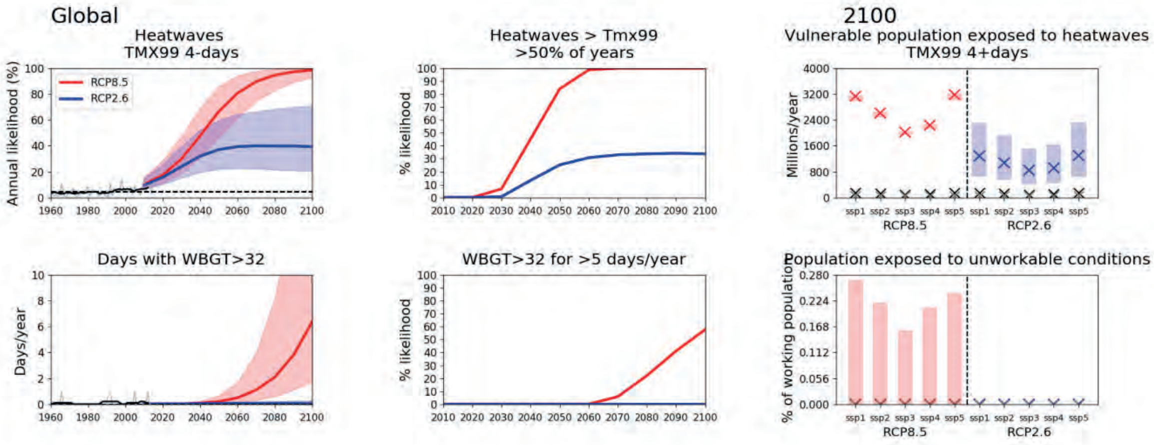
Indicator	**1981–2010**	**2100: low emissions**	**2100: high emissions**
Heat extremes			
Heatwave (% chance of at least one)	4.7	39 (20–71)	99 (93–100)
Days/year with WBGT>32	0	0.05 (0.02–0.26)	6.4 (1.7–25)
Water resources			
Hydrological drought (% chance)	5.9	7.9 (6.5–10.3)	11 (8.5–13.0)
Area with decrease in runoff (% of area)	0	13.5 (5.9–24.8)	35 (25–44)
River flooding			
Flood frequency (% chance of flood >T50)	2	3.4 (2.4–6.9)	12.2 (6.2–23.0)
Coastal flooding			
Area below the 100-year flood level (10^3 km^2)	641	790 (755–842)	896 (845–976)
Agriculture			
Agricultural drought (% chance)	9.4	30 (19–47)	70 (58–79)
Flood frequency (% chance of flood >T30)	3.3	4.8 (3.7–8.0)	12.9 (7.6–20.7)
Maize: heat spell frequency (% chance)	4.2	13.8 (8.7–25.7)	64 (47–81)
Maize: reduction in rainfall (% chance)	15	16.6 (14.7–66.0)	24 (17.0–32)
Maize: decrease in crop duration (% chance)	2.3	34 (15–66)	88 (84–89)
Maize: growing season temperature >23°C (% chance)	46	63 (55–77)	94 (89–97)

Notes: For 2100, the table shows the median plus the low to high range (in brackets); WBGT = wet bulb globe temperature.

3.3.4 Heat extremes

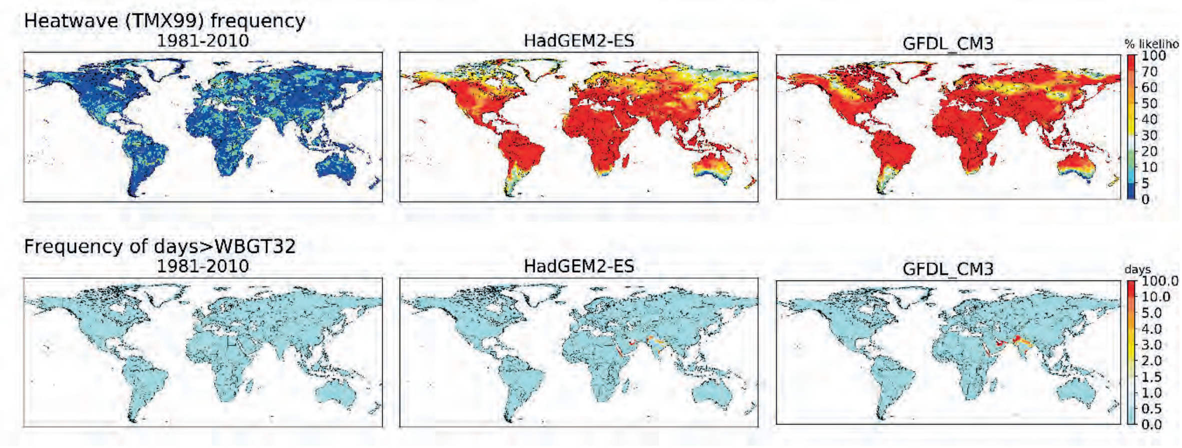
Figure 28 shows the change in the global impacts associated with heat extremes, focusing on the number of heatwaves and the number of days with conditions that are challenging for outdoor work. The number of heatwaves has increased in recent years in a direction consistent with the climate projections, but it is not possible to infer future impacts from recent experience. At the global scale, the number of days with high wet bulb globe temperature (WBGT) is currently very low, but increases very rapidly under the high emissions scenario. The number and proportion of people affected by heat extremes by 2100 (right hand panel) varies considerably between the socio-economic scenarios.

Figure 28: Global-scale impacts on heat extremes. The plots show: change in hazard through the 21st century together with observed hazard occurrence (left column); the risk of hazard exceeding specific thresholds (central column); and the impacts on human society in 2100 (right column) under the two emissions scenarios and five socio-economic scenarios. In the impacts plots in the right column, the coloured crosses show the median estimate of impact in 2100, the grey crosses show impacts in 2010 and the black crosses show the impacts in 2100 if climate remained at the 1981–-2010 level.



The effects of climate change vary spatially and this is illustrated in Figure 29, which shows the frequency of heatwaves and the number of days with WBGT greater than 32°C over the period 1981–2010, and in 2050 under high emissions with two different indicative climate model patterns. The chance of at least one heatwave a year increases to over 70% in most places, except at high latitudes, in parts of east Asia and in parts of South America. High WBGT days are very rare in most places even by 2050, but in parts of south Asia and the Middle East the frequency is considerably increased: note the difference between the two climate model patterns.

Figure 29: Geographical distribution of heat extreme hazard occurrence with the 1981–2010 climate (left panels) and two patterns of change in 2050 under high emissions as projected by two example climate models (middle and right panels)

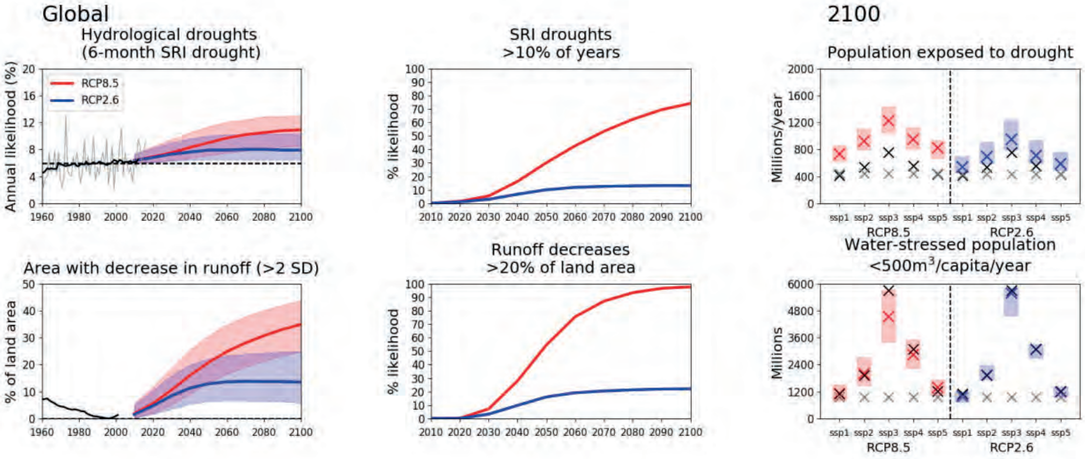


3.3.5 Water resources

Figure 30 shows two sets of indicators of the impacts of climate change on water resources. The area where runoff declines significantly relative to the 1981–2010 mean increases through the 21st century. In this case, the observations represent 30-year running means rather than annual values (because the indicator represents long-term average runoff). As with the drought indicator, the recent area with a significant reduction in runoff is larger than that projected until at least the 2030s, but there is considerable decade-to-decade variability. At the global scale, there are fewer people living in water-stressed watersheds in 2100 under climate change than with the 1981–2010 climate, with big differences between socio-economic scenarios. This is largely because runoff is projected to increase in some highly-populated water-stressed watersheds in south and east Asia (Figure 31).

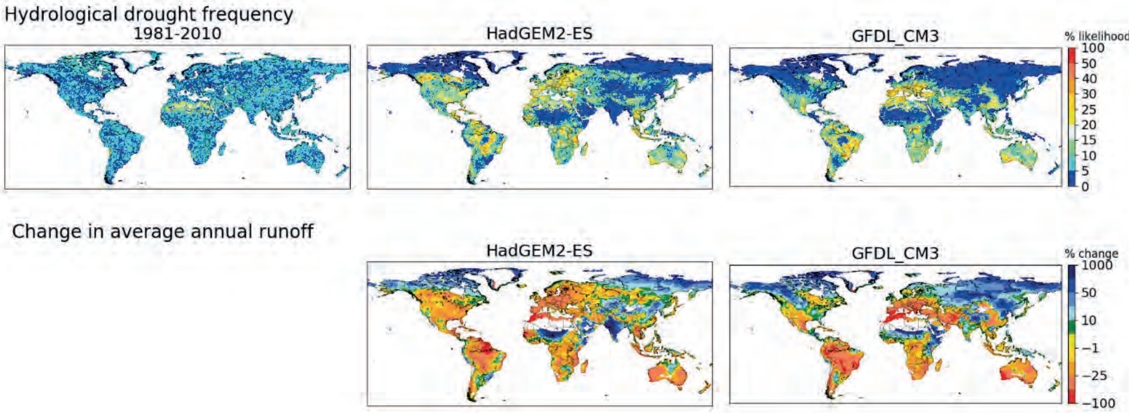
Global-scale hydrological drought risk increases, with a lesser risk under low emissions. The observed frequency of hydrological droughts is increasing more rapidly than under either projection, but there is considerable year-to-year variability. The population exposed to drought is strongly dependent on assumed socio-economic scenario.

Figure 30: Global-scale impacts on water resources.



Note: Key as for Figure 28

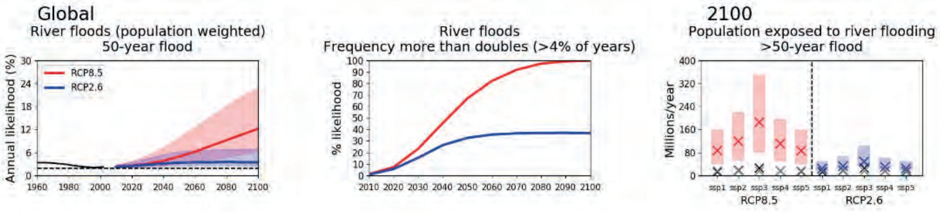
Figure 31: Geographical distribution of water resources hazards: drought frequency and change in average annual runoff, 1981–2010 climate and 2050s climate, high emissions



3.3.6 River flooding

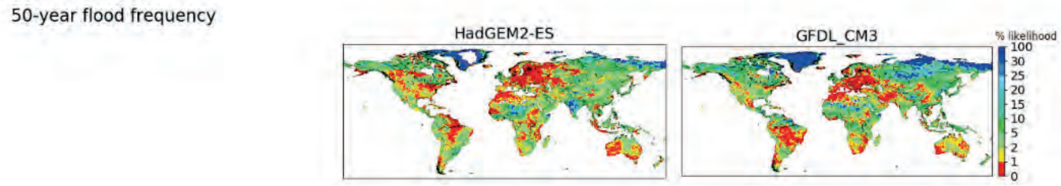
The projected change in river flood hazard occurrence, risk and impact are shown in Figure 32. At the global scale, risk increases through the 21st century and impacts in 2100 are strongly dependent on assumed socio-economic scenario. There has been little observed variability in river flood frequency (30-year running mean), but the climate change projections show little change at the global scale until at least 2030.

Figure 32: Global-scale impacts on river flood risk



The geographical distribution of change in river flood risk is shown in Figure 33 (the frequency in 1981–2010 is by definition 2%). In some parts of the world the frequency of the reference 50-year flood decreases, but in others – particularly in south and east Asia – it increases.

Figure 33: Geographical distribution of river flood hazard occurrence: 2050s climate, high emissions. Under the 1981–2010 climate, the frequency is by definition 2%



3.3.7 Coastal flooding

Coastal flood risk at the global scale is shown in Figure 34. In this case, it is not possible to estimate risk of impacts exceeding a threshold because of the way coastal impacts are constructed using just low, middle and high sea level projections for the two emissions scenarios. The area below the 100-year flood increases substantially through the 21st century, but there is relatively little difference between the two emissions scenarios because the two sea level scenarios are similar (because sea level rise takes time to respond to global warming, a phenomenon known as the commitment to sea level rise). The average annual population affected by coastal flooding varies much more with socio-economic scenario than with sea level scenario. Even if sea levels do not rise, a large area of land (approximately 640 × 10^3 km^2) remains exposed to flooding (black dotted line on Figure 34). Without future sea level rise and only taking into account land level change (black crosses), thousands of people would also remain subject to flood risk. In practice, coastal flood protection levels will increase over time due to economic growth and sea level rise, so this indicator characterises the magnitude of the potential impact rather than actual impact. For this indicator, it is not possible to produce maps describing the distribution of impact.

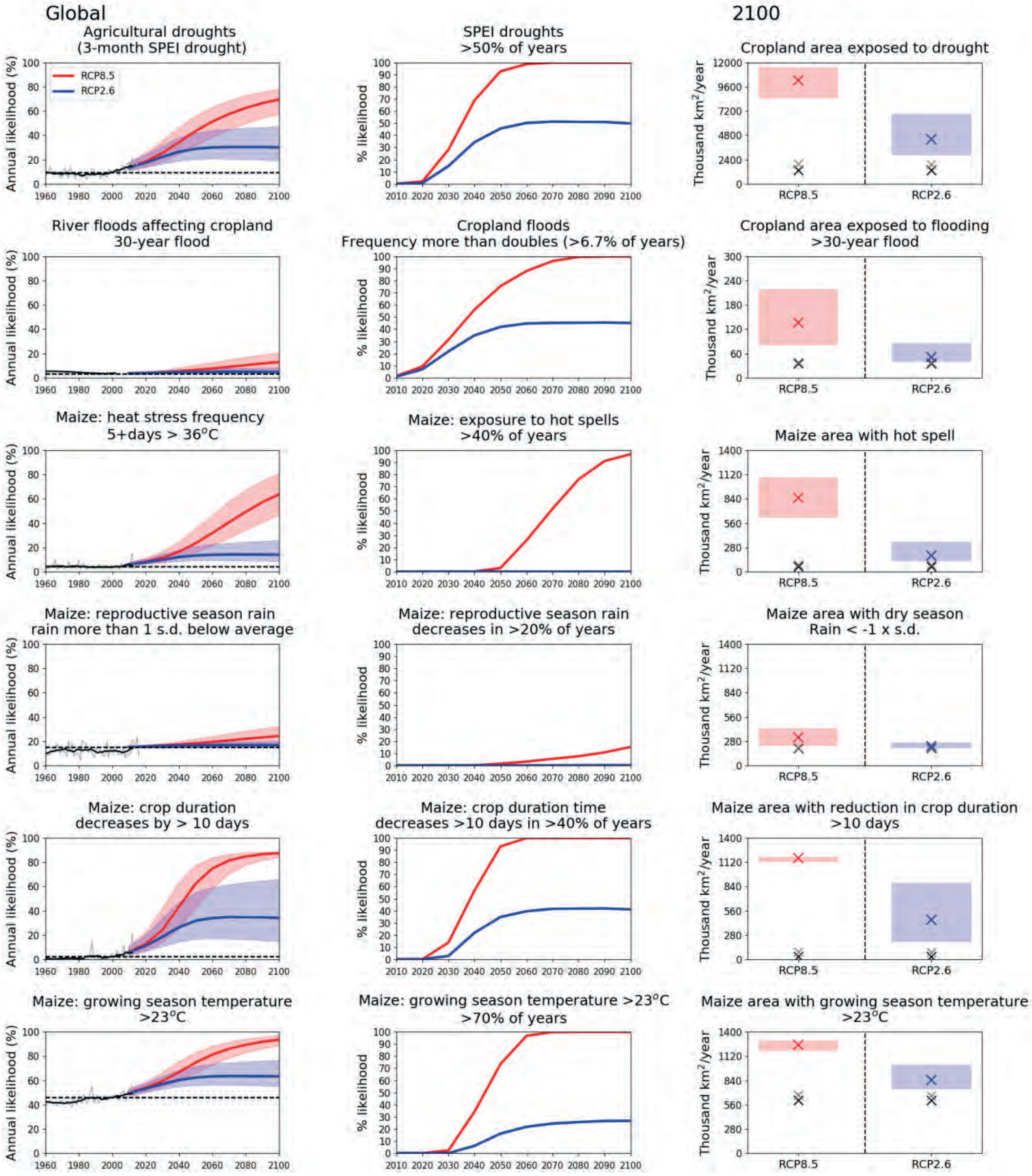
Figure 34: Global-scale impacts on coastal flood risk

3.3.8 Agriculture

Figure 35 shows the global-scale hazard frequency, risk and impact for the six agricultural indicators. In this case, it is assumed that the area of cropland remains constant over time, so there is no variation with socio-economic scenario. For all indicators, the consequences of climate change under both low and high emissions are adverse. The likelihood of drought and flood increases, and higher temperatures mean that the frequency of high and accumulated temperature extremes increases. The climate change effect on the occurrence of dry years during the maize reproductive season is more mixed. In each case, the observed frequency of hazard is broadly consistent with the rate of change in hazard but, as with the other indicators, does not allow an assessment of the future magnitude of impact.

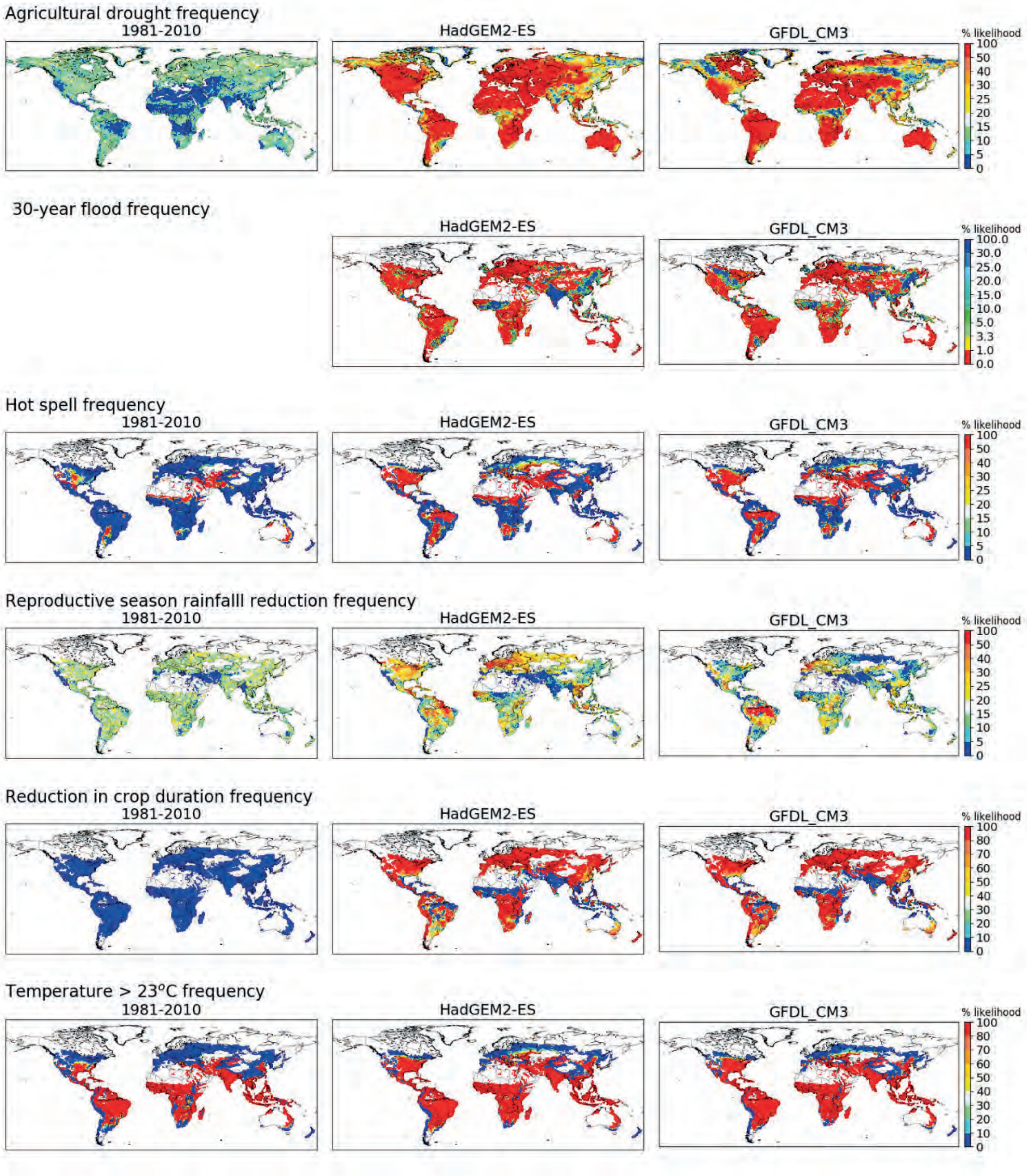
The geographical variability in change in agricultural hazard is shown in Figure 36. Agricultural drought frequency increases almost everywhere (but with some exceptions in parts of east Asia with large projected increases in rainfall), and flood risk for cropland increases in most places but decreases in a few. The frequency of hot spells affecting maize productivity increases most in North America, South America, west Asia and the Sahel region of Africa. There is relatively little change across much of east Asia, but there are some areas where the frequency increases very significantly. The likelihood of a reduction in reproductive season rainfall varies spatially and between the two illustrative climate models. The likelihood of a reduction in crop duration of more than ten days increases in most places, except for south Asia and the Sahel. The likelihood that growing season temperature exceeds 23°C increases across tropical maize regions, but changes little in more temperate maize-growing areas.

Figure 35: Global-scale impacts on agricultural indicators



Note: s.d. = standard deviation; SPEI = standardised precipitation evapotranspiration index.

Figure 36: Geographical distribution of agricultural hazard occurrence: 2050s climate, high emissions. Under the 1981–2010 climate, the flood frequency is by definition 3.33%



3.4 Direct risks at the Chinese scale

3.4.1 Introduction

This section presents an overview of the direct risks posed by climate change at the Chinese scale. It presents changes in physical hazard and the combined effects of changes in hazard and exposure. The section considers the same sectors as at the global scale. The indicators are similar but not exactly the same, because specific indicators are relevant for specific local circumstances. The section also highlights the importance of differences in impact across China.

Hazards and risks are estimated for the same low and high emissions as at the global scale, but the approach taken is slightly different as outlined below.

3.4.2 Indicators

The indicators calculated at the Chinese scale are summarised in Table 4, and described in detail in Annex 2.

Table 4: Risk indicators calculated at the Chinese scale

Sector	**Risk**	**Indicator of hazard**	**Indicator of exposure**	**Indicator of potential impact**
Heat extremes	Health impacts	Average annual maximum temperature		
		Average annual number of days with maximum temperature >35°C		
		Average annual number of heatwaves with 5 or more days >35°C		
Water resources	Periodic water shortage	Annual likelihood of experiencing a drought (12-month SPEI less than −1.5, for at least 6 months)	Number of people	Average annual number of people exposed to drought
	Persistent water shortage	Glacier ice storage		
		Total regional water resources	Number of people	Resources/capita

			Number of people	Number of people living in water-stressed watersheds
Coastal flooding	Coastal flood loss	Area potentially affected by the 100-year flood	Number of people in coastal hazard zone	Population exposed to the 100-year flood
		Area potentially affected by the 100-year flood	GDP in coastal hazard zone	GDP exposed to the 100-year flood
Agriculture	Loss of production (rice)	Annual likelihood of occurrence of heat damage	Area of rice cropland	Average annual area of rice cropland exposed to heat damage
	Loss of production (winter wheat)	Annual likelihood of waterlogging during growing phases	Area of winter wheat cropland	Average annual area of winter wheat cropland exposed to waterlogging

Notes: Impact indicators were not calculated for each hazard indicator. SPEI = standardised precipitation evapotranspiration index.

3.4.3 Overview of methodology

The heat extremes indicators were calculated directly from an ensemble of more than 20 CMIP5 climate models. The water resources indicators were calculated from the ISI-MIP runoff data set (Schewe et al., 2014), which includes projections from five CMIP5 climate models and four hydrological models. Future glacier ice was projected by combining observed current glacier characteristics with changes projected by Kraaijenbrink et al. (2017). The agricultural indicators were calculated from 16 CMIP5 models. The coastal zone impacts for defined increases in sea level were estimated using topographic data with a grid size of approximately 30m and gridded population and GDP data.

The China-scale analysis uses the period 1986–2005 as the reference climate period, compared to 1981–2010 used for the global-scale analysis; there is very little difference between the two.

Table 5 shows the Chinese-scale hazard indicators, for comparison with the global indicators in Table **3**.

Table 5: China-scale hazard indicators with 1986–2005 and 2100 climates: low and high emissions

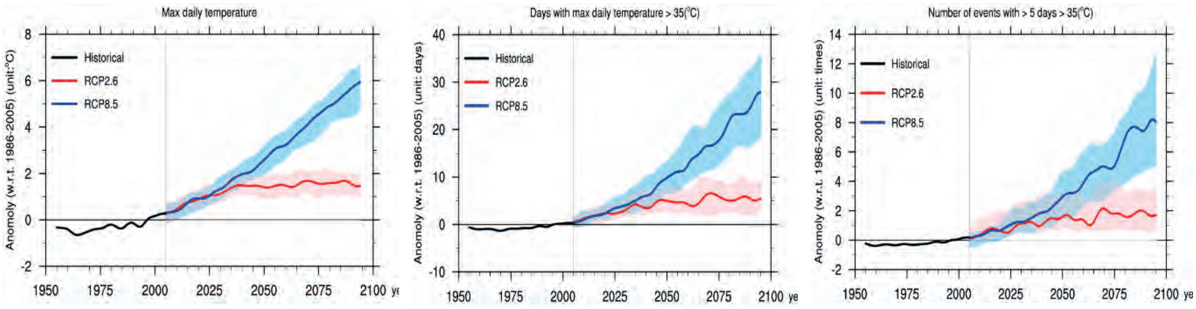
Indicator	**1986–2005**	**2100: low emissions**	**2100: high emissions**
Heat extremes			
Average annual maximum temperature (°C)	31	32.5 (32.0–33.0)	36.8 (35.8–37.8)
Average annual number of days with maximum temperature >35°C (days)	9	14 (11–19)	34 (27–44)
Average annual number of heatwaves with 5+ days >35°C (heatwaves/year)	3	4.8 (4–6)	11 (8–15)
Water resources			
Reduction in glacier mass (%)	0	30 (25–35)	64 (59–69)
National water resource (billion m^3/year)	3,055	3,210 (2,884–3,483)*	3,323 (2,834–3,736)*
Coastal flooding			
Area affected by 100-year flood (10^3 km^2)	84.2		99.2**
Agriculture			
Agricultural land exposed to drought (10^3 km^2/year)	345	481 (393–523)	703 (531–867)
Rice: annual probability of heat damage (%)	19	22 (3–45)	60 (17–80)
Wheat: annual probability of waterlogging (seedling stage)	59	45 (28–80)	40 (22–65)
Wheat: annual probability of waterlogging (heading–filling stage)	74	70 (425–80)	65 (38–75)

Notes: For 2100, the table shows the median plus the low to high ranges (in brackets); * for 2099; ** for 2050.

3.4.4 Heat extremes

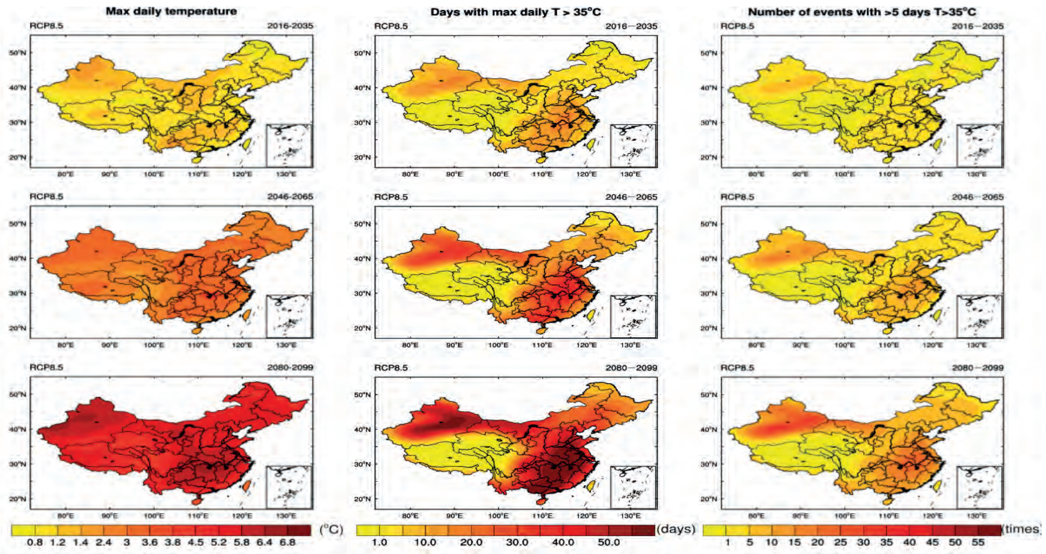
Figure 37 shows the average change across China in the average annual maximum temperature, the average number of days with maximum temperature greater than 35°C (hot days), and average number of heatwaves with at least five days above 35°C (heatwaves) by the end of the 21st century (Xu et al., 2015). Under the high emissions scenario, maximum temperatures are approximately 5.8°C higher than over the period 1986–2005, there are approximately 25 extra days a year with temperatures greater than 35°C, and heatwaves occur approximately eight times as often.

Figure 37: Change in the average annual maximum temperature (left panel), the number of days with daily maximum temperature greater than 35°C (middle panel) and the number of events with at least five days with daily maximum temperature greater than 35°C (right panel). The black lines show observed anomalies from the 1986–2005 mean.



Changes in the frequency of hot days and heatwaves vary across China (Figure 38). The increase in the frequency of hot days is greatest in the north-western basins and south China, and lower over the Tibetan Plateau and north-east China. The frequency of heatwaves increases by the greatest amount over the north-western basins and the lower reaches of the Yangtze River. There is less spatial variability in the increase in maximum temperatures.

Figure 38: Spatial pattern of changes in the maximum daily temperature (left panels), the number of days with daily maximum temperature greater than 35°C (middle panels) and the number of heatwaves (right panels), under high emissions and relative to 1986–2005. The top row shows 2016–2035, the middle row 2046–2065 and the bottom row 2080–2099. The patterns are averaged across more than 20 climate models.

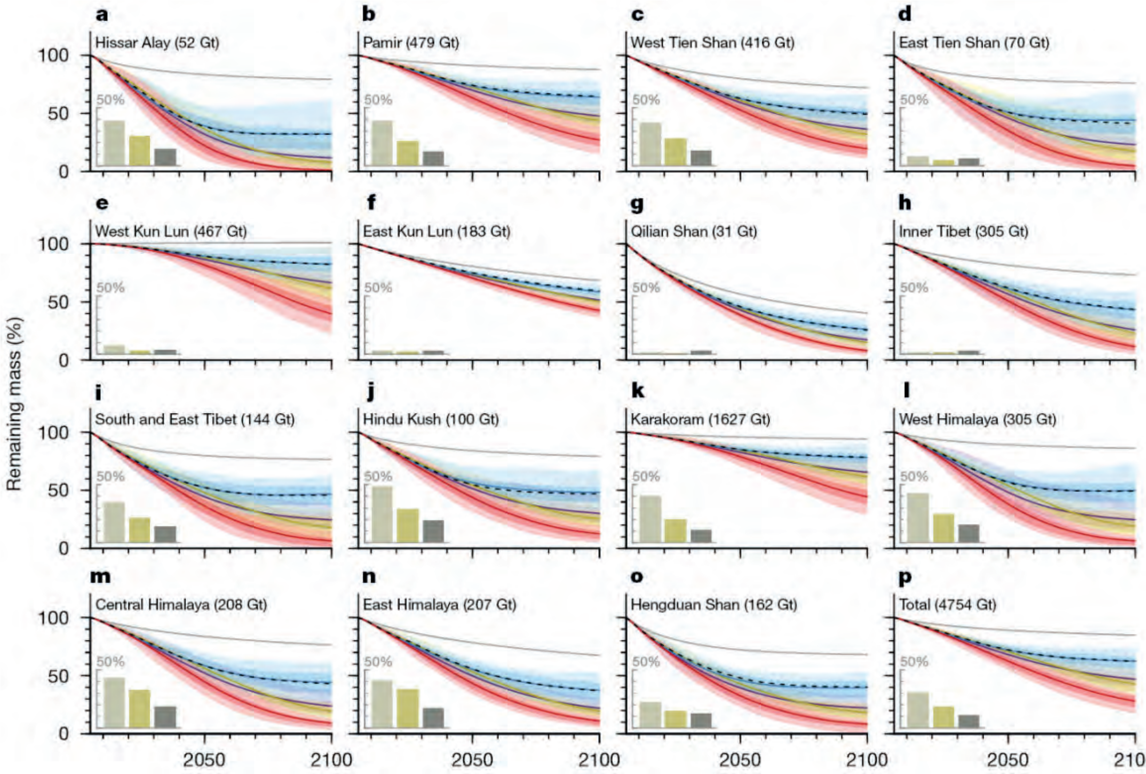


3.4.5 Water resources

China's annual water resources per capita are about 25% of the global mean (Qin et al., 2015), and pollution further limits the amount of water available for use. The distribution of water in China, as in other countries, is highly variable in both space and time. While parts of China have abundant natural water resources, other regions are naturally arid and water scarce; for example, northern China is far drier than southern China. This uneven distribution, combined with China's extensive population, inadequate urban infrastructure and poor management, has caused more than two-thirds of the country to suffer from water shortages. Water melting from glaciers plays an important role in the arid region in western China (National Climate Change Committee, 2015).

Since the 1990s, most glaciers in north-west China have been retreating rapidly, especially in the Tibetan Plateau. Figure 39 shows projected change in glacier ice mass in different regions of the Himalaya (Kraaijenbrink et al., 2017), under scenarios with different rates of climate change. There is variation in impact between regions, and by 2100 the glaciers in Qilian, west Tian Shan, south and east Tibet, west Himalaya and Hissar–Alay will experience the most extreme decline. As glaciers melt, runoff initially increases because water is being released from long-term storage, but as glaciers shrink further the volume of melt reduces and a point is reached where the contribution from melt is lower than the current contribution: this tipping point is known as the 'glacier inflexion' (Chen et al., 2014). This occurs in the late 2050s for basins with larger glaciers and higher ice-cover fractions. In the smaller glacier basins, the tipping point has already been passed, and glacier runoff is in decline. For example, the runoff in the Beida River in the Qilian Mountains will keep decreasing at the rate of 0.013–0.016 × $10^8 m^3$/year. For the Shiyang River in the Qilian Mountains, the tipping point has already passed and total runoff will continue to decrease in the 21st century (Zhang et al., 2015). In other catchments, the tipping point is further away. For example, glacier runoff will increase by about 13–35% from 2011 to 2015 in the Yarkant River, when compared with observed runoff between 1961 and 2006 (Zhang et al., 2012). In the Kumarik River, the glacier area will decline by about 25% in 2050 compared to 1984/5 to 2006/7, but glacier runoff will increase by about 11.6% in 2050 (Zhao et al., 2015). In the Tarim River basin, the proportion of glacier melt water to runoff is high (as much as 50%) and will keep increasing until 2050 (Chen et al., 2014; Huss & Hock, 2018). Glacier runoff makes little contribution to flows in the Yellow and Yangtze rivers (Huss & Hock, 2018).

Figure 39: Future ice mass loss and prevalence of debris-covered glaciers. Mass loss projections aggregated by sub-region (a-o) and the entire Himalaya (p) for the RCP scenarios, a stable present-day climate, and six models that have a temperature rise of 1.5°C at the end of century (Kraaijenbrink et al., 2017)



The total amount of water resources in China is currently (1986–2005) 3,055 billion m^3/year, with the greatest volumes in the south (Figure 40). The total resources available increase through the century under most scenarios (Figure 41), but there is a very large uncertainty range. Water resources are projected to increase in the north, north-west and the Tibetan Plateau (Figure 42), but decrease in the north-east and provinces south of the Yangtze River.

Figure 40: Spatial distribution of number of people exposed to drought (left panel), water resources (middle panel) and resources per capita (right panel). 1986–2005

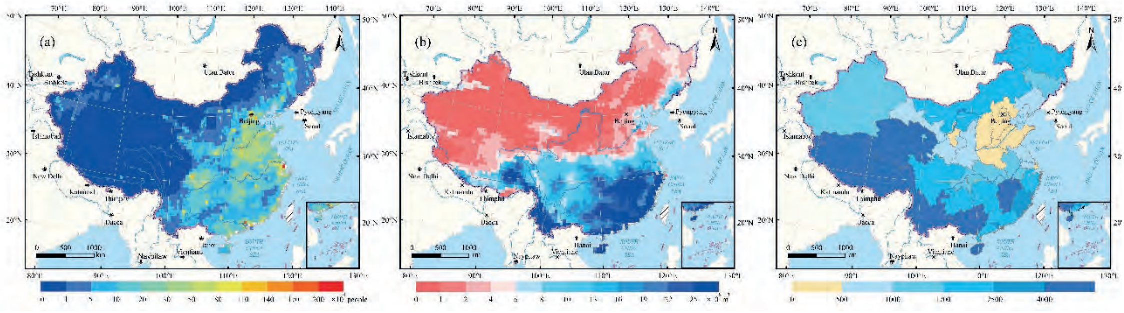


Figure 41: Change in total water resources under low emissions (left panel) and high emissions (right panel)

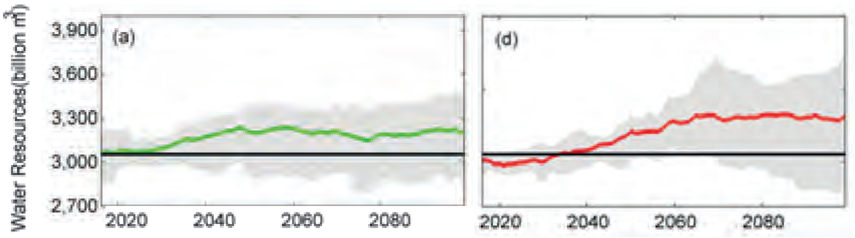
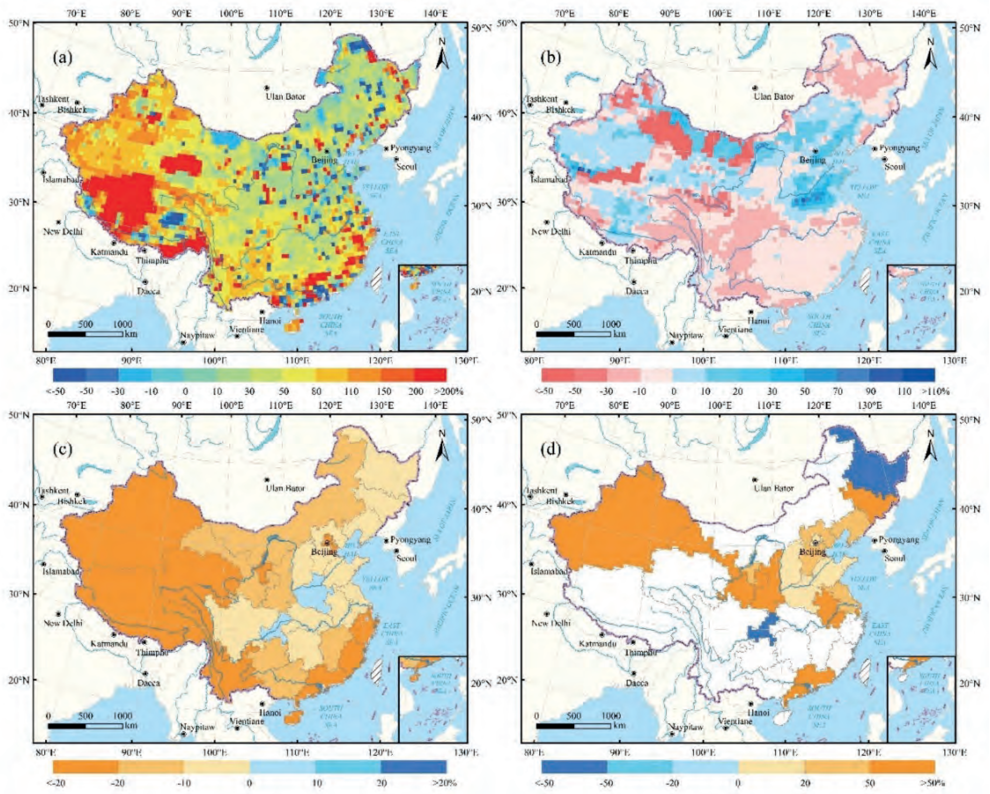
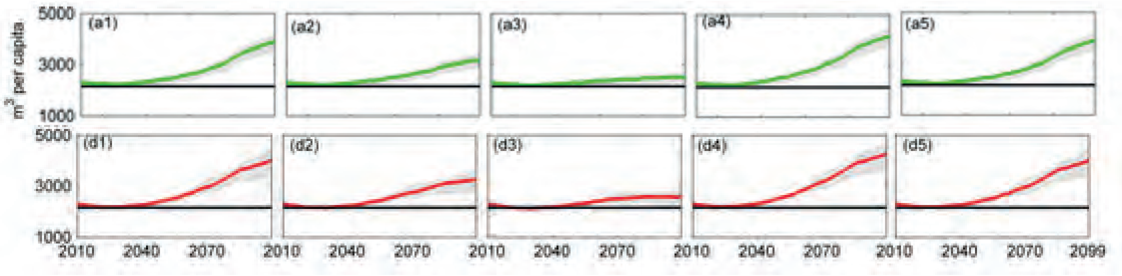


Figure 42: Impact of climate change on water resources: changes in number of people exposed to drought (top left), change in total resources (top right), changes in resources per capita (bottom left), and changes in water-scarce population (bottom right) in 2016–2035 (relative to the reference period 1986–2005), under high emissions. The changes in number of people exposed to drought, resources per capita and water scarcity assume socio-economic scenario SSP2.



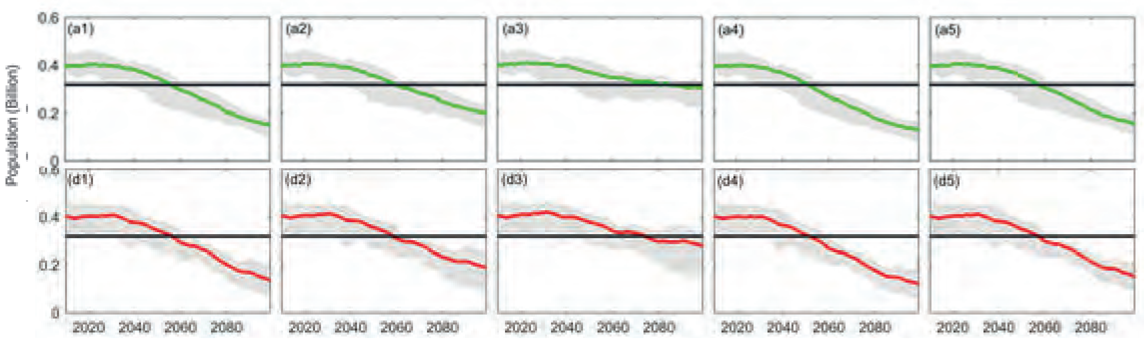
The average water resource per capita across China is 2,152m^3/year, but there is considerable variability between regions (Figure 40). The water resource per capita in Beijing, Hebei, Tianjin, Shanxi, Ningxia, Henan and Shandong provinces drops below 500m^3/capita/year, while in the south it exceeds 3,000 m^3/capita/year. At the national scale, resources per capita increase under both low and high emissions, but vary with socio-economic scenario (Figure 43). Resources per capita decrease across all of China, with a small increase in eastern China.

Figure 43: Resources per capita for China as a whole under low (top) and high (bottom) emissions, for the five SSP socio-economic scenarios



An area is assumed to experience severe water scarcity when average annual runoff falls below 500m^3/capita (Figure 40), and over the period 1986–2005, 319 million people lived in provinces with severe water scarcity. The population experiencing water scarcity increases up to the 2040s, then decreases under all socio-economic scenarios as population decreases (Figure 44). In north China, the population exposed to water scarcity will double in Xinjiang, Gansu and Guangzhou provinces and increase by 50% in the north of China as a whole (Figure 42).

Figure 44: Number of people exposed to water scarcity under low (top) and high (bottom) emissions, for the five SSP socio-economic scenarios



Drought is characterised here by the standardised precipitation evapotranspiration index (SPEI).[10] Over the period 1986–2005, the average annual number of people exposed to drought was approximately 249 million, with most of these in the North China Plain, central and eastern China (Figure 40). Future exposure depends on the change in climate and also population change (Figure 27): China's population is projected to peak in the 2040s and decline thereafter, but at different rates in different socio-economic scenarios. Figure 45 shows the change through the 21st in the average annual number of people exposed to drought. With high emissions, the number of people exposed to drought peaks in the 2040s under three of the socio-economic scenarios, remains approximately constant from the 2040s under SSP2, but continues to increase to 449 million under SSP3. This pattern includes the effects of both climate change and changes in population. Figure 42 shows the change in the number of people exposed to drought under high emissions over the period 2016–2035. The greatest proportional increase is seen in the south-west, north-west and south China.

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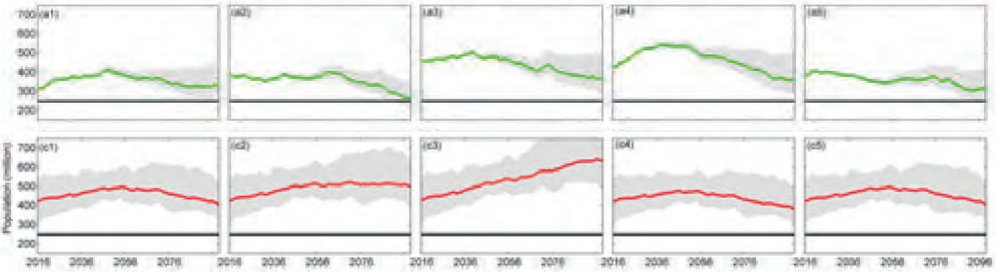
[10] Note that this is different to the global-scale analysis, which used the standardised runoff index.

Figure 45: Temporal variation in population exposed to drought, under low emissions (top) and high emissions (bottom), for five SSP socio-economic scenarios

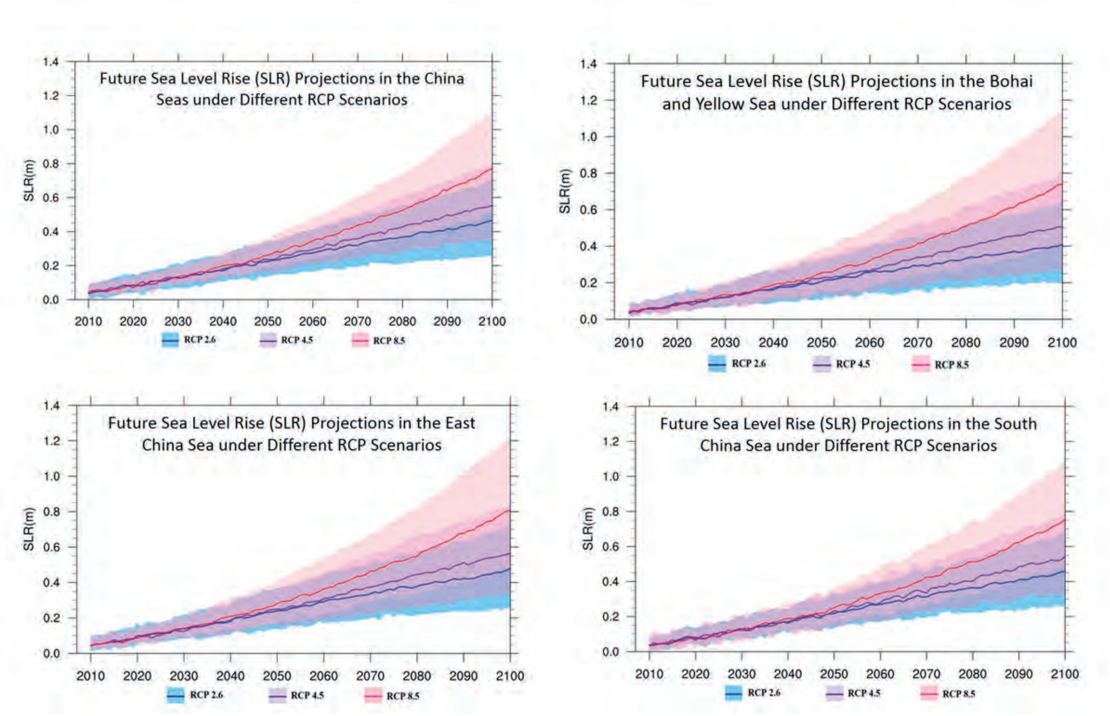


3.4.6 Coastal flooding

Figure 46 shows sea level rise in three different coastal regions (Bohai and Yellow Sea, East China Sea and South China Sea), together with the average for the entire coast. The increase is greatest in the East China Sea (80cm [47–122cm] in 2100 relative to 1986–2005, compared with the average for the whole coast of 77cm [52–109cm] under high emissions), and the sea level rise in all regions is close to the global average increase (Figure 26).

Figure 47 shows the area at risk from a 100-year event in 2050 under high emissions, without taking into account protection provided by coastal defence dikes. The total area is 99,229km^2 (for a sea level rise of approximately 25cm), which compares with an area of 84,237km^2 in 2010 (this does not take into account local subsidence).

Figure 46: Sea level rise projections in different seas and for the Chinese coast as a whole (top left panel) under different RCP scenarios

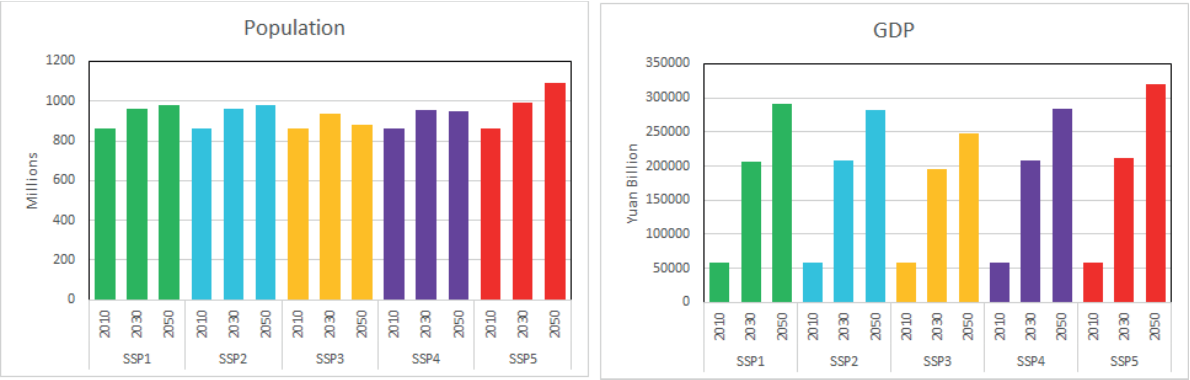


Note: RCP = Representative Concentration Pathway; SLR = sea level rise.

Figure 47: Area exposed to 100-year flood in 2050, with high emissions (sea level rise approximately 25cm)

The population and GDP in the risk areas (below the 100-year flood level) in 2010, 2030 and 2050 are shown in Figure 48. At present (2010) approximately 86 million people live below the 100-year level, with a total GDP of 5,732 billion Yuan. Population increases relatively slowly (by a maximum of 26% by 2050 under SSP5), but the exposed GDP increases very substantially, by a factor of between 4.3 and 5.6. Most of this increase occurs by 2030.

Figure 48: Population and GDP within the 100-year coastal flood level under high emissions and for the five SSP socio-economic scenarios



3.4.7 Agriculture

The impacts of climate change on agriculture are represented by changes in exposure to drought and changes in the potential production of rice and winter wheat.

Drought is represented by the standardised precipitation evapotranspiration index (SPEI), and approximately 345,000 km^2 of agricultural land was exposed to drought over the period 1986–2005. Most of this was in eastern China (Figure 49).

This area increases very significantly under both low and high emissions (Figure 50), with a very high uncertainty range particularly with high emissions. By the end of the 21st century, the area of cropland affected by drought could increase to 481,200 km^2 with low emissions, and 703,100 km^2 with high emissions.

Figure 49: Agricultural land exposed to drought in 1986–2005 (left panel), 2016–2035 under low emissions (middle panel) and 2016–2035 under high emissions (right panel)

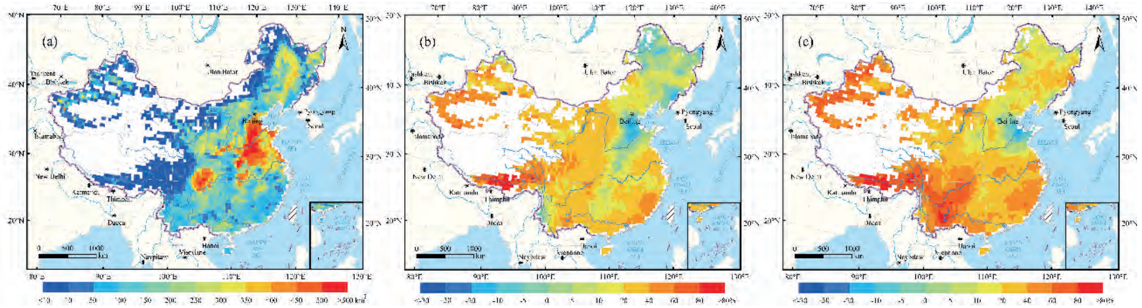
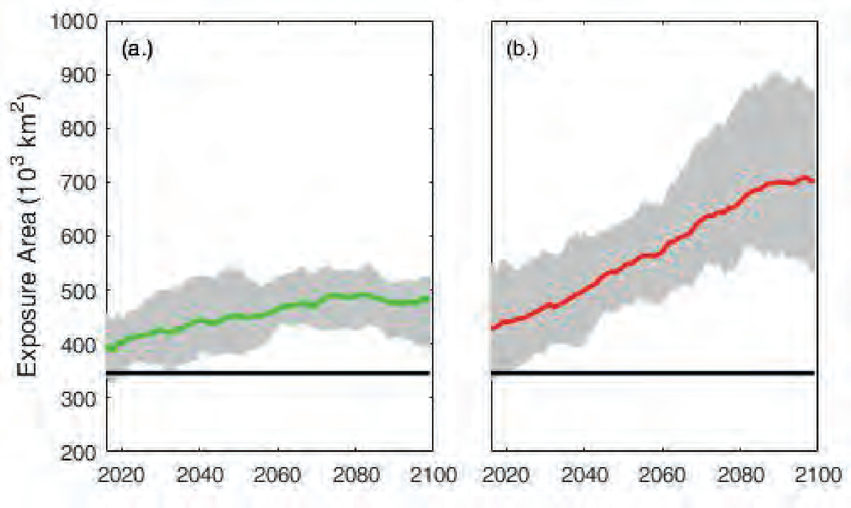


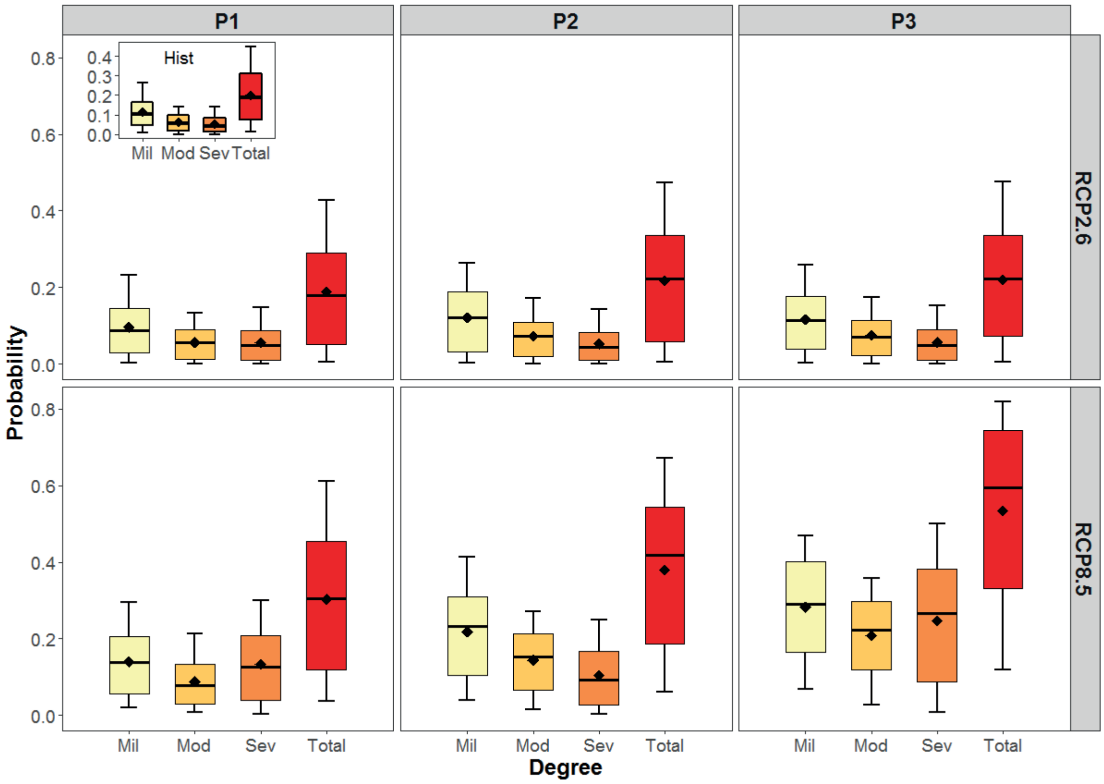
Figure 50: Total agricultural land exposed to drought under low emissions (left panel) and high emissions (right panel)



Rice is one of the most important grain crops in China. The area planted for rice makes up approximately 30% of total area planted for food crops, and rice provides around half the total grain yield. At present, the production of double-cropping rice in the country is concentrated in nine provinces in the middle and lower reaches of the Yangtze River, namely Hubei, Anhui, Zhejiang, Hunan, Jiangxi, Fujian, Guangdong, Guangxi and Hainan. The sown area and yield of double-cropping rice in these provinces make up over 99% of the total sown area and yield in China. The middle and lower reaches of the Yangtze River have both single- and double-cropping rice, and the planting area and total yield constitute more than 50% of rice crops nationwide.

Rice production is mainly affected by heat damage. Figure 51 shows the probability of heat damage for single-cropping paddy rice in the middle and lower reaches of the Yangtze River under low and high emissions, by the end of the 21st century. The plot shows the probability of different degrees of heat damage, as well as the probability of any heat damage. At present (1986–2005), the probability of any heat damage is around 20% (inter-quartile range 10–30%), whilst with high emissions it increases to around 60% (inter-quartile range 40–72%). The probability of heat damage for double-cropping paddy rice is slightly lower than for single-cropping rice, but still increases very substantially with high emissions. The areas with at least a 50% probability of heat damage are shown in Figure 52, for single-cropping paddy rice and both early and late paddy rice in the double-cropping areas. Rice is also sensitive to cold temperatures, but risks are lower than for high-temperature impacts and they decrease through the 21st century.

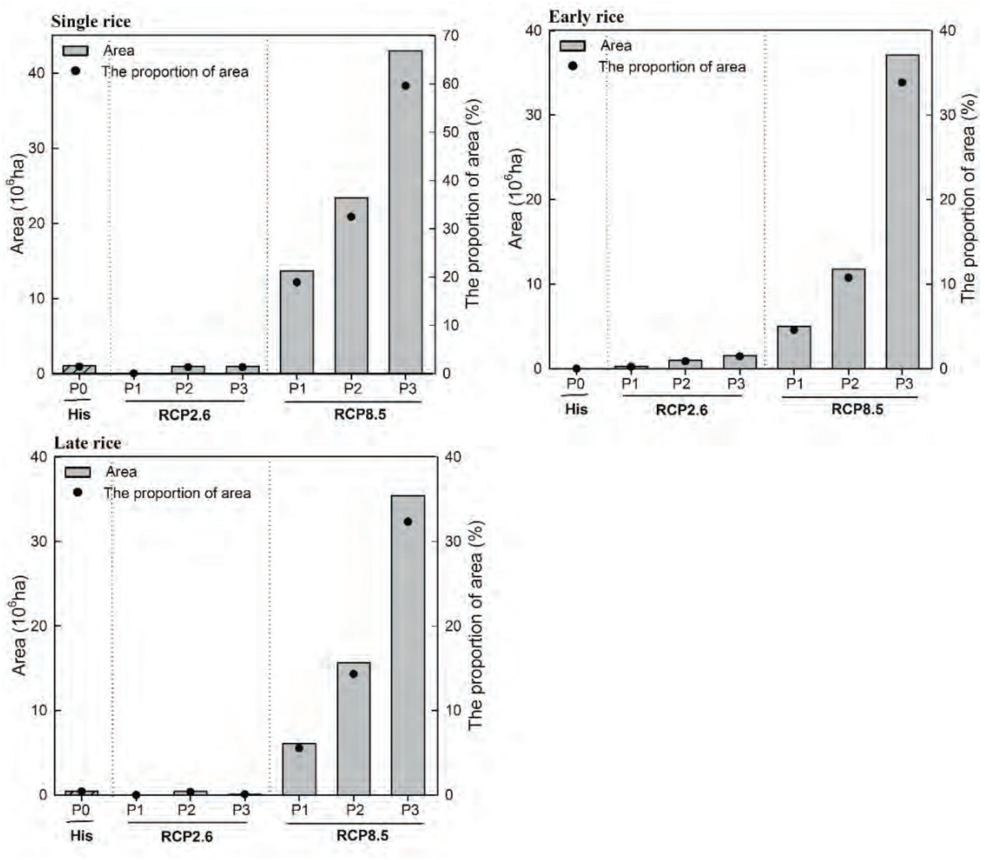
Figure 51: Probability of heat damage for single-cropping paddy rice in the middle and lower reaches of the Yangtze River, under low (top) and high (bottom) emissions. The panels show 2016–2035 (left), 2046–2065 (middle) and 2081–2100 (right). The inset shows the reference period. Black horizontal lines from top to bottom indicate 95th, 75th, 50th, 25th and 5th percentiles, and the black dots indicate the mean.



Note: Mil = mild; Mod = moderate; Sev = severe; RCP = Representative Concentration Pathway.

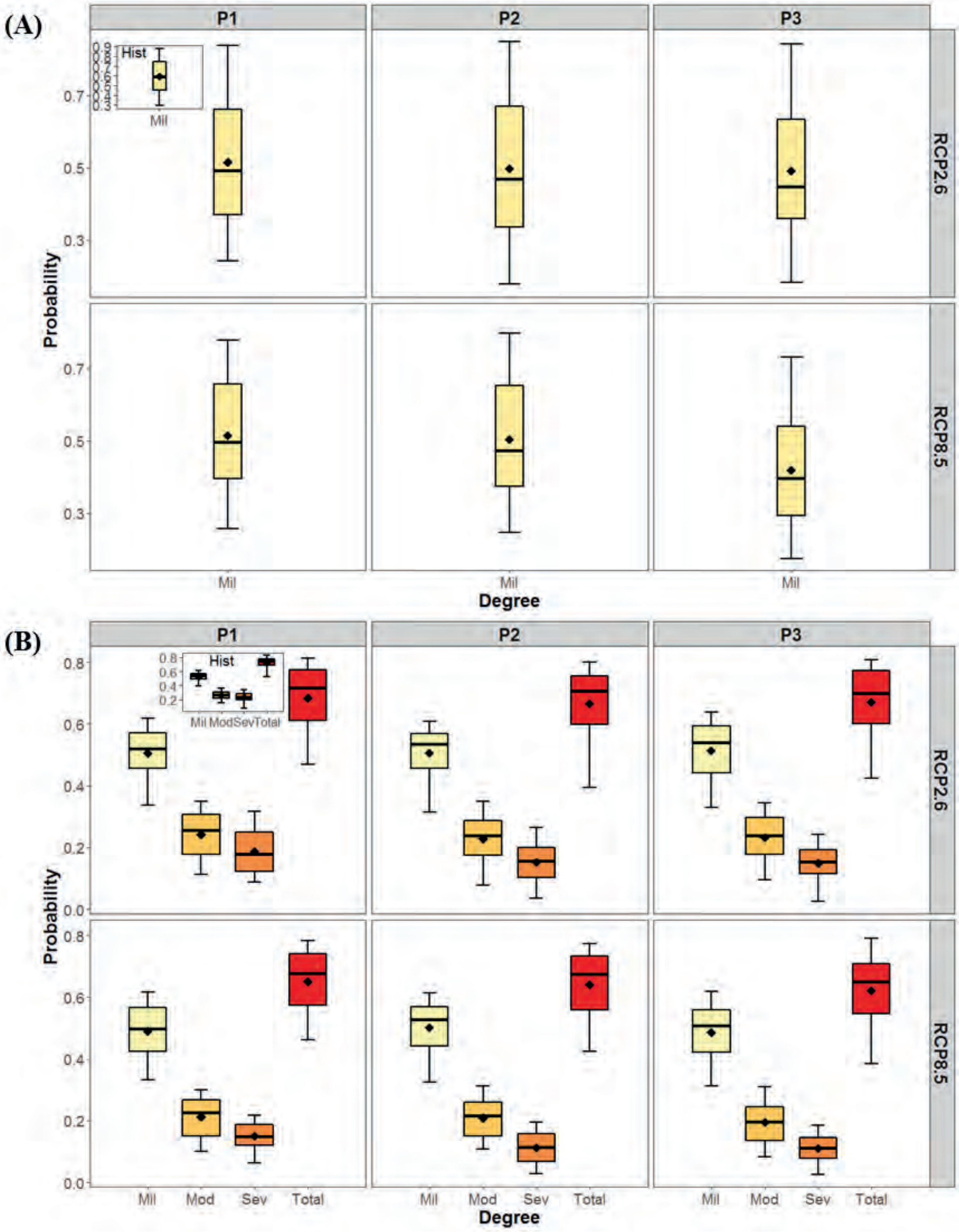
Wheat is the second major food crop in China. Its annual planting area makes up 22–30% of the total cultivated land area and 20–27% of the total area of food crops. Winter wheat makes up the largest area in the country, accounting for over 80% of the sown wheat area. The northern winter wheat area extends across provinces south of the Great Wall, east of the Liupan Mountains and north of the Qinling Mountains–Huaihe River (i.e. Shandong, Henan, Hebei, Shanxi and Shaanxi). This is the largest wheat production and consumption area in China, and the sown area and yield of wheat in this area account for more than two-thirds of the national total. The southern winter wheat area is mainly distributed south of the Qinling Mountains–Huaihe River and east of the Hengduan Mountains, with Anhui, Jiangsu, Sichuan and Hubei provinces being the major producing areas.

Figure 52: Area with a greater than 50% chance of heat damage under low (RCP2.6) and high (RCP8.5) emissions for single-cropping paddy rice, early paddy rice and late paddy rice. P0 is the reference period, P1 is 2016–2035, P2 is 2046–2065 and P3 is 2081–2100.



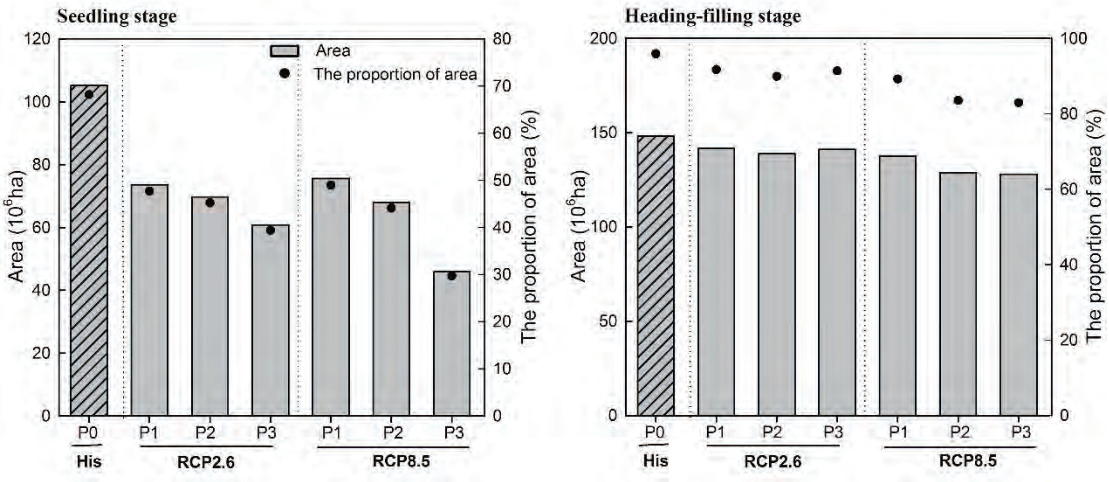
Winter wheat production is mainly affected by waterlogging and drought. The likelihood of waterlogging in the southern wheat area is high during the seedling and heading–filling phases of winter wheat (approximately 40% and 75% under the current climate respectively), and reduces slightly with climate change (Figure 53). The area with a probability of waterlogging greater than 50% therefore also reduces with climate change (Figure 54). Drought probability during critical growth periods also reduces slightly with climate change.

Figure 53: Probability of waterlogging damage during the seedling (A) and heading–filling (B) stages for winter wheat in the southern wheat area, under low (top) and high (bottom) emissions. The panels show 2016–2035 (left), 2046–2065 (middle) and 2081–2100 (right). The insets show the reference period.



Notes: Black horizontal lines from top to bottom indicate 95th, 75th, 50th, 25th and 5th percentiles, and the black dots indicate the mean; Mil = mild; Mod = moderate; Sev = severe; RCP = Representative Concentration Pathway.

Figure 54: Area with a greater than 50% chance of waterlogging under low (RCP2.6) and high (RCP8.5) emissions, for winter wheat in the southern wheat area in the seedling and heading–filling stages. P0 is the reference period, P1 is 2016–2035, P2 is 2046–2065 and P3 is 2081–2100.



3.5 Overview and synthesis

This chapter has examined the potential direct impacts of climate change, focusing on heat extremes, water resources, river and coastal flooding, and agriculture. It has considered impacts at the global scale and at the Chinese scale, using consistent scenarios describing low and high rates of future emissions of greenhouse gases. Impacts are a function of change in physical hazard, change in exposure to hazard and change in vulnerability to loss. This chapter has focused on changes in physical hazard and the combined effects of changes in hazard and exposure, and does not account for changes in the factors that drive vulnerability.

Under the high emissions scenario considered here, the central estimates for the increase in global average temperature and global mean sea level by 2100 are approximately 5°C and 80cm respectively. However, the increases could plausibly be higher than this: plausible 'worst case' increases in temperature and sea level could be 7°C and 100cm.

At the global scale, plausible 'worst case' impacts are extremely challenging. At least one heatwave could occur in all years (compared with around 5% now). The global average frequency of hydrological droughts doubles, and the chance of experiencing an agricultural drought increases by a factor of nearly ten. River flood frequency increases by a factor of up to ten, and the area along the coast exposed to a 100-year flood increases by 50%. High temperatures which threaten maize production would occur in around 80% of years (compared with 4% at present), and in more than 90% of years the time taken for maize to mature would reduce sufficiently to impact significantly upon productivity. Human impacts – on people exposed to heatwaves, droughts and floods – depend on the socio-economic scenario, and under high population scenarios the increase in impact compared to the present day could be extremely large.

There is, of course, considerable variability in the impacts of climate change between regions, and whilst the global aggregate for most impact indicators shows an adverse impact, climate change does reduce hazards in some places.

At the Chinese scale, the number of heatwaves may increase by a factor of three by the end of the 21st century. Glacier mass may reduce by almost 70%, affecting water resource availability in water-stressed parts of western China. Increases in rainfall across China as a whole suggest that total national runoff is likely to increase (although a decrease is plausible), but there are big variations across China. The average annual area of cropland exposed to drought could plausibly increase by a factor of more than 2.5. Rice production may be significantly impacted by increases in the likelihood of heat damage – which may occur in 80% of years (compared with 20% at present). Impacts on wheat productivity are more mixed.

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Chapter 4: Systemic risk in the context of climate change

4.1 Introduction: systemic risk and its importance in the context of climate change

This chapter develops indicators and narratives that exemplify the systemic, human risks from climate change, precipitated by climate hazards and amplified by, and transmitted through and across, multiple inter-related social, economic and environmental domains of human systems. We consider high-impact, low-probability and high-impact, high-probability hazards, focusing on Chinese-specific and global systemic risks.

Systemic risk is a concern whenever systems are integrated. Systemic risk, and system failure, may be triggered by concurrent or sequential hazards – which may be chronic or acute in nature – and propagated across time and space where human systems and responses to a trigger amplify rather than dampen the risks. As extreme climatic shocks and weather events become more frequent and more extreme, the ability of national governments and supra-national organisations to avoid systemic crisis in the future will be weakened. Policymakers do, however, have key roles to play in reducing the likelihood of a potential system failure being triggered – not least through more aggressive climate change mitigation activities – and in minimising and containing any crises after the trigger, for example, through enhancing the resilience of components within the system and of the system as a whole.

The global food crisis of 2007–2008 is an exemplar of system failure triggered by a climate event. Sequential droughts in Australia precipitated shortages in the global food system. These shortages were amplified by individual and government actions, and ultimately led to food riots and even regime change in some countries. Climate change is likely to make the events that can trigger system failure, such as droughts in key grain production regions, more frequent. In many circumstances, economic growth combined with pursuit of sustainable development principles may permit countries to avoid the worst of such crises. For example, poverty no doubt exacerbates the impact of rising prices on food insecurity, under-nutrition and consequential unrest; where populations are better nourished, where food expenditure accounts for a smaller proportion of their income, and where governments have greater fiscal reserves and are better equipped to provide social security mechanisms, there will be greater resilience to food price shocks. Yet conversely, if, for example, economic growth results in a greater dependence on complex or highly integrated infrastructure vulnerable to weather shocks, the likelihood of contagion and impacts of systemic risks and the probability of system failure may be increased rather than reduced. Thus economic growth may change the nature of the risks from systemic shocks rather than eliminate them.

Despite the increasing frequency of high-impact climatic events, their mutation into full-blown systemic crises remains relatively rare, meaning there are insufficient precedents from which to develop a full understanding or probabilistic risk-transmission model or forecast (Challinor et al., 2018). The relationship between an initial climate hazard and subsequent systemic risk is complex, noisy and non-linear, with much depending on the sequence and timing of events. Without sufficient generalisable knowledge about how to distinguish signal from noise (Haldane & Madouros, 2012; Tangermann, 2011), attempts to model such complexity may result in erroneous overfitting of risk indicators. The extent of systemic crisis is typically strongly determined by socio-economic factors including policy choices, which may result from incomplete information or in reaction to market sentiment rather than underlying fundamental conditions, but which can nonetheless cause strong positive and negative feedback loops with systemic effects. Such dynamics may be unquantifiable or may have a wide plausible range of manifestations over medium- to long-term time horizons.

Thus the potential effects of climate change on systemic risks in the future can only be fully characterised by combining quantitative projections of potential changes in relevant climate risk drivers with narratives describing how these drivers translate into risks with plausible socio-economic and policy assumptions.

We therefore adopt an alternative pragmatic approach to assessing systemic risk:

- We develop a broadly applicable conceptual framework of systemic risk characteristics and cascade mechanisms.
- In specific systems, we build narratives of plausible transmission pathways and assemble a series of readily available leading indicators of risk factors. These indicators can be used together to develop an aggregate picture of systemic risks and to identify nodes within the system that are particularly at risk; we do not, however, attempt to develop a full system model.

Narratives, informed by historical events (and ‘non-events’ where climate-related shocks have been dampened rather than amplified, and thus have not led to systemic risk cascades), articulate possible pathways of systemic risk. They provide an indication of whether these events may be more or less likely in future based on different pathways and scenarios presented in the preceding two chapters.

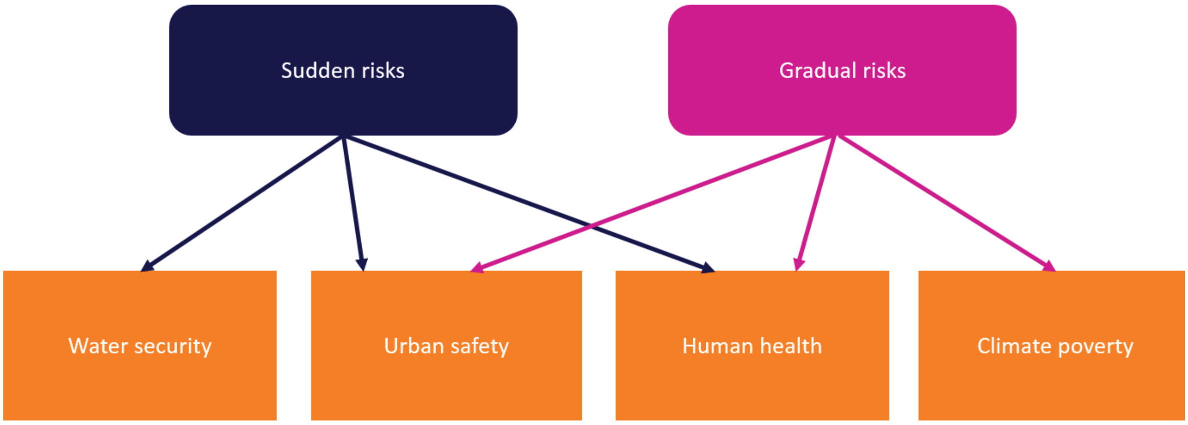
To the extent that systemic indicators are quantified in this chapter, they signal current risk rather than forecast future risk. This suggests that the indicators presented here may be particularly useful as contemporary early warning signals for high-cost events that society may not be able to address without costly and irreversible consequences. Nonetheless, considering how systemic risk indicators are evolving in tandem with the emissions indicators and climate hazard indicators addressed in earlier chapters usefully signals whether the likelihood of systemic risk is increasing or decreasing, and why. The indicators addressed in this chapter are not predictors of risk outcomes over decadal time horizons, but, in combination with explanatory narratives, they usefully:

- Demonstrate the benefits of mitigation activities in reducing the probability of systemic risk.
- Signal where interventions now might usefully be made to build systemic resilience in anticipation of future risks.
- Assist with diagnosis of the build-up of systemic risk once a climate hazard is imminent or in motion.
- Assist understanding of whether local issues (e.g. failure of a crop in one part of the world) might cascade into wider, more global issues.

First we provide examples from China, which highlight the linkages between climate hazards and indirect impacts on socio-economic systems in the country and region. With its vast territory, China has more than five major climatic zones and faces a variety of climate risks. The risks considered here (Figure 55) have been identified based on literature research and expert judgment. Although they have some Chinese characteristics and are considered in that context, they are not unique to China and have broader applicability to other countries and regions. The risks considered are the potential impacts of the following:

- Glacial melt (water security).
- Extreme precipitation and sea level rise in urban environments (urban safety).
- Migration and poverty (climate poverty).
- Human health outcomes (human health).

Figure 55: Major climate-driven indirect and systemic risks in China



These case studies predominantly consider in-situ indirect risks from climate change, and emphasise first-order human impacts from the climatic hazard (e.g. mortality from extreme heat) relative to subsequent second- and third-order impacts. Thus, while consideration is given to how a wide range of possible indirect disruptions from climatic shocks may be precipitated in human and economic systems, those risks are considered within relatively geographically contained boundaries such as the city or region directly affected by the climate shock. The full chain of conceivable risk cascades is not developed for most of these examples, although an illustration of a plausible systemic cascade that could subsequently develop is provided (see Section 4.3).

We then switch to a global perspective to focus on climate-driven risks to the international food system that catalyse broader risk cascades which threaten to drive or escalate wider social, political and economic instability. Such climate shocks may initially cause nutritional scarcity at the same locations as the underlying climatic events. Whether such localised shocks impinge on systemic stability depends on the extent to which these shocks are mediated (amplified or dampened) at a global level, by the aggregate actions of individuals, governments and private-sector actors, manifested in changes in global food prices, and affecting the ability of individuals to access food.

We provide an example narrative that combines qualitative description of systemic risks with a quantitative approach to tracking key indicators of those risks. The food system is an exemplar of how systemic risks might permeate from initial localities and climate hazards to other geographies and manifestations of risk. Our focus therefore is not on the mechanisms through which meteorological events disrupt agricultural or infrastructural conditions; it is rather how these disrupted conditions affect food supply, how this is reflected in price changes, how these price signals may cascade internationally, and the degree to which different actors are insulated and/or resilient to such price perturbations and the ensuing actions taken. Whilst some of the proposed metrics are specific to the food system, the overall approach is generalisable to other sectors through which systemic risk may be transmitted, such as health and infrastructure.

The global case study of the food system therefore provides a complementary perspective to the Chinese cases since the predominant focus on only one initial climate shock permits a more expansive geographical focus and, by developing a plausible full risk cascade, gives more prominence to second- and third-order effects.

Section 4.2 describes the common methodology adopted when examining systemic risks. Sections 4.3 and 4.4 then demonstrate the application of this methodology for consideration of systemic risks in Chinese and global contexts respectively.

4.2 Methodology

Systemic crises are complex and multi-causal; they evolve and cascade in unpredictable ways, and they occur relatively infrequently. All of these factors make the identification and quantification of systemic risk difficult, with analyses often depending on suppositions about hypothetical counterfactuals. Risk indicators will in many cases be necessarily contextual, depending on the origin and cascade chain of the systemic risks in question. As such, analyses of systemic risk need to be routed in robust and generalisable conceptual frameworks to ensure that understanding and insights generated about the specificities of a given chain of events have broader applicability, and that all relevant risks are enumerated.

We therefore use two complementary conceptual structures to delineate systemic risks engendered or catalysed by climate change: one to define the characteristics of systemic risk, the other to explain the mechanisms determining the realisation and magnitude of systemic risk. Our narrative review of systemic risks draws on the former framework, and we situate the discrete indicators that we propose for the global food system within the latter framework.

4.2.1 Characteristics of systemic risk: conceptual framework

The degree to which different systemic risks deserve attention by policymakers can be characterised according to four criteria: the affected domains, speed of onset, severity of impact and probability of occurrence. An additional distinction of whether climate change plays a catalytic or amplifying role in different systemic crises can also be useful for identifying additional contexts in which climatic events can pose additional risks, even if the systemic threat is initially triggered by non-climatic drivers.

4.2.1.1 Domain

Systemic risks from climate-induced or climate-exacerbated events may affect different facets of society. Here we identify five pertinent domains on which systemic risks may impinge. A given hazard may have a differential impact across and within these domains; to be systemic we would expect multiple domains or populations or territories to be placed at risk from the initial or subsequent events.

I. **Economic prosperity:** potential impacts on transport, communications, energy, water and sewerage infrastructure, commerce, and finance and investment are all typically considered within standard risk assessment frameworks, as the economic losses are readily apparent and relatively straightforward to quantify. Economic valuations, however, provide only a partial assessment of risk. Other factors such as the spatial and socio-economic distribution of impacts also need to be considered across all domains.

II. **Social stability:** social instability may be caused by major famines, diseases and economic turmoil. Ensuing outbreaks of large-scale poverty, population migration and social violence are priority concerns.

III. **Human health:** systemic risks may lead to large-scale spread of communicable and non-communicable disease and malnourishment.

IV. **Homeland security:** territorial threats, rising cost of international peacekeeping, surge in international climate assistance needs, international water resource competition, serious damage to international transport routes and damage to defence infrastructure facilities may all be affected by systemic risks.

V. **Existential risk:** the threat of loss of lives and habitats, including from sea level rise, and natural hazards may lead to mass migration. This is particularly pertinent to densely populated coastal cities, such as the many economically prosperous cities in south-east China.

4.2.1.2 Speed of onset

Systemic risks vary in the speed at which they materialise and in the latency of their impacts:

- Chronic, or creeping, risks are typically less visible but can pose severe threats (World Economic Forum, 2010) with long latency periods often contributing to serious underestimates of impacts and long-term consequences. Most climatic risks are gradual with impacts accumulating slowly, though potentially leading to sudden and irreversible tipping points.
- Acute risks may materialise from sudden onset events, such as extreme weather hazards, which, depending on the degree of exposure and vulnerability of those affected, can rapidly induce disasters.

4.2.1.3 Severity of impact

The severity of a hazard’s impact is a function of the magnitude of the event itself, the exposure of people to the hazard, the vulnerability of the exposed population, the presence and effectiveness of any mitigating circumstances or responses, and the domains of society affected. Where external hazards interact with individual behaviours and collective responses, social amplification of risk may occur even if the initial hazard is relatively benign. Risks are more likely to become political crises if they are sudden in onset, affect a large number of people, and have significant short-term impacts (Challinor et al., 2018).

4.2.1.4 Probability

Low-probability, low-impact events and high-probability, low-impact events are worthy of relatively little attention for systemic risk assessments. In the former case, the low likelihood of occurrence, and the minimal anticipated impacts if and when they do occur, suggest resources should be prioritised elsewhere. In the latter case, likely events with small impacts should already be well anticipated and well managed. Of more interest for this work are high-probability, high-impact events and low-probability, high-impact events. These have potential to be overlooked due to their infrequency or the perceived cost of taking prior action.

4.2.1.5 Role of climate change

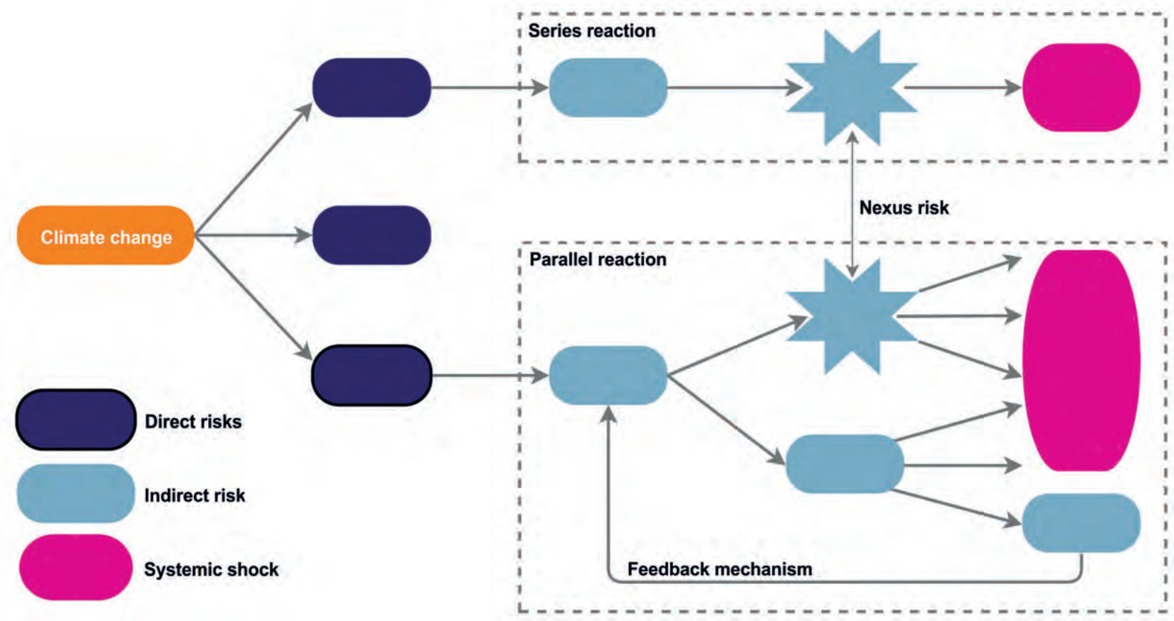
A final element of the framework is the identification of the role played by climatic events. In many of the risk cascades considered here, a climatic event plays an inducing or catalysing role. However, it is also possible that the initial trigger is unrelated to climatic events, with more tangential climatic impacts (such as degradation of soil fertility or resilience of infrastructure) serving to either amplify the severity or propagation of impacts, or to decrease the return period of any given impact.

4.2.2 Mechanisms of systemic risk: conceptual framework

The purpose of systemic risk analysis is to elucidate the dynamic interdependencies, causal chains and feedback loops between hazard events and the various system elements that they may impinge upon. Following the initial hazard and the direct impacts that result, subsequent indirect risks may cascade in a variety of ways depending on the nature of system interdependencies. Risk cascades occur through chain reactions that have the potential to affect the structure, function and stability of the entire system, thereby differentiating systemic risk from direct risk.

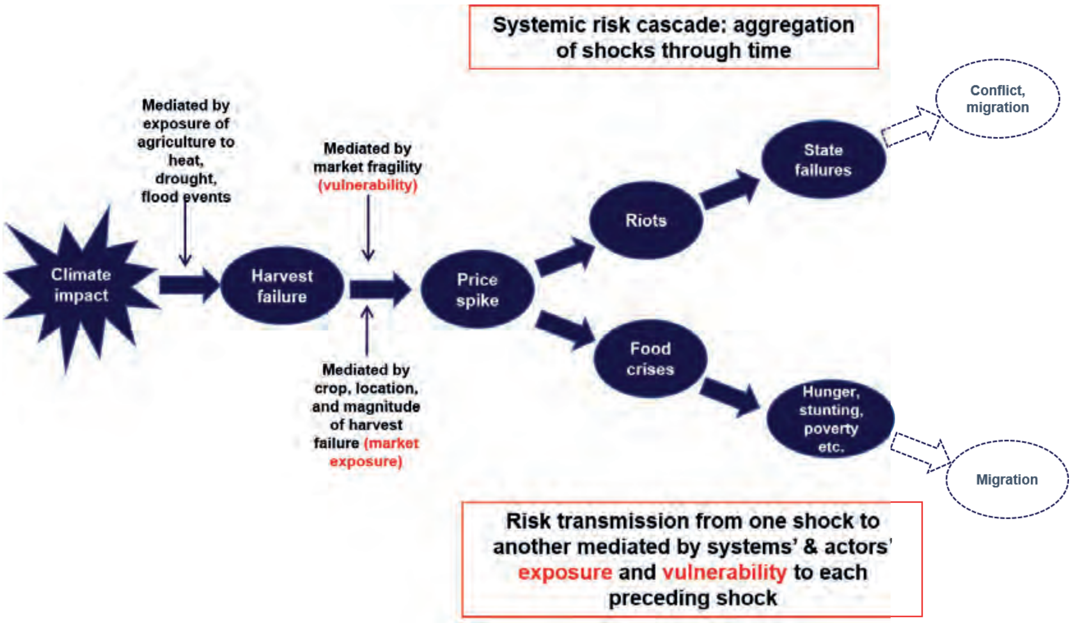
Discrete risks may occur in series or in parallel. When two or more types of risk occur simultaneously and interact with one another, they constitute a nexus risk (Figure 56). Feedback loops may be positive (amplifying) or negative (dampening). However, once the system reaches a certain tipping point threshold it becomes impossible to return it to the previous equilibrium state.

Figure 56: Systemic risk characteristics



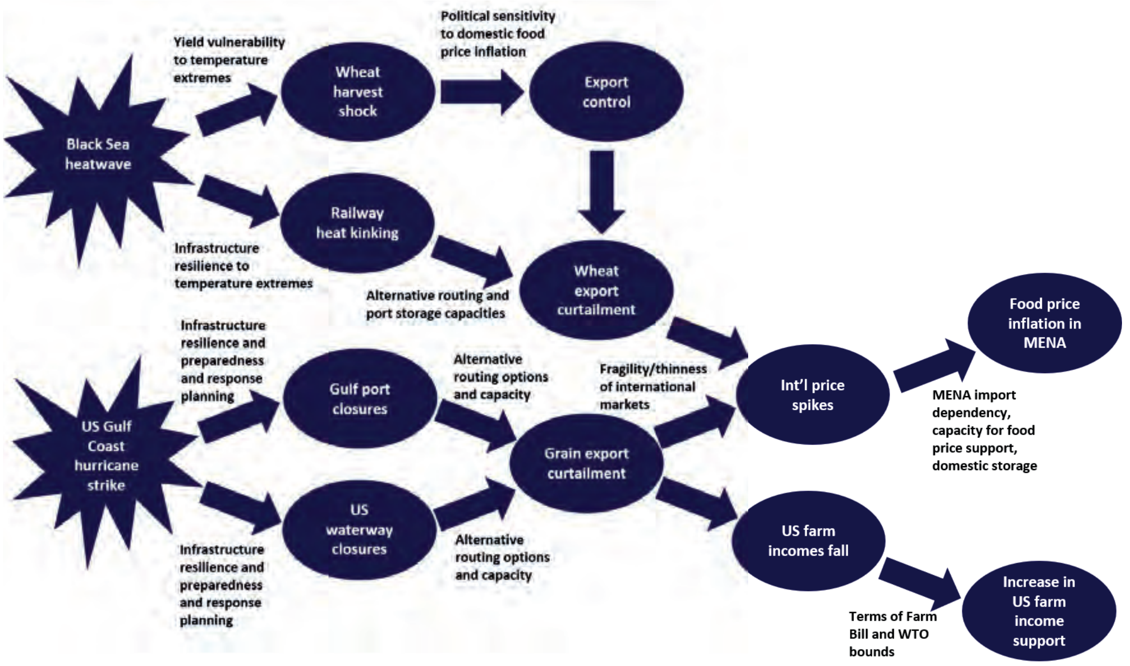
For any given risk it is important to understand how it may materialise both before it occurs and in light of a given trigger. Policymakers can then identify and plan actions in advance and in real time to reduce or prevent further cascading of the shockwaves from the hazard. A stylised example of how a systemic crisis might cascade from an initial climate hazard triggering a harvest failure is illustrated in Figure 57. In this example, the potential for a systemic, rather than contained, crisis depends on the extent to which global food systems are integrated, and whether the climate hazard negatively affects harvests in key exporting countries.

Figure 57: Conceptual example of systemic risk transmission originating in a climate hazard



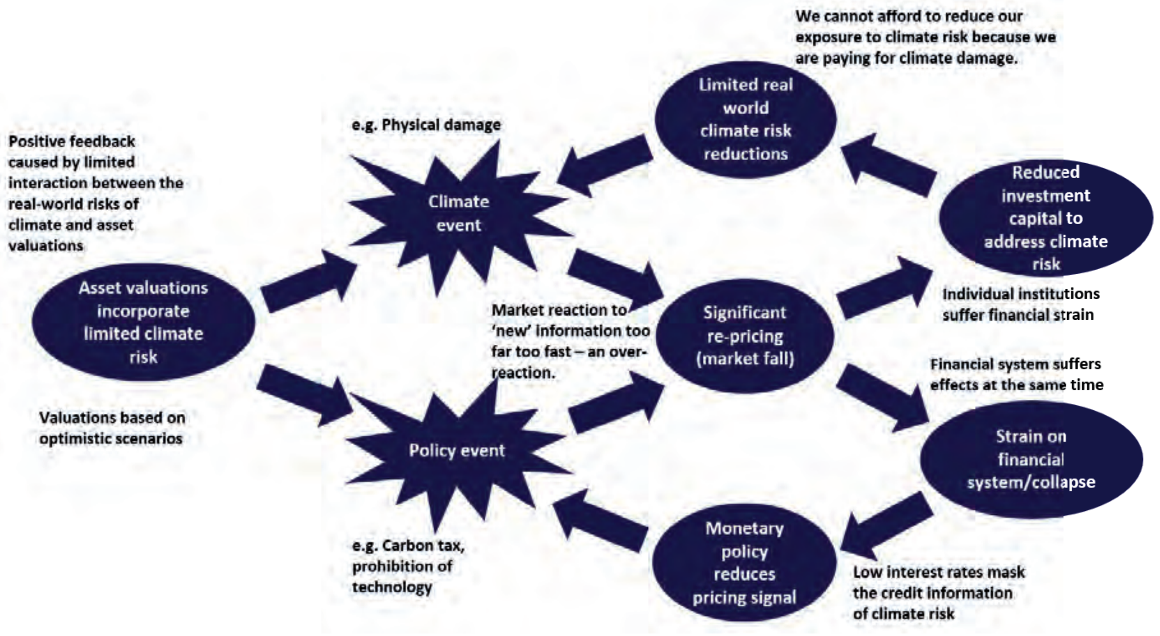
This same framework can equally be applied to other sectors or forms of systemic risk, as illustrated in Figure 58 and Figure 59, which show two further plausible systemic risk cascades in the food system and financial system respectively.

Figure 58: Plausible future systemic cascade in the food system due to infrastructure failures



Source: Based on Bailey & Wellesley (2017).

Figure 59: Plausible future systemic cascade in the financial system



Source: Nico Aspinall Consulting (2018) (personal communication).

More generally, risk transmission is determined to a large extent by the degree of exposure and vulnerability to each sequential hazard/shock: high vulnerability with negligible exposure (and vice versa) is unlikely to lead to further propagation of the initial risk to other downstream hazards.

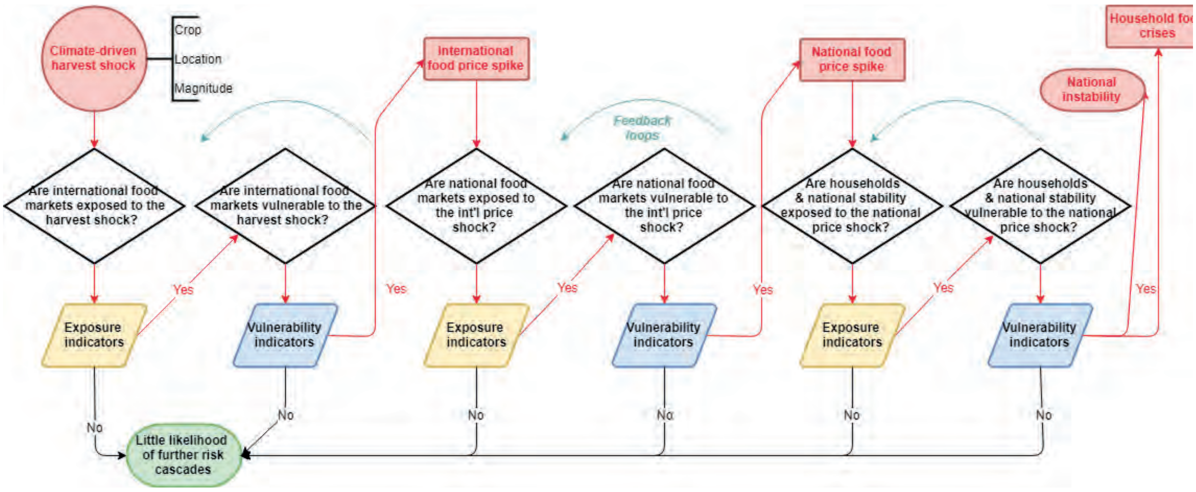
However, exposure and vulnerability may not relate only to the hazard itself but also to the social responses which result both from the reaction to exposure to risks and from anticipation of risks. Overall risk amplification may originate in the interaction of political systems, market systems, media coverage, behavioural responses and the perceptions of physical harm (Challinor et al., 2018).

The degree of exposure and vulnerability to any given shock is also dependent on the duration and nature of perturbation itself, such as whether the hazard is acute or chronic in nature, and whether its magnitude or volatility is the more significant factor (for example, changes in price levels may have different impacts to changes in price stability).

As such, our characterisation of the mechanisms of systemic risk includes indicators of the severity of each discrete hazard event and the degrees of exposure and vulnerability of different populations or system domains to each sequential event:

- The indicators identified are ‘leading indicators’ that have historically correlated with future amplification or dampening of risk cascades and ultimately system failure or system resilience.
- They provide both a means of determining where in the overall cascade chain the greatest risks exist and a mechanism by which to identify where any breaks in the potential cascade already exist – accepting that these are not immune from sentiment-based behaviour – or where policy interventions might most successfully contain further risk contagion. Figure 60 graphically presents this framework for a climate-driven harvest shock in a key breadbasket region propagating through the food system, though the framework is generalisable to other sectors through which systemic risk may be transmitted.

Figure 60: Detailed exposition of how climate shock can propagate across complex systems



4.2.3 Application to systemic risk case studies

We apply these two frameworks to the case studies developed in the Chinese context and to the global food system. Through the indicators that we track, we are interested in the links between how the risk, exposure and vulnerability of the system has evolved, and how climate change indicators are predicted to evolve over time. Though we can learn from previous systemic crises, and whilst in this chapter we are tracking real-time indicators with a historical perspective, our interest is forward looking: to what extent will climate change, or conversely the mitigation of climate change, influence the likelihood of systemic risk triggered or amplified by meteorological events. Thus our narratives link closely to Chapter 3.

In the Chinese cases (Section 4.3) we draw predominantly on the former framework to provide illustrations of a variety of indirect climate risks with different characteristics – from the domain affected, to the speed of onset, to the plausible degrees of severity. We emphasise a range of first-order indirect risks, and do not consider specific cascade chains and propagation mechanisms in detail.

In the case of the food system (Section 4.4) we use both conceptual frameworks as a starting point, combined with a review of the literature, to derive a suite of indicators that are relevant to systemic risk. The choice of indicators takes a pragmatic approach to the reality of employing indicators that have credibility and can be updated on a fairly regular basis. We combine key quantitative indicators, using readily available data wherever possible, with a narrative approach relying on the literature that has built up around earlier examples of systemic crisis originating in the global food system. Using historical data, we explore the extent to which simple and composite indicators, based on ready-to-access data, and often validated in the literature, can be used to demonstrate whether we are on trajectories that suggest a higher or lower likelihood of systemic risk, and, indeed, whether we need to identify new, more focused indicators.

4.3 Systemic risk: a Chinese perspective

In this section we present four types of indirect risk stemming from both acute – typically low-probability – and chronic, creeping climate hazards, with specific examples of historical and projected future impacts in multiple regions of China. These indirect risks could be the starting point for developing a suite of systemic risk indicators for each discrete risk cascade. An example cascade and potential indicators is illustrated in Figure 61.

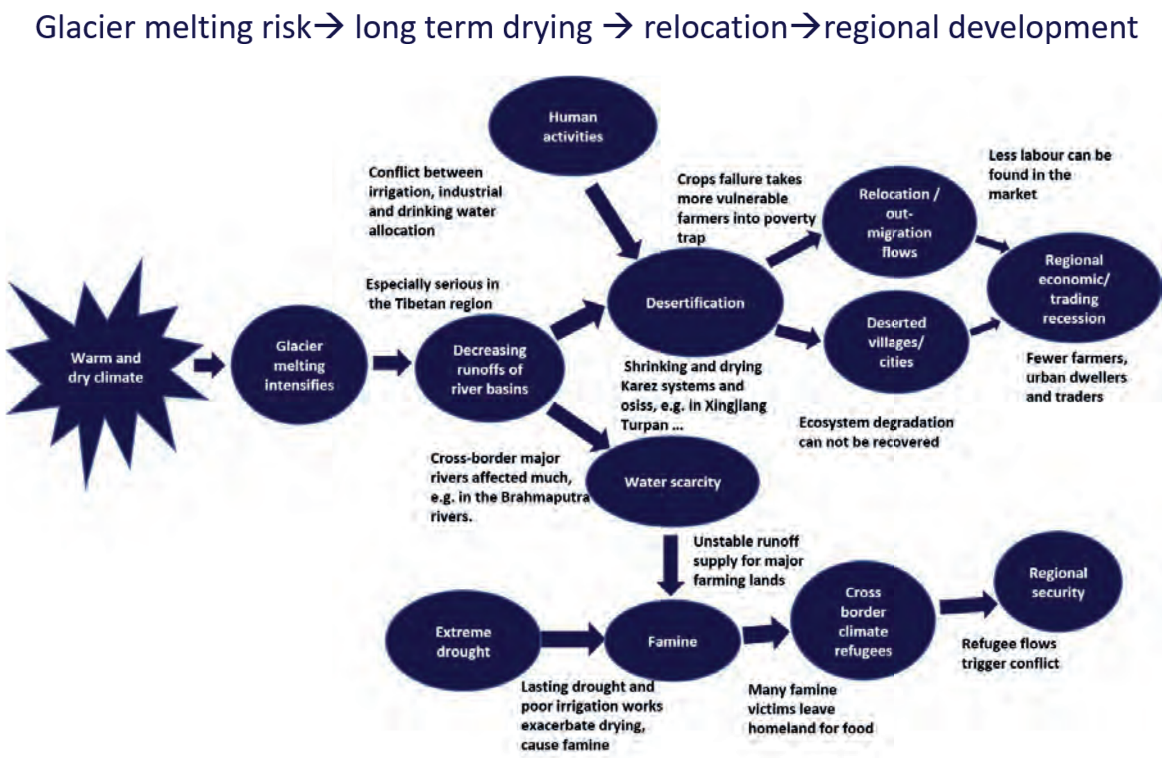
4.3.1 Water resource risks triggered by glacial melting

Most major rivers in China originate from the glacial plateaus in the west of the country. With global warming, it is expected that by 2050 the runoffs in China's western river systems will initially increase as a result of glacial melt and then decrease as the source glaciers diminish. The systemic risks caused by melting glaciers and a warming and drying trend will likely manifest in complex and diverse ways.

Intensified flooding and drought along the borders, especially in the west, could trigger disputes over water resources and may have ramifications for regional security and international relations. The diminishing oases and their agricultural systems and settlements, population migration, and resource tensions would have severe impacts on minority ethnic groups and in border areas. For example, Xinjiang Uygur Autonomous Region in north-west China is a climate vulnerable area that covers one-sixth of the national territory and is populated with 47 ethnic groups. As a major production area for grain, cotton, fruit and dairy, the region depends primarily on water supply from the glaciers of the Tian Shan Mountains and Kunlun Mountains. The accelerated melting of glaciers will eventually affect the water supply for agriculture and cities in the region, and may further destabilise a volatile society.

In the south-east of Tibet and the Hengduan Mountain area, the coverage of glaciers is expected to decrease rapidly due to global warming. During the period 2046–2065, the amount of water supplied by the transboundary Ganges (which has part of its drainage basin in Tibet) and Brahmaputra rivers will fall. About 60 million people in these areas will be threatened by shortage of food (Immerzeel et al., 2010). The South-East Asian countries along the river basins will likely face serious poverty and migration issues due to decreased runoffs from the Tibetan Plateau.

Figure 61: Systemic risk of glacier melting in western China and South-East Asia



Case 1: Diminishing Karez and adaptation in west China

Karez – one of ancient China's most significant infrastructure projects – relied on wells to collect water from surface runoff at the base of the Tian Shan Mountains and a series of underground water canals to irrigate agricultural lands above the water table. There are 1,540 Karez wells in the Xinjiang Karez system, among which Turpan city has 1,108 wells with a total length of about 5,000km. However, only 20% provide water resources. In the face of glacier melting (the Tian Shan Mountain glaciers are expected to shrink by 80–90%, threatening glacier-dependent cities such as Urumchi, Turpan and Hami), desertification and human activities, dozens of underground tunnels have dried out in the past half century and the Karez system as a whole is at risk of becoming obsolete. The drying Karez threatens millions of residents and much productive farming land. To prevent the number of Karez from decreasing in the Turpan area, the Xinjiang government launched, in 2006, the Protection and Utilisation Plan for the Karez System, and has initiated water-source protection legislation.

4.3.2 Urban security risks

In recent years, a stream of extreme and sudden climatic events – including great regional floods triggered by continued rainstorms, smog sweeping across central and eastern China, and high temperatures and heatwaves – inflicted serious damages on the societies and economies of densely populated areas along China's south-east coast (Qin et al., 2015). Over the longer term, sea level rise also poses a threat to China's major economic areas and key city clusters in the south-east. Here we consider the risks of both sea level rise and urban flooding.

4.3.2.1 Sea level rise: the survival and economic security risks to three city clusters along China's south-east coast

China's population and economy have increasingly been gravitating towards key cities: 32 city clusters are expected to have a total population of 800 million by 2030. Among these city clusters, the Big Three (the Pearl River Delta, Yangtze River Delta and Bohai Economic Zone) are in China's strategic planning. The climatic security of these regions will be important to China's sustainable development effort, especially considering that rising sea levels along China's south-east coast have the potential to inflict serious damage on these economic powerhouses.

Shanghai is the most important national financial and industrial centre located near the estuary of the Yangtze River Delta. It is the central city of the Yangtze River Delta Urban Agglomeration, home to a quarter of the Chinese population and producer of two-fifths of all products in China, despite its relatively small size, occupying only 5% of the Chinese land area. This concentration of wealth and population will increasingly be at risk from sea level rise caused by climate change. Shanghai's Huangpu River flood control wall is designed to withstand 1000-year floods, but with a 1m sea level rise, the sea walls will only be protective against 100-year floods (Xu et al., 2013). Given the confluence of sea level rise and land subsidence, the urban sections of the Huangpu River flood control wall need to be equipped to deal with 200-year floods. Similarly, the urban areas of Guangzhou and Shenzhen require the capacity to cope with 200-year floods in 2020, prefecture-level cities should be able to cope with 100-year floods, and important embankments should be resilient against 50- to 100-year floods.

Sea level rises in the coming century require significant increases in investment to address climate risks in China's coastal cities, and to deal with the resulting changes to the overall geographical distribution of urban population and industries.

4.3.2.2 The nexus risks of climate change and human activities: China's urban floods

Climatic events such as heatwaves, severe convective weather, thunderstorms and smog are frequent occurrences in urban areas, and extreme weather events have become a common occurrence in city clusters along China's south-east coast in recent years. It is not unusual for these climatic events to impact large areas and last a very long period of time, causing extensive damage to society and the economy (Qin et al., 2015). Typhoons, rainstorms and flooding have caused major disruptions to Chinese cities located on the banks of major rivers, on the coast and even to inland cities remote from major water bodies. During 2008–2010, nearly two-thirds of Chinese cities were affected by flooding, yet a recent assessment of 280 larger Chinese cities found that only 11% have medium to high levels of resilience to rainstorms and the majority have low levels of resilience (Figure 62) (Zheng et al., 2018).

Figure 62: Classification of Chinese urban resilience to rainstorms

Those cities shown in Figure 62 that are low-risk and resilient to rainstorms are predominantly wealthier cities. They may still be threatened by torrential rains. For example, Beijing, Yuyao in Zhejiang province, and Wuhan in Hubei province (located in eastern, central and coastal areas respectively) still suffered serious consequences from recent episodes of extreme rainfall, despite having a far better performance than most other cities in terms of economic development, urbanisation level, drainage network density, and green infrastructure for responding to rainstorms (Case 2).

Unlike conventional meteorological disasters, extreme weather events often set off chain reactions, and insufficient investment in basic facilities for dealing with such hazards has led to the amplification of risks. The ensuing casualties, economic losses and disruption to normal city operations can be extremely costly and pose a significant challenge to municipal governments' systems and capacity for managing risks.

In 2018, the Chinese government established a new Ministry of Emergency Management to combine and better manage the disaster prevention, mitigation and relief functions and resources of 13 separate agencies. This major institutional adjustment should increase China's capacity to deal with natural hazards and reduce the systemic risks they create.

Case 2: Urban floods in China and actions to increase resilience to rainstorms

Beijing was hit by a 70-year flood on 21 June 2012. The torrential rain affected 1.6 million people across the city, resulting in 79 deaths and direct economic losses of RMB 11.8 billion. In October 2013, Yuyao city in Zhejiang province suffered serious flooding resulting from typhoon Fitow. About 70% of urban built-up areas were submerged and 25,650 houses were seriously damaged. The public transport system in major districts was paralysed. In total 833,000 people were affected, and direct economic losses were estimated at RMB 20 billion. Wuhan, capital of Hubei province suffered persistent heavy rainfalls in July 2016 affecting 1 million people, damaging 1.8 million hectares of crops, destroying 8,326 homes, and resulting in direct economic losses of RMB 4 billion. A lack of risk planning and ecological conservation in the urbanisation process amplified the risks and river basin flooding.

These cases illustrate that climate hazards can have significant risk cascades in large, well-developed cities. In the case of Beijing, for instance, the impact on transportation, tourism, agriculture, forestry and other downstream industries, the psychological trauma suffered by affected families, and the negative influences on the government's crisis management capacity and credibility provoked serious reflection in all sectors, from the government to academia and the general public (Zheng & Ruan, 2013). Beijing has consequently developed much greater resilience to rainstorms by taking measures such as extending the coverage of flood early warning systems, improving drainage systems in old communities, and adopting an intelligent traffic monitoring system.

In 2015 and 2016, the Chinese Ministry of Housing and Urban-Rural Development selected 30 cities for a pilot programme on 'sponge cities'. Each city will be granted a three-year national investment in the region of RMB 100–150 million per square kilometre to restore water-related ecosystems, conserve water resources and increase the city's flood control capacity.

4.3.3 Climate-induced poverty risks

In China, environmental degradation, natural disasters, resource scarcity and social and geographical marginalisation are all contributing factors to people living in poverty. With hundreds of billions of yuan (365 billon RMB since 2010) invested in poverty alleviation, the proportion of the population living in poverty declined from 17% in 2010 to 3% by the end of 2017 (Zhu & He, 2018). However, about 30 million people in rural areas are still living below the national poverty line (RMB 2,300 per capita net income, constant 2010 prices). Most of these people live in ethnic minority areas, border areas and mountain areas that are extremely ecologically fragile. These populations are at high risk from climatic events, as commonly evidenced by high levels of disaster exposure, low levels of resilience, scattered residences, poor infrastructure, and insufficient provision of basic public services such as disaster early warning and social security systems (Oxfam, 2015). For many natural resource- and agriculture-dependent rural areas, climate change has aggravated poverty and environmental degradation, making it very hard for impoverished populations to escape the poverty trap. Despite China's active and successful promotion of targeted poverty reduction in the past decade, many of these rural poor may need to become environmental migrants to escape the entrenched poverty of their homelands (Case 3).

Arid inland areas are at high risk of climate change-induced poverty and migration; around 10 to 30% of the people in these areas are expected to become permanent migrants. Since the 1980s and 1990s China has launched a large number of ecological migration projects – in poor western areas that are ecologically fragile, and in the Yangtze River Basin areas where natural disasters (many of which are closely related to environmental and climate change factors) occur frequently. Many of the government-led ecological migration projects in China are a type of active, planned adaptation. For example, between 1983 and 2015, Ningxia region carried out a series of ecological migration projects, relocating a total of 1.1 million people to eliminate poverty, protect the environment and adapt to climate change (Case 3) (Zheng et al., 2013). In 2011, Shaanxi province launched China's largest ecological migration programme, expected to last ten years and cost RMB 110 billion, with the aim of relocating 2.4 million people from the arid northern areas of the province and from mountainous areas hit by rainstorms and mudslides in southern areas.

The relocation projects carried out by local governments have effectively helped to reduce the population exposed to climate change-induced poverty and to break the vicious cycle of poverty and forced climate migration.

Case 3: Desertification in western China and potential climate-induced migration

Ningxia region is in the arid and semi-arid area of western China. It suffers serious drought and relies heavily on the Yellow River and underground aquifers as major water sources. The per capita water resource of Ningxia is only one-third of the average level in China as a whole, and 44% of the region is desert. The sensitive ecology of the region is vulnerable to the increasing average temperatures and markedly decreasing average rainfall witnessed over the last 50 years. The harsh natural environment and frequent occurrence of climatic hazards also makes it hard for the population to earn a livelihood; the long-term entrenched poverty has forced many young people to move away, either as temporary migrant workers or to permanently resettle.

In the arid area of central Ningxia, Hongsibu district now accommodates 190,000 immigrants that have resettled since the early 1990s. However, in years of extreme drought, these immigrants are expected to be relocated for a second time. With the continued influx of new immigrants, the pressures on land and water resources are expected to intensify, and the runoff of the Yellow River will decrease in the long run; the population of Hongsibu short of water is expected to exceed 26,000 by 2020. In spite of the ecological migration projects, desertification, salinisation and water shortages caused by continuous warming and drying episodes are expected to require the relocation of two-thirds (420,000 people) of the central and southern Ningxia population by 2020 (Ma, 2012).

4.3.4 Human health risks

4.3.4.1 Climate change impacts on vector-borne diseases in China

According to the World Health Organization (WHO), climate change is considered to be the key cause of the expansion of dengue fever globally (Benitez, 2009). The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) concluded that dengue fever is associated with climate variables at both global and local levels (high confidence) while malaria and the occurrence of haemorrhagic fever with renal syndrome showed a positive association at the local level (high confidence) (Huang et al., 2017).

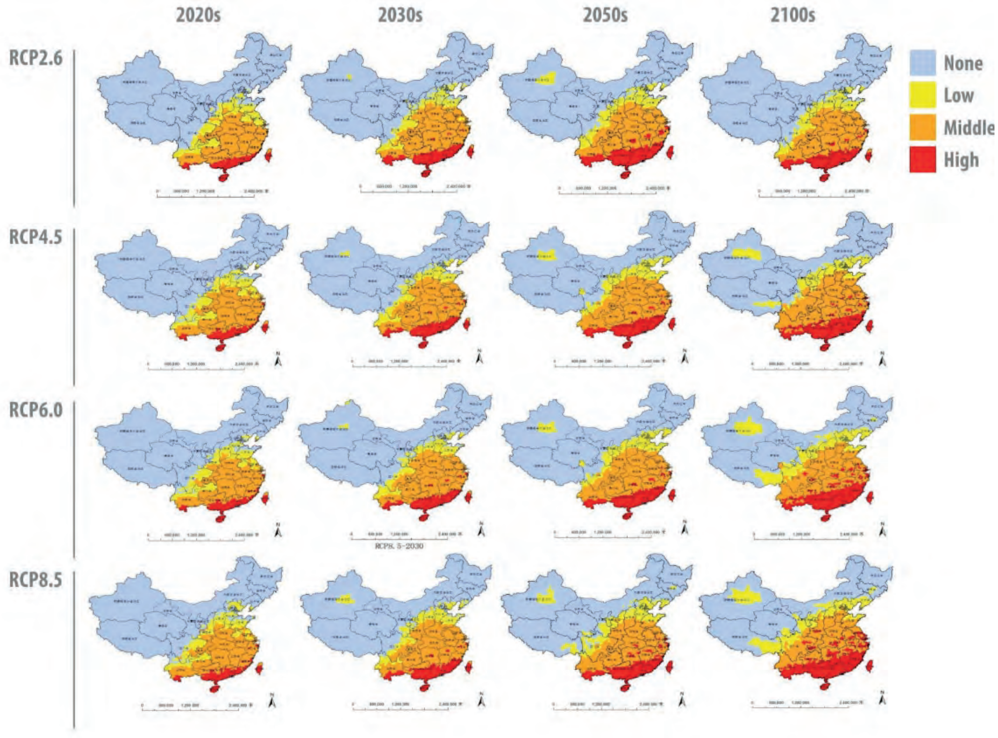
1. Dengue and its vectors

Dengue fever is a major mosquito-borne disease caused by four types of dengue virus and transmitted via the bites of *Aedes* mosquitoes (Biernat et al., 2015). In recent years, dengue fever has become an important public health threat in China with multi-site outbreaks in provinces including Guangdong, Yunnan, Fujian, Zhejiang, Guangxi, Henan and Shandong (Chen & Liu, 2015; Li et al., 2017; Lai et al., 2015).

Climate variation drives dengue dynamics in China (Xu et al., 2017). With meteorological data from 1981 to 2010, the CLIMEX model was used to project changes in suitable habitat ranges for the *Ae. albopictus* vector under different climatic scenarios (Representative Concentration Pathways [RCP]2.6, RCP4.5, RCP6 and RCP8.5) with different time horizons. Currently, highly suitable areas are concentrated in 269 counties (6,090km^2) in Hainan, Taiwan, Guangdong, Guangxi, Yunnan and Fujian. Future climate change will expand the suitable habitats to higher latitudes. Under the RCP2.6 scenario, 400 counties (9,320km^2) are projected to be habitable in the 2050s, and then the area would fall to cover 227 counties (5,080km^2) by the 2100s – a smaller area than under current climatic conditions. Under RCP8.5 the distribution of *Ae. albopictus* is projected to be larger, inhabiting an additional 333 counties (13,070km^2) in the 2050s and 580 counties (20,450km^2) in the 2100s (Figure 63).

In terms of dengue transmission risk, the *Ae. albopictus* habitat expansion translates into an increase in people at high risk from 168 million today (in 142 counties) to 277 million (in 344 counties) in the 2050s and 233 million (in 277 counties) by the 2100s under RCP2.6, and 490 million (in 456 counties) by the 2100s under RCP8.5 (Liu et al., 2016).

Figure 63: Changes in dengue fever risk areas under different scenarios



2. Malaria and its vectors

Predictions based on the Maxent species distribution model suggested that the environmentally suitable area for two vector mosquito species (*Anopheles dirus* and *An. minimus*) will increase by 49% and 16% respectively in the 2030s. By the 2050s, the suitable habitat for *An. lesteri* and *An. sinensis* under two scenarios (RCP4.5 and RCP8.5) will increase by 36% and 11% respectively. Given expected changes in land use and urbanisation in the affected regions over the same period, the population exposed to the four *Anopheles* mosquito species is expected to increase significantly (Ren et al., 2016). The future trend of malaria incidence under different scenarios is similar in the absence of malaria control (Hundessa et al., 2018).

4.3.4.2 Health impacts of high temperatures and heatwaves

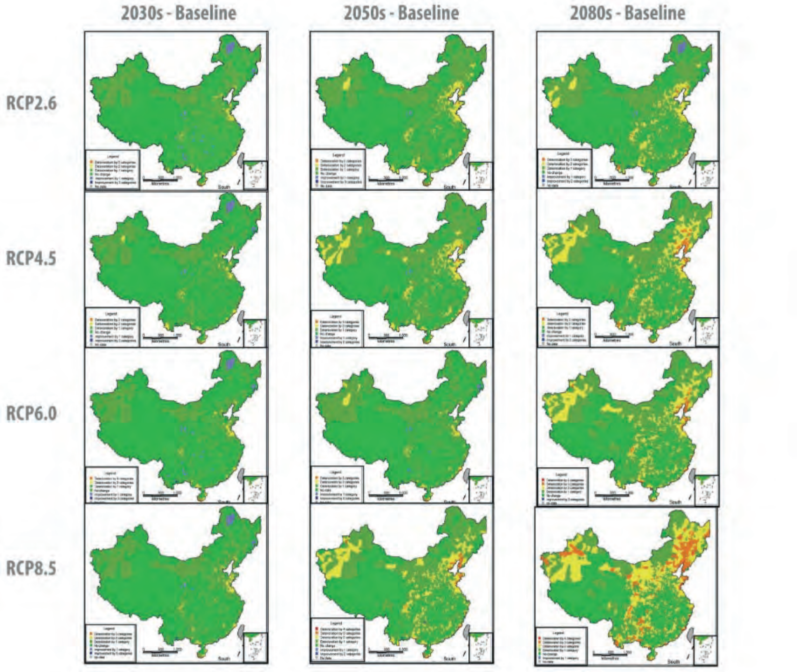
Heat stress from high temperature extremes has a direct impact on human health. This effect will become more frequent and widespread under different climatic scenarios in future, leading to a rise in morbidity and mortality. High temperatures and heatwaves will also increase the incidence of non-communicable diseases, such as cardiovascular, cerebrovascular and respiratory-system diseases, as well the transmission risk of infectious diseases, thereby exerting a significant impact on the whole population.

1. Assessment of high temperature impacts on health vulnerabilities

The Chinese populations particularly vulnerable to heat-related diseases include infants, those over the age of 65, and those with occupational exposures (such as bus drivers, traffic police, cleaners and construction workers). They are at risk from cardiovascular disease, stroke, acute myocardial infarction, ischaemic heart disease, hypertension, respiratory disease, diabetes, kidney disease and urinary system diseases. High-temperature health vulnerability assessments suggest populations are at particular risk in in south-west China, Anhui and Gansu provinces.

Analysis of high-temperature health vulnerabilities under different RCP scenarios (RCP2.6, 4.5, 6.0 and 8.5) and over different periods (2030s [2016–2035], 2050s [2046–2065] and 2080s [2080–2099]) suggests significant increases in vulnerabilities under all scenarios and time periods. The high-temperature health risks in 27% of Chinese counties will significantly change under all climate scenarios between the present day (1986–2005) and the 2030s. Between the 2030s and 2050s an additional 9% of counties will witness marked increases in health risks under all scenarios. Relative to the 2050s, an additional 8, 9 and 21% of countries will experience risk increases by the 2080s under RCP2.6, 4.5 and 8.5 respectively (Figure 64).

Figure 64: Projection of high-temperature health risks in China



2. Health impacts of heatwaves in representative regions of China

In July and August 2013, China's central and eastern regions suffered the strongest and most prolonged heatwave since 1951. According to the Chinese Center for Disease Control and Prevention's heatstroke and death surveillance systems, 5,758 cases of heat-related diseases were reported nationally over the 2013 summer period, an increase of 211% and 184% relative to the same period in 2011 and 2012 respectively. Such diseases were concentrated in the urban areas of the middle and lower reaches of the Yangtze River, and the symptoms were mostly heat convulsion, heat radiation and heat stroke. In terms of mortality, there were 5,322 excess heat-related deaths in 16 capital cities in middle and east China compared with the same period in 2011 and 2012. These were predominantly cardiovascular (3,077) and respiratory-system (959) related and mainly in the population aged over 65 (4,863) (Bai et al., 2014).

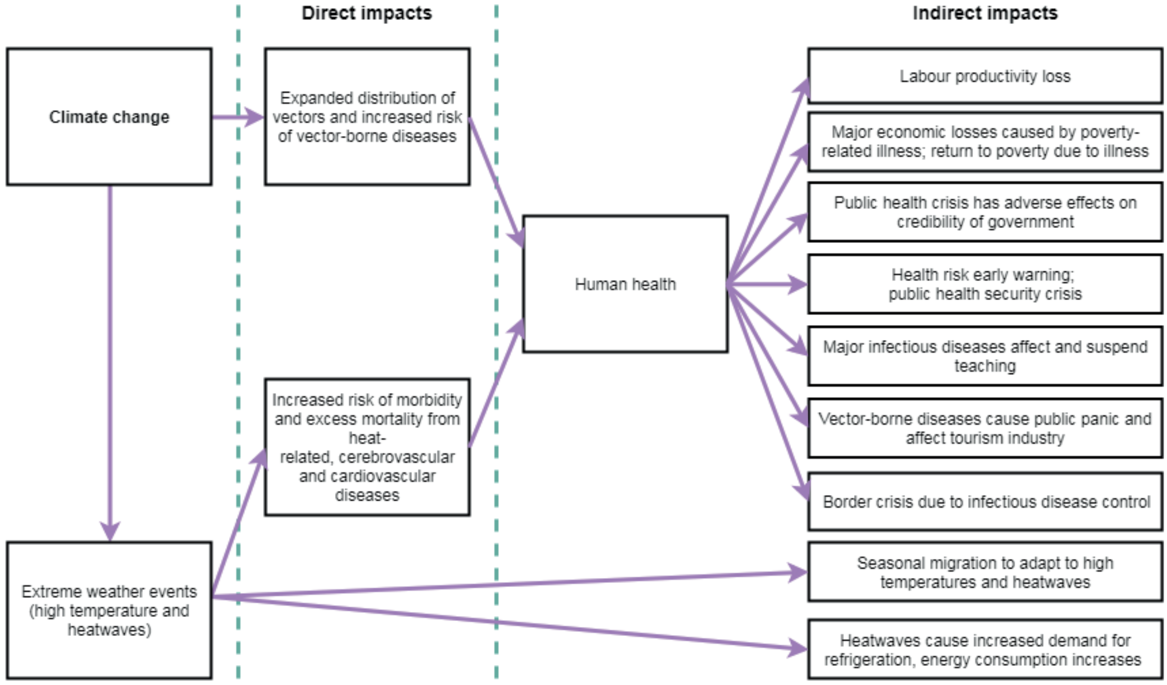
3. Impacts of high temperatures and heatwaves on cardiovascular disease

Extreme high temperatures can affect the cardiovascular system (Yang et al., 2016, 2017), with northern and north-western regions of the country currently most affected. Under future climate change scenarios, the number of excess cardiovascular deaths relative to a 2000s baseline rise by between 6 and 9.5% (RCP2.6 and 8.5 respectively) in the 2030s, and by between 8 and 30.3% by the 2080s.

4.3.4.3 Summary of significant impacts

Climate change and extreme weather events have caused, and are expected to continue to cause, the expansion of disease-vector habitats, vector-borne disease risks, and heat-related morbidity and mortality. These factors can result in declines in labour productivity and economic growth, potential public health crises, interruptions to education systems, migration and border instability, among other risks, challenging the capacity of government adaptations and responses (Figure 65).

Figure 65: The direct and systemic impacts of climate change and extreme weather events on human health



4.4 Systemic risk: a global perspective

In this section we first provide four sketches of climate-related systemic crises that have been identified as such in the literature, and explore the key exposure and vulnerability pathways for each that are likely to evolve with economic growth and climate change. These brief sketches of environmental systemic crises highlight distinct elements of risk cascades:

I. The state of the system before the climate shock (the ex-ante environment of exposures, vulnerabilities, and long-run drivers).

II. The trigger (the climatic hazard that initiates the cascading of risks resulting in systemic crises).

III. How individuals, governments, and private entities respond immediately after each sequential hazard (short-run responses).

IV. The exposures and vulnerabilities, or resilience, of populations and countries to a cascading crisis.

At a global level, the frequency and severity of the meteorological hazards that triggered these systemic crises in the four examples are likely linked to climate change. All else being equal, efforts to mitigate climate change are likely to reduce the frequency and severity of these hazards relative to not doing so. We then apply the framework described above to derive indicators to track systemic risk, using the food system as a case study.

4.4.1 Risk, exposure and vulnerabilities: four examples of climate-linked systemic risk narratives

4.4.1.1 2007–2008 food crisis

The food crisis of 2007–2008 is an exemplar of system failure triggered by a climate event. A number of longer-term, non-climate-linked drivers made the food system more vulnerable and exposed to climate events. These included protracted under-investment in the agriculture sector; growth in biofuels demand (at the time taking 30% of the US maize crop), which diverted grains to fuel; and increasing meat consumption, especially in Asia, as poverty levels fell rapidly, which led to grains being diverted towards animal feed (Headey & Fan, 2008; Tangermann, 2011). These drivers were reflected in falling stocks and upwards pressure on food prices. There are various disagreements in the literature as to the relative importance of each of these factors. For example, Dawe (2009) suggests that falling stocks were driven primarily by stock drawdown in China, and did not contribute to the 2007–2008 food crisis.

The central climate hazard that triggered the 2007–2008 food crisis was a succession of droughts in Australia, a key ‘breadbasket’ supplier of wheat to the world markets. In 2006 there was a drought described in the popular press as Australia’s ‘worst drought in 1000 years’, and this was followed by further droughts, resulting in sequential loss of harvest across multiple seasons.[11] These droughts precipitated shortages in the global food system, which was already strained by increasing diversion of grains into livestock feeding and biofuel production, and by falling global stocks.

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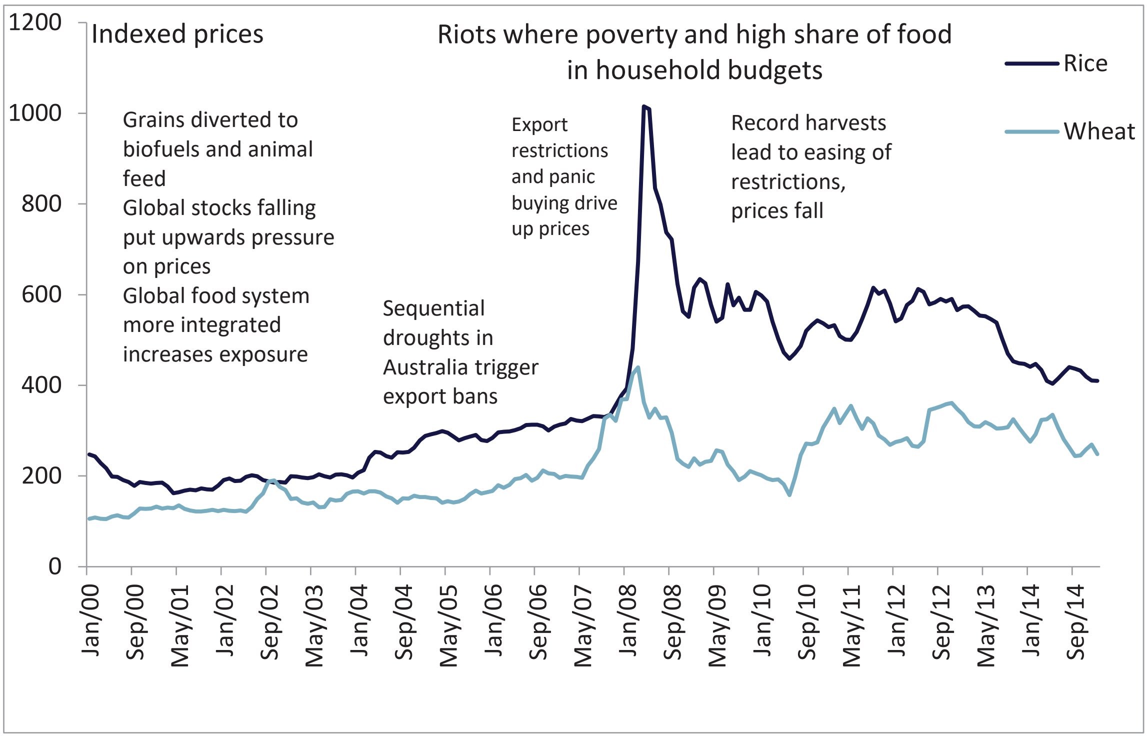
[11] For example, https://www.theguardian.com/world/2006/nov/08/australia.drought

With low global food stocks, and poor harvests in Australia, governments and individuals around the world rapidly reacted. Vietnam and India restricted exports, then Egypt and China followed suit. Panic buying was reported in the Philippines. Even Thailand, a net exporter of rice, discussed an export ban (Abbott, 2011; Headey, 2011). In total, six of the top 17 wheat exporters and four of the top nine rice exporters imposed some level of trade restriction (Puma et al., 2015). As a consequence, the volume of grain available on the world markets shrank considerably, which drove a corresponding spike in the price of grains, particularly acute for rice, which is a thin market with only around 7% of global production traded, and which experienced a shorter run-up to the crisis (Headey & Fan, 2010; King, 2015).

Whilst in higher-income countries food expenditure is a relatively small share of total expenditure, it is the opposite in lower-income countries. Those lower-income countries highly dependent on food imports, with a high share of food expenditure in household budgets and relatively low levels of nutrition, suffered particularly badly when prices spiked. Riots broke out in countries across the globe, including Haiti, where the prime minister was ousted from office following violent riots by protesters over the sudden spike in food prices (von Braun, 2008; Berazneva & Lee, 2013; Hossain & Scott-Villiers, 2017).

Prices fell rapidly after record harvests were recorded in the following season, and export restrictions were eased (Figure 66).

Figure 66: 2007–2008 Food crisis



Source: Authors' construction from multiple sources.

4.4.1.2 Southern India 2015: a 'people' event

In 2015, the southern states of India experienced the most severe rainfall event for a century (Krishnamurthy et al., 2018), exacerbated by the concurrent El Niño (Boyaj et al., 2018). Chennai recorded 1,049mm of rainfall during the month of November with peak intensities reaching 490mm in a 24-hour period on 1 December. Chennai was declared a disaster area on 2 December: transport, power supplies, water supplies, public health services and food distribution were all interrupted due to inundation across the city, with flood waters reaching 7m.

Set in a major city of 7 million people, the 2015 Chennai floods had many of the attributes of a 'developing world' disaster. There were notable elements of systemic failure: poor urban planning and concentration of social housing in flood-prone areas; a lack of resilience planning in infrastructure; releases from over-topping dams compounding downstream flood risk, causing populations to be evacuated and worsening the flooding of 400,000 hectares of agricultural land that supports the local population; and failures of utility services that exacerbated the emergency. The number of fatalities is not accurately known, but reports put the figure at over 500 in Chennai alone. Losses and damages are today estimated between US$3 billion and US$16 billion.

4.4.1.3 Thailand 2011: a 'supply chain' event

System complexity has been attributed to a lack of predictability with respect to the impact and scope of flooding (Merz et al., 2015). Exposure of people and assets appears to be increasing in many emerging economies. In Thailand, many of the natural floodplains have been built on, making such built environments particularly vulnerable to flooding. In 2011, a systemic crisis in the country was triggered by particularly high rainfall during a La Niña period that led to five typhoons making landfall, 90 days of floods (Merz et al., 2015), and severe and widespread disruption in 65 of Thailand's 77 provinces. The country's reservoirs were not able to contain the increased volumes of water. Whilst some have attributed the 2011 floods to La Niña rather than climate change, recent research suggests that the 2011 localised rainfall and sea level are both linked to anthropogenic greenhouse gas (GHG) emissions (Promchote et al., 2016). The probability and intensity of flooding – the hazard – is likely to increase as a result of climate change (see Chapter 3).

More than 880 people lost their lives, and 2.5 million people are estimated to have been displaced by the 2011 floods, which also destroyed a quarter of the rice crop with losses in the global agricultural sector amounting to some US$1.3 billion. In addition to the direct impacts of the flooding, the industrial sector was particularly hard hit. Damage to manufacturing was estimated to be US$32 billion, with annual car production falling 20% (also affected by the Japanese earthquake), and the least diversified companies were the most harmed (Haraguchi & Lall, 2015). In the context of globalised supply chains, much of Thailand's manufacturing sector had been moving towards what was perceived to be a more efficient, just-in-time delivery. Yet within that same context, supply chains were becoming increasingly vulnerable to systemic crises triggered by weather shocks. The insurance industry is reported as not having factored these changes to the system into its calculations (Merz et al., 2015).

4.4.1.4 2005 US Hurricane Katrina: an 'economic' event

In the USA in 2005, Hurricane Katrina resulted in the New Orleans levee system failing. The city was flooded, with a direct impact on the health and wellbeing of the city's population. In the broader Gulf region, loss of electricity meant that drinking water treatment plants were not fully functioning. Damage to the Port of New Orleans affected all industries that relied on access to the Gulf of Mexico (Crowther et al., 2007). Gas shortages were experienced throughout much of the south-east United States, and heath infrastructure was reported to have 'collapsed in the wake of Hurricane Katrina' (DeSalvo, 2018). Seven months after the hurricane, only 15 out of the 22 hospitals in the area were open (Berggren & Curiel, 2006). Total costs resulting from the hurricane damage were estimated at $200 billion (Dolfman et al., 2007). Over 100 people lost their lives. This number would have been much higher but for the significant post-Katrina Federal and State investments in planning and interventions that were effective in rescuing, evacuating and safeguarding local populations.

The recent 2017 Hurricane Irma (affecting the south-eastern USA and the Caribbean) is estimated to have caused even greater economic damage, and the impact showed up in, for example, rapidly increasing orange juice futures, reflecting anticipated damage to the agriculture sector in Florida.

4.4.1.5 Lessons: systemic crisis and economic growth

In many circumstances, economic growth enables individual countries to avoid the worst of systemic crises. For example, poverty exacerbates the impact of rising prices on food insecurity, under-nutrition and consequential unrest. The countries hardest hit by the 2007–2008 food crisis were those highly dependent on food imports, and where poverty and under-nutrition were already prevalent, Haiti being a case in point. In sub-Saharan Africa, limited food availability, restricted access to food, and a coastal location (with greater exposure to global economic conditions, such as international high prices and their consequences) were found to be closely linked to countries experiencing riots over food price spikes (Berazneva & Lee, 2013). More broadly, poverty headcount, child mortality and under-nutrition have been found to be positively associated with the outbreak of conflicts (Pinstrup-Andersen & Shimokawab, 2008); and food protests have been found to be most violent in countries with 'low government effectiveness' (von Braun, 2008).

Economic growth and poverty reduction can, all other things being equal, reduce food insecurity at the individual level and thus reduce the likelihood that systemic risk, triggered by a climate-related food shock, will result in conflict and violence. However, in contrast to the 2007–2008 food crisis example, Thailand appears to have been more vulnerable to flooding because of the nature of the preceding economic growth and development. If, for example, economic growth results in an increase in infrastructure that is vulnerable to weather shocks, such as an increase in high value properties in coastal areas at risk of storms or flooding, economic growth may amplify rather than reduce the impact of systemic risk and the likelihood of system failure. Indeed, globally, assets have been found to be increasingly exposed to flooding, both river and coastal. For example, the exposure of global assets to river flooding has been shown to have increased from US$1.8 trillion in 1970 to US$35 trillion in 2010 (Jongman et al., 2012). This increased exposure has been attributed to increased population exposure (48%) and increased wealth exposure (52%), reflecting growth in population and in gross domestic product (GDP). Looking forward, growth in exposed assets is likely to increase more rapidly than growth in exposed populations (Jongman et al., 2012).

Thus, over time, whether populations, countries and economic systems are more or less likely to experience climate-change-related systemic crises depends on a number of trends. Specifically, economic growth can make populations more or less vulnerable to systemic crises; the growth of populations and assets can occur in areas that are more or less exposed to weather shocks; and governments can choose the extent to which they take actions to reduce the vulnerability of exposed populations in these areas.

Generally, coastal cities in higher-income countries are better protected than those in lower-income countries (Xian et al., 2018), but also comprise higher value physical assets. However, this is not the case for Shanghai and New York. These two cities share a number of similarities. They are their countries' financial centres, they are densely populated, and both have experienced cyclones/hurricanes and flooding. Yet Shanghai, though less wealthy, has much higher standards of flood protection than New York (Xian et al., 2018), reflecting the influence of government policies and choices on the extent to which a country is more or less exposed and vulnerable to climate change as it grows economically.

4.4.2 Applying the methodology: case study of the food system

Food crises – frequently manifested in sporadic extreme price spikes following both acute and chronic developments in contributory factors – are systemic crises that have the potential to adversely affect several domains of society. Production shocks and subsequent losses in income and purchasing power clearly have economic ramifications, but protracted periods of unaffordable food prices can also lead to adverse health outcomes (especially among infants and other vulnerable populations), and breakdown in the social fabric of families, communities and societies. Despite increases in total food availability per capita, food crises continue to be likely (Tangermann, 2011). There is ample recent evidence of systemic risk in the food system. In addition to the 2007–2008 global food crisis, the 2007–2010 drought and crop failures in Syria have been implicated in that country's protracted conflict (Kelley et al., 2015) and rising food prices have been linked to the 2011 Arab Spring. We recognise that systemic food-linked crises are at most only partially rooted in 'natural' phenomena (Buharg et al., 2015). The conflicts and crises that are triggered by short-term food shortages and price spikes are often more deeply rooted in discontent regarding injustice, inequality, political repression, poverty, labour disputes and poor public service provision (Bush, 2010; Smith, 2014). Nonetheless, as food systems become increasingly complex and globally integrated, and as the impacts of climate change are manifested in the increasing frequency and severity of what were historically low-probability, high-risk weather events – such as floods, droughts and extreme heatwaves – the systemic risks are increasing and, with them, the need for both more aggressive climate mitigation activities and the development of more resilient systems.

Using the characterisation of a plausible food system risk cascade presented in Figure 60**:** Detailed exposition of how climate shock can propagate across complex systems Table 6**:** Candidate systemic risk indicators in the food system summarises the leading indicators we consider here that can aid in the diagnosis of system weaknesses and in the identification of entry points for policy intervention. These are briefly discussed in the following sections.

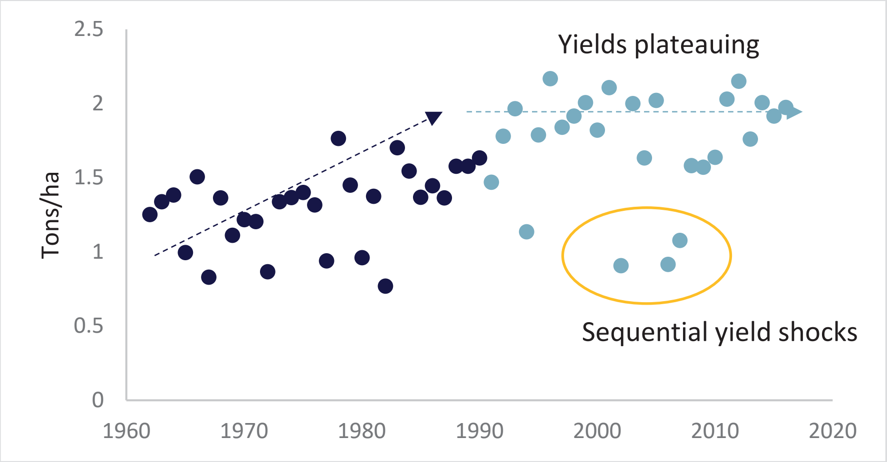
Table 6: Candidate systemic risk indicators in the food system

Initial hazard: Climate-driven harvest shock	
Hazard indicator(s)	• Production volumes/yields
Exposure indicator(s)	• Share of production traded • Export concentration
Vulnerability indicator(s)	• Stock-to-use ratio • Grain diversions • Biofuel production • Biofuel mandates
Subsequent hazard 1: International food price spike	
Hazard indicator(s)	• Food price trends • Food price volatility
Exposure indicator(s)	• Cereal import dependency • Strategic grain reserves
Vulnerability indicator(s)	• Export restrictions
Subsequent hazard 2: National food price spike	
Exposure indicator(s)	• Share of food expenditure • Variety of diet
Vulnerability indicator(s)	• Composite indicator of number of countries vulnerable to one, two or three of undernourishment, import dependency and/or political instability
Subsequent hazards 3: Household food crises and national instability	

4.4.2.1 Hazard: climate-driven harvest shocks and trends

Chapter 3 presents a suite of indicators tracking direct risks from climate-related hazards. Most pertinent to the food system are those indicators that signal the potential impingement of extreme weather conditions on agricultural commodity production volumes in key breadbasket countries and whether such shocks are increasing in frequency and intensity. Sequential droughts in Australia, examples of 'sudden risk', have already been demonstrated to trigger a global food crisis in 2007–2008 (Figure 67). Also evident is a potential long-run 'creeping risk'. For example, yields for Australian wheat are plateauing, and potential yields falling.

Figure 67: Australia wheat yields 1960–2016



Source: FAOSTAT.

4.4.2.2 International food markets: indicators of exposure and vulnerability to production hazard

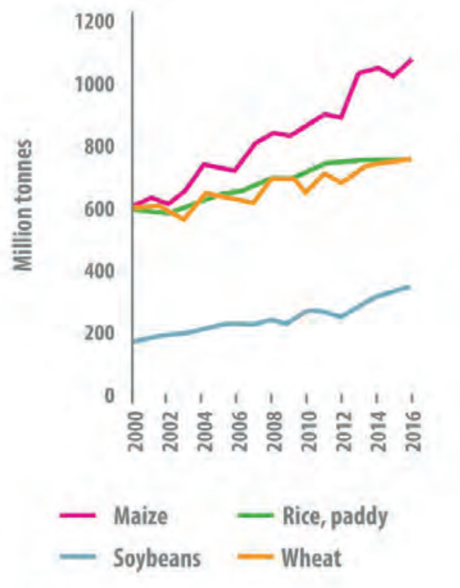
We consider a cluster of four indicators to represent the exposure and vulnerability of international food markets to climate-driven production shocks. Exposure is represented by metrics for the share of global production volumes that are traded, and for the concentration of exports from a small number of countries. Vulnerability is measured by indicators of grain diversion – specifically into biofuels in this instance (though a parallel indicator could also be developed to demonstrate the proportion of staple cereals allocated to livestock feed) – signalling demand-driven factors that could undermine access to food staples; and by stock-to-use ratios that indicate the degree of slack that exists in global and national grain inventories.

Exposure: share of production traded and export concentration

Share of production traded

The impact on world markets of a production shock for a given crop will likely be determined in part by the proportion of production that is traded internationally (Figure 68). In aggregate, a larger proportion of goods may be affected for highly-traded commodities, whereas if the global market is thinner (e.g. for rice) the absolute impact may be smaller, but more severe for those portions of the market that are traded internationally. Much also depends on the significance of the affected producer(s) to global supply and the extent to which production is spatially diversified.

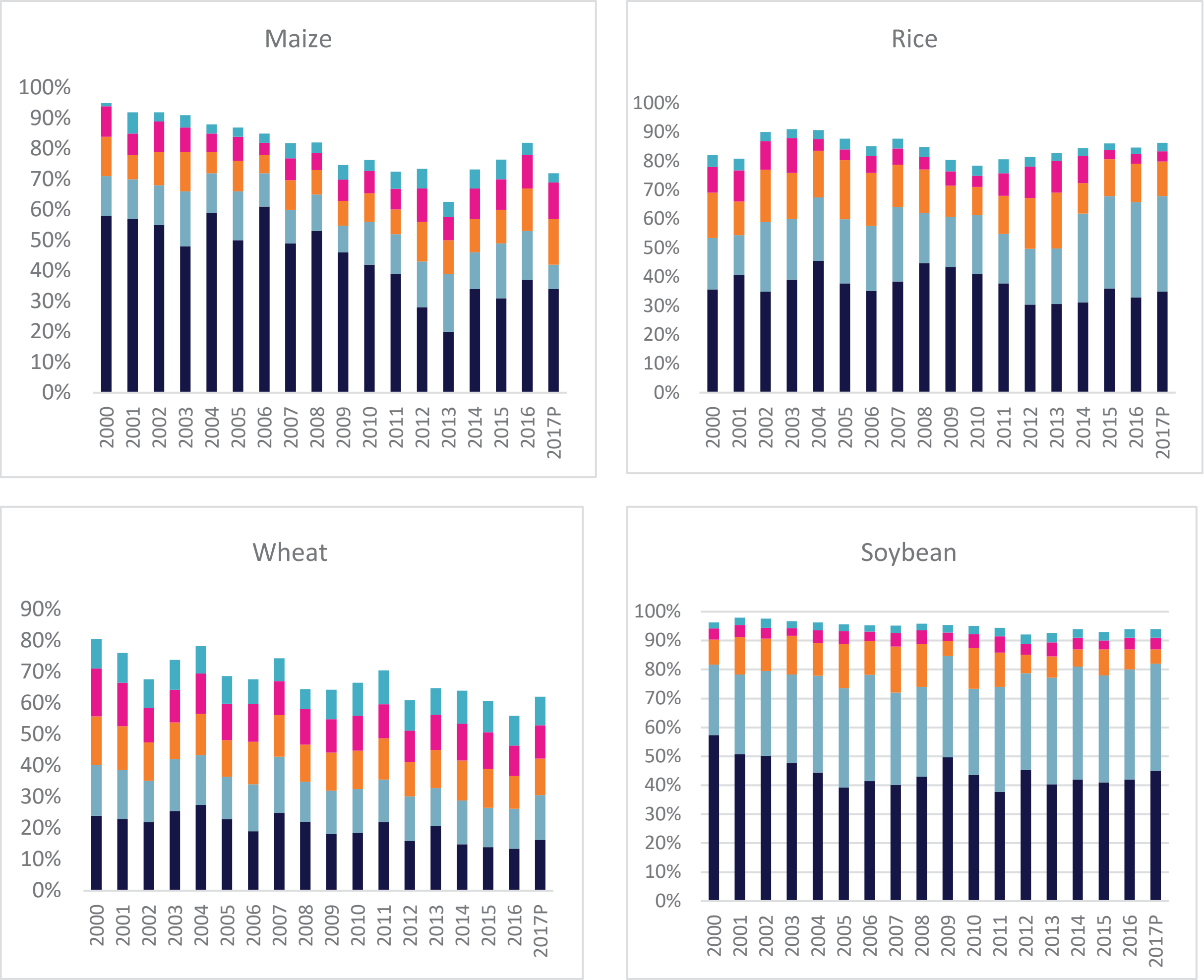
Figure 68: Share of production traded internationally for four key crops



Export concentration

A small number of countries dominate key crop exports. Greater concentration over time suggests higher exposure to production shocks in key exporter countries. Figure 69 shows that wheat and maize export markets have become slightly less concentrated over time, suggesting exposure to climate shocks in ‘breadbaskets’ has fallen slightly.

Figure 69: Share of top five exporters for four key crops



Source: FAOSTAT.

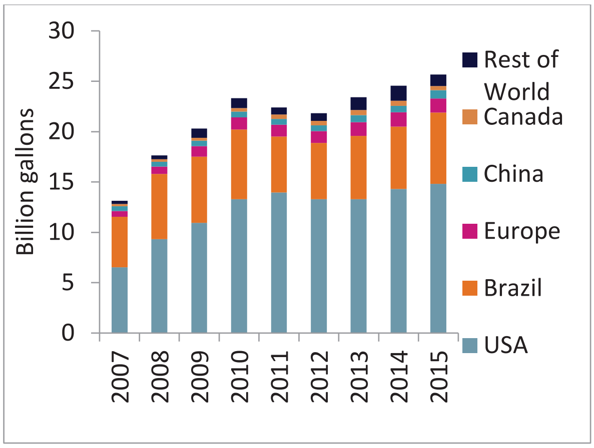
Vulnerability: grain diversions and stocks

Grain diversions

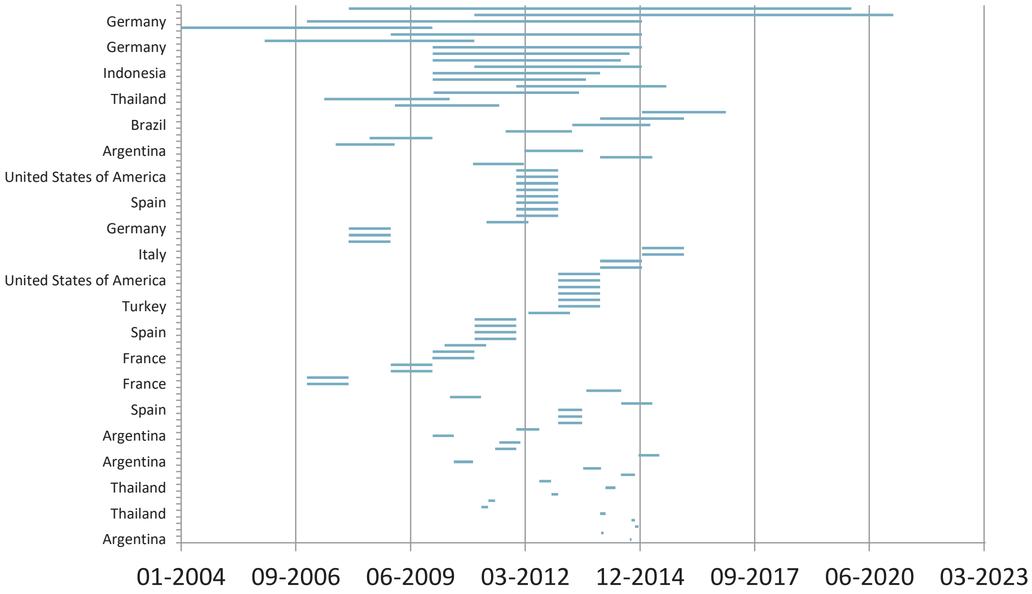
Grain diversions to biofuel production are linked to higher oil prices and government biofuel mandates; and in turn, along with diversions for animal feed, have a long-term upward impact on global food prices (Headey & Fan, 2008; Bertini et al., 2013; Konandreas, 2012). Growth in global ethanol production has slowed down, reducing the pressure on stocks. However, many countries continue to implement biofuel mandates, ensuring that a portion of harvests cannot be used flexibly to augment food supplies when they may be required (Figure 70).

Figure 70: a) Global ethanol production 2007–2015 and b) documented biofuel mandates

a)



b)



Source: a) FAOSTAT and Alternative Fuel Data Center[12]; b) Agricultural Market Information System (AMIS).[13]

Stocks

Stocks-to-use ratios for key staples have, in the main, been increasing since 2008. However, the stocks-to-use ratio for rice and coarse grains has levelled off over the past four years suggesting a system less able to buffer the impact of harvest shocks in key production areas (Figure 71).

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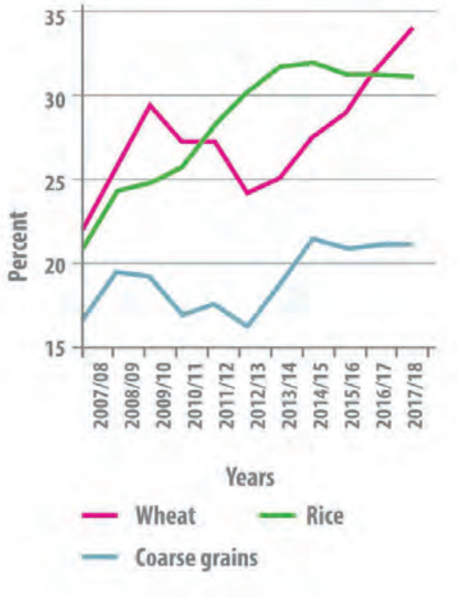
[12] www.afdc.energy.gov/data/

[13] http://statistics.amis-outlook.org/policy/queryAndDownload.html

Figure 71: World stocks-to-use ratios (%)



4.4.2.3 Hazard: international food price spike

Food price trends

Real food prices, though high compared with the 1990s, are comparable with 1960s prices, and have fallen from their localised peaks in 2008 and 2011. Real price spikes can be observed in 1974/75, 1980/81, 1995/96, 2008 and 2011.[14] Food price spikes, which have triggered systemic crises in 2007/08 and 2011/12, appear to follow periods of nominally gradually increasing prices (Figure 72). When observing real, deflated, food prices, this has also been the case for the three most recent price spikes.

Whereas monthly data highlight more extreme price spikes that are often the result of responses to perceived future food shortages, for example, hoarding, speculation, or the imposition of export bans (FAO, IFAD, IMF et al., 2011), annual prices, as presented here, highlight longer-term trends in prices. Since 2011, real and nominal food prices have been falling, suggesting a global food system less vulnerable to systemic crisis triggered by a poor harvest in an important exporter country (Figure 72).

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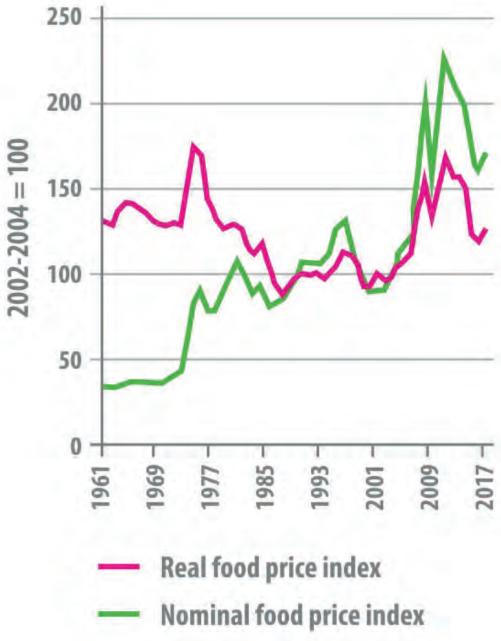
[14] FAO identifies price spikes in 1972–1974, 1988, 1995 and 2008, ftp://ftp.fao.org/docrep/fao/012/i0854e/i0854e01.pdf

Figure 72: Global food price index, 1961–2017



Source: FAOSTAT.

Food price volatility

In addition to absolute food price levels, the propensity for volatility is another key determinant of whether a food price crisis emerges in international markets. Indeed, it was concerns about food price volatility that motivated the decision of the G20 to establish the Agricultural Market Information System (AMIS). Both producers and consumers can be negatively affected by the uncertainties of volatility, as can countries reliant on the commodities affected. For consumers, it can result in consumption of less food or less nutritious foods; for producers risk management can be a problem given the uncertainties of future harvest prices at the point of production.

Measures of both backward- and forward-looking volatility can be instructive. Historical volatility can be useful for signalling recent periods of excessive price variability, and therefore determining appropriate responses, whereas forward-looking implied volatility (often referred to as a fear index) captures expectations of large market moves, typically over the following 30 days.

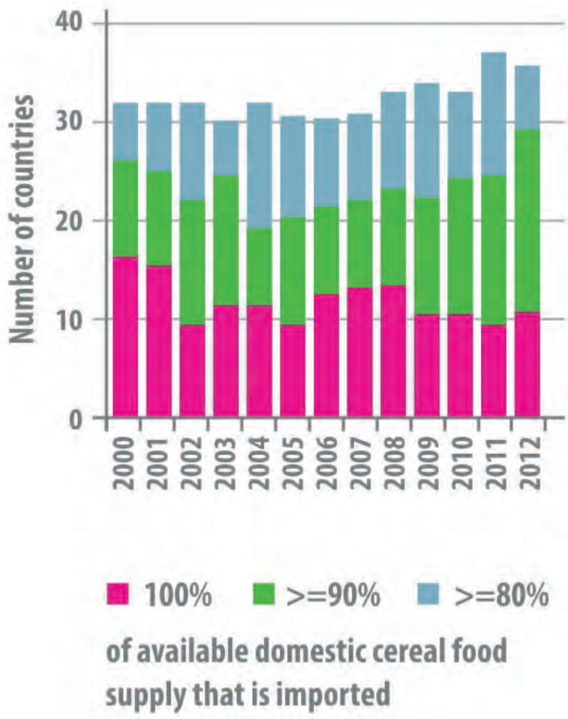
4.4.2.4 National food markets: indicators of exposure and vulnerability to international market hazards

Exposure: reserves and import dependency

Key measures of countries' exposure to perturbations in global food markets are the extent to which they depend on international imports, how sensitive domestic prices are to international prices, and whether the country has its own grain reserves (Ivanic et al., 2012). Countries that are particularly dependent on food imports have been found to be more vulnerable to systemic risk in the global food system (Ahmed et al., 2009; d'Amour et al., 2016). Food storage – strategic grain reserves – has been an important means of reducing exposure to import disruptions but became less popular as governments have been encouraged to rely more on the market and private-sector commodity chains to respond to rising prices (Fraser et al., 2015). In this proof of concept, we only track import dependency.

Countries' dependence on cereal imports relative to their own production[15] is part of the FAO suite of food insecurity indicators. The number of countries highly dependent on imports is increasing (Figure 73), suggesting increased exposure to systemic crises in the food sector, though possible reduced exposure to idiosyncratic domestic harvest shocks.

Figure 73: Countries highly dependent on cereal imports



Source: FAOSTAT.

A more sophisticated indicator would take account of both import dependency and grain reserves at a regional level. Strategic stock building can be expensive, particularly in countries with little comparative advantage in agriculture or where weak governance means stocks are likely to be mismanaged (Bailey & Wellesley, 2017). Yet for countries that consider themselves exposed because they rely heavily on imports, strategic reserves can potentially reduce vulnerability to unexpected import curtailments, and it may therefore make sense to develop strategic reserves.

Vulnerability: export restrictions

Export restrictions, implemented by individual countries in response to a trigger event, can collectively amplify the shock through rapidly increasing prices reflecting shortages of grains in the international markets. The imposition of export restrictions, as prices started to rise, amplified the 2007–2008 shocks, and are widely acknowledged to have contributed to price increases of key grains (Headey, 2011; Tangermann, 2011). Because countries cannot be forced not to impose export restrictions in response to shocks, 'second best' approaches are needed that include greater self-

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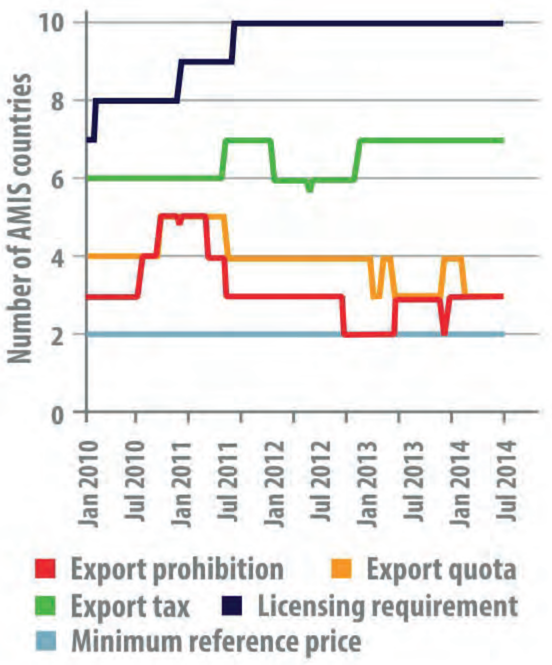
[15] (cereal imports − cereal exports)/(cereal production + cereal imports − cereal exports)

sufficiency, larger reserves, and bilateral or regional agreements (Headey, 2011). Greater transparency on the status of countries' export restrictions is also important. Identifying a trackable indicator that links to the number of countries likely to impose export restrictions after a food shock is tricky (Sharma, 2011; Howse & Josling, 2012). Nonetheless, historical data are useful both in indicating countries' propensities to impose restrictions and to monitor the ex-ante status of restrictions in the run-up to potential food crises. For these reasons we include the database of export restrictions among AMIS member countries, as maintained by AMIS (Figure 74). This differentiates the types of restriction and the durations for which they are imposed. The data suggest little change since 2011 in the number of countries imposing restrictions.

Figure 74: AMIS database of countries with export restrictions on wheat, maize, rice or soybeans



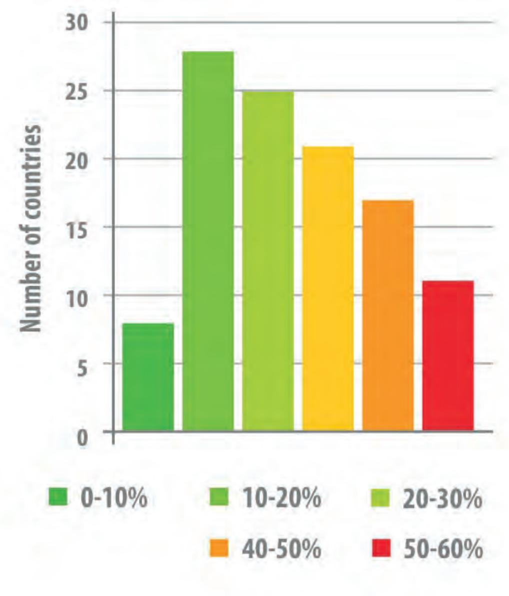
Source: AMIS.

4.4.2.5 National nutritional and non-food outcomes: indicators of exposure and vulnerability to national food price hazards

In the event that national food prices and market dynamics are not immune to the hazards and perturbations occurring outside national borders, then these supra-national dynamics may affect national prices (in the same way as described for international prices) and, in turn, may affect the populations and institutions within the country. Adverse nutritional, economic and political outcomes are all feasible.

Poor households that spend a large share of their income on food and have a high dependence on a few unvaried staple crops are particularly exposed to food price increases. Those who are already undernourished or who perceive that they are food insecure are among the most vulnerable to reductions in the quality and quantity of their diet. For this reason, we track the proportion of household expenditure spent on food consumption. Figure 75 illustrates the number of countries per decile of expenditure, using the latest available data, but for any given country or regional risk analysis, disaggregation by nation will be more informative. We additionally suggest utilising the FAO indicator 'share of dietary energy supply derived from cereals, roots and tubers'[16] on the same basis for additional context on dietary diversity within a country.

Figure 75: Household expenditure on food consumption, number of countries per decile



Source: Economist Intelligence Unit (2017) *Global Food Security Index.*

National governments can take a number of actions after a global price shock to reduce domestic food price volatility and the vulnerability of households, including subsidies, price controls, reduced taxes and safety net programmes such as cash transfers, food for work, and school feeding (Wodon & Zaman, 2009). However, in contexts where governments have weak capacity or are unstable, these measures are likely to be less feasible or effective, increasing exposure to price shocks – food protests have been found to be most violent in countries with low government effectiveness (von Braun, 2008). Further, the prevalence of undernourishment, poverty and food insecurity, and low socio-economic indicators in general, have been found to be key determinants of armed conflict (FAO, 2017).

We track a composite indicator, using FAOSTAT data for comparability, that addresses countries that score particularly poorly on one, two or all of the following indicators: under-nutrition, import dependency and political instability. Though the trend has been towards a larger proportion of countries scoring high across one of these dimensions, the number of countries scoring high across all three dimensions has fallen (Figure 76).

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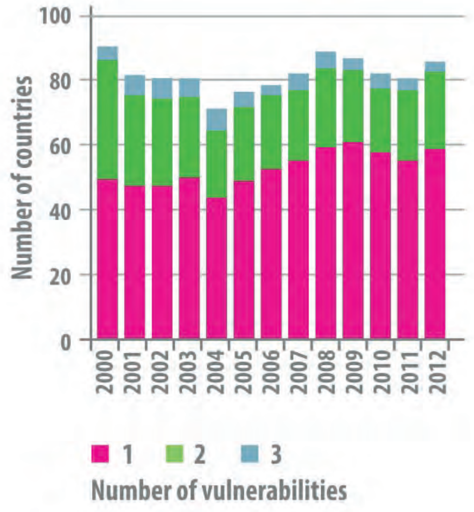
[16] http://www.fao.org/economic/ess/ess-fs/ess-fadata/

Figure 76: Number of countries vulnerable to one, two or three of the following: undernourishment, import dependency and/or political instability



Source: FAOSTAT.

Notes: Number of countries with complete data = 122; import dependency = 1 if 'cereal import dependency ratio' >50%; political instability = 1 if 'political instability and absence of violence' indicator ≥1; undernourishment = 1 if 'prevalence of undernourishment' indicator >20%.

4.5 Conclusions and key messages

Climate-related impacts will increasingly threaten the stability of complex human systems, particularly if these systems develop in ways that increase exposure to impacts (e.g. through the location of critical infrastructure) or vulnerability to disruption. Systemic crises triggered by climatic hazards are already occurring. They materialise when the direct impacts of the hazard – whether an acute shock or a gradual, creeping risk – are propagated and amplified through different components of complex socio-economic systems that are increasingly interconnected at national and global scales. The more complex and closely connected the system, the greater the potential impact of systemic risk. Systemic crises are difficult to predict, can manifest in a multitude of ways, and are typically costly, whether in economic, social, political or environmental terms.

In China, the implications of melting glaciers for flooding and water scarcity may increase the risks of poverty and migration in western regions and neighbouring countries, whilst the spread of vector-borne disease could trigger risk cascades that disrupt education systems and the tourism sector and create cross-border tensions.

Increasing direct risks to agricultural production in key export countries could have serious negative consequences for global food system stability and lead to significant wider risks to security where food insecure, fragile states are adversely affected. Recent bouts of volatility in international food markets have illustrated the vulnerability of the global food system to extreme weather and demonstrated how risk transmits across borders, potentially contributing to social instability. Other 'at risk' complex systems include finance, health and critical infrastructure.

Governments cannot assume that economic growth will simply reduce risk. It may reduce vulnerability in some instances (e.g. wealthier populations are less vulnerable to food price volatility) but may increase exposure in others (e.g. if populations and assets accumulate in risky areas, as is happening in the prosperous coastal cities of south-eastern China). Thus countries cannot necessarily 'buy their way out' of the risk of systemic crisis.

The climatic triggers of systemic risk are likely to become more frequent and more severe with climate change (see Chapter 3) and higher temperatures are more likely to result in highly non-linear system responses and tipping points being reached, resulting in irreversible changes that countries cannot adapt their way out of. Climate change mitigation is therefore critical in ameliorating these events (see Chapter 2). Mitigation efforts require global cooperation as the rewards of action do not accrue to nations proportionate to the contribution each country makes. Rather, mitigation represents a global public good, reducing atmospheric warming and thus the frequency and severity of climatic hazards globally.

Climate adaptation measures and actions to build resilience to each discrete hazard within a potential risk cascade are equally necessary in coping with systemic risks. The transboundary nature of indirect risks means that unilateral responses will be insufficient. Although the primary beneficiaries of adaptation actions are often the peoples and countries undertaking them, national adaptation strategies may be unable to fully address risks beyond borders. In some cases, unilateral responses to reduce exposure and vulnerability to systemic risks may inadvertently *increase* systemic risks if pursued in isolation or in a beggar-thy-neighbour fashion. In such instances there are also benefits to collective and coordinated responses across countries. For example, within the food system, effective actions might include individual country adaptations to climate-smart agricultural practices, commitments to improved nutritional outcomes, social protection mechanisms responsive to inflationary prices, and international cooperation and transparency to avoid food export bans and ensuring sufficient food stocks.

Whilst the scale and frequency of systemic risks may be increasing and are already influencing business and investment decisions, as yet the world has not experienced a systemic crisis on a truly massive scale. However, under a 4–5°C global temperature increase, non-linearities and tipping points could result in qualitatively new crises, resulting in permanent system changes that would provide new challenges to global cooperation, making new governance mechanisms necessary.

4.5.1 Implications for policymaking

4.5.1.1 Increased international commitment and cooperation on climate change mitigation are required

Systemic crises catalysed by climate change impose high costs across multiple countries that are not necessarily fully understood, yet at the national level the incentives to mitigate further temperature rises are low, compared with the incentives to adapt to climate change. Thus there is an increasing need for policymakers to identify areas where climate change mitigation activities have clear national co-benefits. For example, reducing point-source air pollution through reduced burning of fossil fuels will directly benefit the health of populations in proximal locations, whilst also contributing to limiting GHG emissions, reducing the likely geographical expansion of climate-sensitive diseases such as dengue (Watts et al., 2018).

The likelihood and costs of systemic risk tend to be understated. Greater and more immediate efforts are needed to more fully understand the nature of different climate-induced systemic risks (e.g. for financial markets, the global food system, health systems, critical infrastructure systems) and the costs of these risks for both higher- and lower-income countries. Factoring in better estimates of the probability and cost of systemic risk can help strengthen international climate change mitigation activities and drive cooperation to better manage systemic risk.

China has an opportunity to play a leadership role in this area, both through accelerated investment in decarbonising activities, technologies and infrastructure, and through conducting evidence-based assessments of national climate impacts, such as have been demonstrated here.

Given that poverty is a major contributory factor to many expressions of systemic vulnerability, there is also a need to strengthen cooperation on international poverty reduction within the UN Sustainable Development Goals framework, focusing both on improving climate adaptation and climate resilience capacity building – especially in high-risk, lower-income countries – and on ensuring poverty reduction strategies are supportive of climate mitigation actions. China is already playing a leading role through its South-South Climate Change Fund, assisting lower-income countries in addressing climate change challenges through South-South cooperation within the 2030 Agenda framework. Such efforts serve as an example for broader international cooperation and investment to align development objectives, mitigation activities and long-term climate resilience.

4.5.1.2 New governance arrangements are needed to manage systemic risks

Overcoming the particular challenges of coordination and extra-territoriality inherent in systemic risk management will require new governance approaches at international, regional and national levels that are tailored to the particular systems in question. Given the long lead times involved in building new institutions and developing existing ones, efforts should begin immediately to develop risk management frameworks and identify data requirements for collective risk monitoring. As demonstrated by the global food system, risk management practices at multiple nodes within a plausible risk cascade can be beneficial even in the absence of increasing extreme climatic impacts.

4.5.1.3 China-specific actions are required to manage domestic systemic risks

Within China, actions are required to reduce the likelihood of systemic crises stemming from both long-term insidious climate hazards and from acute climate shocks. These include:

Actions to reduce systemic risks from insidious climatic hazards

- Enhance the awareness among national policymakers and society at large of climate security risks, and incorporate climate security objectives into national security strategies. Integrate climate risk management strategies with national governance arrangements across all sectors and build institutional capacity around this.
- On the basis of the precautionary principle, fully consider climate risks within all planning frameworks; particularly, introduce climate security planning into national medium-term and long-term strategic planning, national economic and social development planning, urban master planning, land use planning and functional area planning.
- Clarify the various climate risk functions of newly established ministries of the People's Republic of China (including the Ministry of Ecology and Environment, Ministry of Natural Resources, Ministry of Emergency Management, and the National Health Commission). Ensure that these new institutions have the requisite capacity to respond to climate risks.
- Ensure that national poverty alleviation efforts, especially in areas of entrenched poverty, clearly introduce climate risk prevention measures and systems within their operations.

Actions to reduce systemic risks from acute climate shocks

- Explicitly target low-carbon development, climate adaptation and climate resilience in urbanisation and urban-agglomeration plans to prevent climate risks from spreading and triggering systemic crises.
- Strengthen the risk management systems of multi-level emergency response mechanisms, to include monitoring (including health risk surveillance), early warning and emergency response systems to better prevent the spread of risks; ensure such systems are comprehensive and are fully coordinated, with the government leading the relevant organisations to formulate comprehensive response plans.

4.5.2 Implications for risk assessment and monitoring

Systemic risk indicators can be updated using publicly available data from relevant sources (as demonstrated for global food system risk in this chapter). At any point, comparing the current indicator to historical averages or past extremes may provide information on the stability or fragility of the system of concern. Over time, the trends in these indicators will provide some insight into whether the system is moving towards greater stability (or resilience) or towards instability and/or fragility. This should help decision-makers judge the need for systemic reforms and other measures to manage risk and avoid system failures.

Given the urgent need to build greater resilience to climate change and other hazards within system risk cascades, we suggest that organisations with a responsibility for assessing any of the relevant risks should consider how to update their assessments on a regular and consistent basis, allowing for comparability across time, and giving decision-makers the benefits of the insights described above. In particular, organisations with expertise and responsibilities pertaining to the systemic risks discussed here are well placed to contribute to the development of this proof of concept of risk indicators into a full risk monitoring framework. For systemic risks these organisations include:

- The FAO and AMIS for data related to indicators of food system risk; the FAO for data related to agricultural and land use emissions risk.
- The Bank of International Settlements for data related to financial system risk.
- WHO for data related to health systems risk.
- The World Bank and other multilateral development banks for data related to critical infrastructure risk.

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Chapter 5: Conclusions and recommendations

Below we summarise the results of the three preceding chapters and explore some of the implications for decision-makers and risk assessment and monitoring.

5.1 Emissions risk

We have developed a framework for monitoring emissions risk at the global level, using three tiers of increasingly granular indicators. As an initial proof of concept, this was applied to carbon dioxide emissions in the energy sector, but it could in principle be expanded for non-CO_2 greenhouse gases (GHGs) and adapted for the agriculture and land-use sector. The framework consists of three tiers:

- Tier 1: two 'macro' indicators to track the energy intensity of economic activity and emissions intensity of energy consumption.
- Tier 2: seven energy-sector-wide indicators to track the energy mix across primary energy production, final energy consumption and power generation.
- Tier 3: twelve policy-relevant, sub-sectoral indicators to track progress in decarbonising the energy sector.

The results of this exercise indicate that if progress in emissions reduction and technology deployment continue in line with historical trends, energy-sector CO_2 emissions will continue to rise slowly to 2030 and then remain around 35 Gt (3 Gt higher than today). This is not consistent with the Paris goal of limiting temperature increase to well below 2°C, which requires global emissions to peak and decline well before 2030. This trend is consistent with a median temperature rise in 2100 of around 2.7°C (with a 10–90% range of 2.1–3.5°C), with less than a 5% chance that it will be below 2°C and around a 25% chance that it will exceed 3°C.

In the case that emissions policymaking stalls at current levels, rather than continuing to tighten in line with historical trends, this would place the world on a high emissions pathway consistent with temperature increases approaching those projected under Representative Concentration Pathway (RCP) 8.5 (used as the high emissions scenario in Chapter 3).

Since 2000, the amount of energy consumed per unit of GDP has fallen by around 1% each year; this needs to accelerate to over 2.5% per year to achieve Paris Agreement temperature objectives. The level of CO_2 emissions per unit of energy consumed also needs to fall in parallel, by around 2% per year in 2020 and over 4% per year after 2030; yet, despite recent policy efforts, this has risen marginally since 2000. The pace of transition to achieve a high-efficiency, low-carbon energy system therefore needs to accelerate rapidly.

At the sub-sectoral level, only one of the 12 selected indicators (mature renewables) is on track with the pace required to achieve the 2°C goal; no others are progressing at the necessary rate. Five indicators (passenger transport, the emission intensity of fuels consumed in the industry sector, efficiency in residential and service buildings, and the deployment of nuclear capacity) have shown some recent improvements but require much greater policy efforts. And six are significantly off track and require urgent policy attention. These are carbon capture and storage, freight transport, levels of advanced biofuel produced and consumed, efficiency improvements and the share of zero carbon fuels in industry, and the level of zero carbon fuels consumed in buildings.

As well as providing a proof of concept of a framework for the regular monitoring of emissions risk, these results provide valuable information for policymakers about the scale of additional emissions reductions that must be made from the energy sector, and the areas where policy attention is most needed. This therefore has obvious utility for the upcoming global stocktake and facilitative dialogue at the United Nations Framework Convention on Climate Change (UNFCCC), as governments prepare to assess recent progress and enter into discussions about revising their nationally determined contributions (NDCs).

5.2 Direct impact risk

As a proof of concept, we have examined the potential direct impacts of climate change on heat extremes, water resources, river and coastal flooding, and agriculture. We have also demonstrated how the approach can be applied at both global and national scales using consistent scenarios describing low and high rates of future emissions. Plausible worst case impacts were defined in terms of the 90% confidence interval under the high emissions scenario.

As shown in Chapter 2, should mitigation action stall at the level of current policies, the world would find itself on an emissions pathway broadly similar to RCP8.5. Under this high emissions scenario, the central estimates for the increase in global average temperature and global mean sea level by 2100 are approximately 5°C and 80cm respectively. However, the increases could plausibly be higher than this: plausible 'worst case' increases in temperature and sea level could be 7°C and 100cm.

At the global scale, plausible 'worst case' impacts on a high emissions pathway are extremely challenging. At least one heatwave could occur in all years (compared with around 5% now). The global average frequency of hydrological droughts doubles, and the chance of experiencing an agricultural drought increases by a factor of nearly ten. River flood frequency increases by a factor of up to ten, and the area along the coast exposed to a 100-year flood increases by 50%. High temperatures which threaten maize production would occur in around 80% of years (compared with 4% at present), and in more than 90% of years the time taken for maize to mature would reduce sufficiently to impact significantly upon productivity. Human impacts – on people exposed to heatwaves, droughts and floods – depend on the socio-economic scenario, and under high population scenarios the increase in impact compared to the present day could be extremely large.

At the Chinese scale, the number of heatwaves may increase by a factor of four by the end of the 21st century. Glacier mass may reduce by almost 70%, affecting water resource availability in water-stressed parts of western China. Increases in rainfall across China as a whole suggest that total national runoff is likely to increase (although a decrease is plausible), but there are big variations across China. The average annual area of cropland exposed to drought could plausibly increase by a factor of more than 2.5. Rice production may be significantly impacted by increases in the likelihood of heat damage – which may occur in 80% of years (compared with 20% at present), implying up to a 20% loss in Chinese food production. By 2050, over 100 million people could be exposed to coastal flooding risk.

5.3 Systemic risk

Recognising that the range of possible disruptions to complex, interconnected systems is almost infinite and impossible to model, we have developed a narrative approach to characterise a systemic disruption as a sequence of cascading indirect impacts initially triggered by a (direct) climate impact. Indicators of exposure and vulnerability at critical transmission points within the system pinpoint particular areas of concern and in aggregate paint a picture of overall system fragility. These indicators also provide a basis for monitoring the evolution of systemic risk over time.

At the global level, proof of concept was provided for the global food system. At the national level, proof of concept was provided by quantitative analyses of first-order indirect risks to local communities and economies resulting from direct climate impacts. These could, in turn, plausibly lead to higher order indirect impacts, such as urban insecurity, higher poverty and internal migration.

These approaches can be applied to other complex systems at international, regional and national scales, including finance, health and critical infrastructure.

Recent bouts of instability in the global food system, such as the 2008 global food price crisis and the 2011 wheat price spike, demonstrate how systemic risk cascades can have severe consequences for populations and economies. Long-term trends such as increasing connectivity of markets, technology and infrastructure and increasing exposure of populations and assets due to underlying demographic and development trends, mean that many systemic risks are likely to increase. Climate change will compound this by increasing the frequency and severity of climate impact trigger events – such as agricultural droughts in the food system, for example. It may also act to increase the fragility of the system, for example in the case of the food system, by reducing long-run yield growth or undermining economic growth in vulnerable food-importing countries.

By their nature, systemic risks are difficult to anticipate and manage. Avoiding a high emissions pathway will reduce but not eliminate risks – extreme weather is already increasing systemic risks, as recent experience with the food system demonstrates. Nor will economic growth necessarily reduce systemic risks. It may help to reduce vulnerability in some instances (for example, wealthier populations are less vulnerable to food price volatility) but may increase exposure in others (for example if population and critical infrastructure accumulate in risky areas, as is happening in China's three major city clusters, and as was witnessed when Hurricane Katrina struck the Gulf Coast of the United States). Moreover, the transboundary nature of indirect systemic risks means that unilateral responses will be insufficient. National adaptation strategies may be unable to fully address risks beyond borders and in some cases, unilateral responses to reduce exposure and vulnerability to systemic risks may inadvertently *increase* systemic risks if pursued in isolation or in a beggar-thy-neighbour fashion. As systems become more complex and interconnected in the future, cooperation between states and new governance arrangements will be needed to manage transboundary risks.

5.4 Implications for decision-makers

Based on current climate science, this collaborative research endeavour has assessed, and developed indicators for, three categories of climate risk: the future pathway of global energy-sector emissions; the direct risks arising from the climate's response to those emissions; and the risks to complex human systems. The findings regarding these risks have a number of important global implications for decision-makers in government, international organisations and the private sector.

5.4.1 Climate change risks need to be addressed with greater importance by all countries

As unconventional security risks, direct and systemic climate change impacts should be included in national and global security risk assessments. Addressing climatic change impacts and implementing low carbon development should be regarded as significant parts of a strategy for economic and social development. The push for low carbon economies needs to be approached with greater determination and political courage.

5.4.2 Emissions reduction efforts must accelerate if a low emissions pathway is to be achieved and a high emissions pathway avoided

Energy-sector decarbonisation is not progressing at the pace required and a step change in ambition is necessary. Continued policy efforts and technological development in line with historical precedent would still be insufficient to limit temperature increases to well below 2°C by the end of the century. Any stagnation or backsliding of policy risks migration onto a high emissions pathway more consistent with RCP8.5 (median 5°C temperature increase by 2100). The upcoming facilitative dialogue and deadline for governments to resubmit their NDCs presents a critical opportunity for collective action to manage global emissions risk.

5.4.3 Future risks cannot be eliminated and will increase in both low and high emissions scenarios

Decision-makers must prepare for a future of increasing direct and systemic risks in all emissions scenarios. Increasing exposure of human populations and assets to direct and indirect impacts is likely to be an important driver of direct and systemic risks. Increasing frequency and severity of direct impacts at the global scale will increase the risk of trigger events for systemic disruptions. Increasing complexity, due to more extensive global supply chains and increasingly interconnected technologies and systems, for example, is likely to exacerbate systemic risks.

5.4.4 New governance arrangements are needed to manage systemic risks

Overcoming the particular challenges of coordination and extra-territoriality inherent in systemic risk management will require new governance approaches at international, regional and national levels and tailoring to the particular systems in question. As national and international security concerns arise from many systemic climate risks, these concerns and existing security-sector organisations should both be factored into future governance arrangements. Given the long lead times involved in building new institutions and developing existing ones, efforts should begin immediately to understand more fully the nature of different climate-induced systemic risks (e.g. for financial markets, the global food system, health systems, critical infrastructure systems, etc.) and develop risk management frameworks and identify data requirements for collective risk monitoring.

5.4.5 The omission of tipping points from this analysis means that worst case impacts may be underestimated

The chance of passing climate system tipping points during the course of this century is thought to increase with temperature rise. Therefore, on a high emissions pathway there is a significant risk of critical thresholds being exceeded, particularly with a plausible worst case temperature rise of 7°C by the end of the century. There is also a non-trivial risk of tipping points on lower emissions pathways, as argued in a recent paper (Steffen et al, 2018). Certain thresholds may be reached at lower levels of temperature increase – possibly around 2°C – and trigger a cascade of tipping elements that could accelerate climate change and generate catastrophic direct and indirect impacts. For example, accelerated melting of the Greenland ice sheet could lead to more rapid sea level rise and slow the Atlantic over-turning circulation with profound implications for weather patterns, and also contribute to melting of Antarctic ice. Consequences of these changes could include dieback of the Amazon rainforest, leading to higher levels of atmospheric carbon, and a catastrophic drop in agricultural output.

5.4.6 Decisions-making should take a long-term perspective on future climate risks

The outlook for direct and systemic risks has implications for decisions with long-run outcomes and investments with long lifetimes. For example, infrastructure built today might still be operational by the end of the century when risks will be considerably more severe; the effectiveness of long-term carbon sequestration by reforestation or afforestation will depend on future climate change in the areas concerned. It is therefore important that decision-makers consider the full range of future climate risks over the coming century, including the possibility of a high emissions pathway and the associated plausible worst case outcomes for direct and systemic risks, to ensure that their decisions are resilient to climate change in the long-run.

5.4.7 Integrating analyses of climate risk and resilience into decision-making can have wider economic benefits

Economies with resilient infrastructure and strong risk management practices are likely to enjoy lower costs of capital and attract higher rates of investment, all other things being equal. Nonetheless the primary financial incentives for investing in resilience are avoiding future costs and protecting cash flows in the wake of a shock. As such, short-term interest in financial rewards can result in inefficient capital allocations to resilient infrastructure, and real demand for such investments is hampered. For example, governments are discouraged by additional upfront capital costs and political opportunity costs; investors lack relevant benchmarks and tools to guide their capital allocations; and multilateral development banks struggle to assess and report the resiliency of their operations. It is therefore paramount that investment appraisal methods provide better pricings of physical climate risks so net present values reflect improvements in resilience; that capital market instruments are devised to direct capital to resilient infrastructure projects by integrating insurance risks; and that credit rating methodologies are adjusted to improve their assessments of resilience and provide resilient projects with improved capital costs.

5.4.8 The prospects of future climate resilience are improved by accelerating current mitigation efforts

Whilst future risks cannot be eliminated, the best prospects for minimising climate hazards and avoiding reaching adaptation limits are offered by expediting and increasing the ambition of current mitigation actions. Delays in action will constrain future development options, whilst ambitious economic, social, technological and political transformations enacted now may maximise the prospects of resiliency to future climatic risks.

5.5 Implications for risk assessment and monitoring

A key conclusion of this project is that a common framework for the regular and consistent assessment and monitoring of climate risk is a feasible proposition.

The 2015 report, *Climate Change: A Risk Assessment* (King et al., 2015), demonstrated how the general principles of risk assessment could be applied in relation to climate change. These include assessing risks in relation to objectives; identifying the largest risks; considering the full range of probabilities; using the best available information; taking a holistic view; and being explicit about value judgments.

In this new project, we have demonstrated proof of concept of a framework for the regular and consistent assessment and monitoring of emissions risk, direct impact risks and systemic risks, based on a set of indicators. The methodologies developed here can certainly be further refined and improved, but they are tractable and generate results that can inform decision-making. They are based on data that can be readily and regularly compiled.

Emissions risk indicators can be updated on a consistent basis using information from the International Energy Agency (IEA) database. Regular updating of these indicators (e.g. on an annual basis) will show whether the rates of deployment of clean technologies are converging towards the trends required for consistency with the ‘well below 2°C’ goal, or diverging further from them.

Over a longer time period, the mixture of technologies assumed in the 2°C consistent scenario is itself likely to change, and this will in turn influence the indicators. The effect of any changes in assumptions should be reported explicitly, and the trend of such changes monitored over time, as this will give decision-makers useful information on the direction of change in expert judgment on the relative importance of different clean energy technologies.

Direct impact risk indicators can be updated to reflect material changes in scientific knowledge and expert judgment regarding climate sensitivity and the relationships between general climate variables (such as temperature or sea level rise) and the probability of specific impacts and extreme events. Such material changes may not be frequent, but over a long time period the trend in these indicators will provide decision-makers with useful information on which to judge whether the scientific community has tended to underestimate or overestimate the risks. In each case, it will be important to provide analysis of the reasons for any change in indicators, so as to distinguish between the effects of, for example, changes in the real world and changes in modelling assumptions.

In addition, direct impact risk indicators can be updated to reflect changes in the exposure and vulnerability of human populations. Over time, these trends will show whether adaptation challenges are increasing or decreasing, which may inform development priorities and investment decisions.

Systemic risk indicators can be updated using publicly available data from relevant sources. For example, official statistics from the Food and Agriculture Organization of the United Nations (FAO) and the Agricultural Market Information System (AMIS) were used to develop indicators of global food system risk. At any point, comparing the current indicator to historical averages or past extremes may provide information on the stability or fragility of the system of concern. Over time, the trends in these indicators will provide some insight into whether the system is moving towards greater stability (or resilience) or towards instability and/or fragility. This should help decision-makers judge the need for systemic reforms and other measures to manage risk and avoid system failures.

Given the urgent need to accelerate the pace of emissions reduction, as well as the pressing need to build greater resilience to climate change, we suggest that organisations with a responsibility for assessing any of the risks of climate change should consider how to update their assessments on a regular and consistent basis, allowing for comparability across time, and giving decision-makers the benefits of the insights described above.

In particular, organisations with expertise and responsibility that mean they are well placed to contribute to the development of this proof of concept of risk indicators into a full risk monitoring framework include:

- The IEA for data related to energy emissions risk.
- The IPCC for data and expert judgments related to direct impact risks.
- The FAO and AMIS for data related to indicators of food system risk; the FAO for data related to agricultural and land use emissions risk.
- The Bank of International Settlements for data related to financial system risk.
- WHO for data related to health systems risk.
- The World Bank and other multilateral development banks for data related to critical infrastructure risk.

Since all governments would benefit from a holistic view of the risks of climate change and of the trends in relevant risk indicators, it could be valuable for one international body to take the lead in compiling indicators from different sources (such as the organisations listed above) into a single set. The UN Secretary-General's office for example, could be a candidate for overseeing this process, given its position at the apex of the UN system and its links to the UN General Assembly and Security Council.

This would facilitate the use of the indicators to inform other relevant processes, such as updates of national risk registers, the regular international stocktake of progress towards global emissions reduction targets and the five-yearly submission of increasingly ambitious NDCs at the UNFCCC.

5.6 Final thoughts

We have used climate models and publicly available data to assess the risks presented by climate change according to the three areas originally identified in *Climate Change: A Risk Assessment.* We have found that these risks are serious and will increasingly threaten national and international security. On a high emissions pathway, the risks of direct and systemic impacts are particularly severe, especially under plausible worst case outcomes, with potentially profound consequences for human populations.

As such, more concerted action at national and international levels to manage these risks is required. This is urgent. The scale of future risks depends on the ambition of actions – to reduce emissions and build resilience – taken today. We cannot assume that we will simply be able to adapt to climate change. There will be limits to what we can adapt to, and these will be more extreme with higher temperature increases.

There is much that needs to happen. The energy transition must be accelerated with policies to increase the consumption of low- and zero carbon energy, speed the development and deployment of energy storage technologies and improve energy efficiency. Greater efforts in research, development and demonstration of new technologies are needed to drive decarbonisation in challenging sectors such as heavy industry and transport. In the land-use sector, restoration of forests and wetlands can increase carbon sinks whilst parallel efforts are needed to reduce GHG emissions from farming. Ultimately, climate change should be mainstreamed into all aspects of development and economic planning. At the political level, governments should implement the Paris Agreement and increase the ambition of NDCs to ensure that global GHG emissions peak as soon as possible and that the Agreement's goals remain within reach.

But this will not be enough to avoid all climate risks. This analysis has shown how, even on a Paris-compliant 'well below 2°C' pathway, climate change will present increasingly serious direct and systemic risks, particularly in a worst case outcome. Efforts are therefore also required to enhance adaptation and build resilience at national, regional and international levels.

Increasingly societies are growing to realise that investing in emissions reduction and climate resilience is not a burden, but an opportunity. It creates new industries, new business opportunities, new employment opportunities and can bring numerous co-benefits including cleaner air and water, improved health and enhanced security.

We are fortunate. There is still time to avoid the worst risks and reap the benefits of doing so.

References

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Annex 1: Global-scale climate risk indicators

1.1 Overall methodology

Direct risks at the global scale are represented by indicators characterising the consequences of climate change for heat extremes, water resources, river flooding, coastal flooding and agriculture. In each case, indicators are defined characterising change in both the physical hazard and the potential impact: impact is a function of both hazard and exposure. The change in physical hazard is dependent on change in climate, and the change in exposure varies between socio-economic scenarios.

The coastal flooding indicators are calculated from sea level rise projections using a coastal flood model, as outlined below (Section 1.2.5). The other indicators depend on the spatial pattern of change in climate (primarily temperature and precipitation) associated with a given increase in global mean temperature. One way of estimating these impacts is to run impact models with the output from the global climate models used to project the patterns of change in climate associated with a given emissions scenario. This involves correcting climate model output for bias, and a range of approaches are available. The Chinese-scale analysis (Annex 2) uses this approach.

The global-scale analysis adopts a different approach. It uses *damage functions* which show the relationship between increase in global average temperature and impact, and combines these with estimates of the range in increase in global average temperature in a year under a given emissions scenario to produce probability distributions of impact in each year. These distributions of impact therefore incorporate the effect of (i) uncertainty in the increase in temperature in a year for an emissions scenario and (ii) uncertainty in the spatial variability in change in climate associated with a given change in temperature. The uncertainty in the increase in temperature is estimated by using a probabilistic energy balance model to estimate the temperature response to an emissions scenario, reflecting uncertainty in key model parameters (particularly climate sensitivity). The uncertainty in the spatial variability of change in climate is represented by using several damage functions, each corresponding to a different plausible pattern of change as estimated by a global climate model. As outlined below, the damage functions are constructed empirically from scenarios derived from climate model output. This two-stage approach is used for two reasons. First, it allows the estimation of impacts under any emissions scenario and set of projected temperature increases – not just the emissions scenarios that were used to run the climate models used to construct the climate scenarios. Second, it takes into account uncertainty in both the overall magnitude of change in climate and its distribution over space: using just climate model output (where one pattern of change is associated with one estimate of the magnitude of change) potentially underestimates the range in impacts.

1.2 Risk indicators

1.2.1 Introduction: climate, sea level and socio-economic data

With the exception of the coastal indicators, the damage functions relating impact and risk to change in global mean surface temperature are constructed from 21 CMIP5 climate models (Taylor et al., 2012). These are the climate models assessed in the IPCC's Fifth Assessment Report (IPCC, 2013). For each of the 21 models, scaled patterns are available defining the spatial variability (at a spatial resolution of 0.5 × 0.5°) in change in mean monthly temperature, precipitation, relative humidity, net radiation and number of wet days per month, together with change in the year-to-year variability in monthly precipitation (Osborn et al., 2016). These patterns are then rescaled to correspond to a specific increase in global mean temperature (e.g. 2°C), and the changes are applied to the CRU TS4 1961–1990 observed climatology (Harris et al., 2014) to construct perturbed 30-year time series of monthly average weather climate in each 0.5 × 0.5° grid cell. Each of the 21 patterns is assumed to be equally plausible. Impacts and risks are calculated for each pattern and global mean temperature increase using spatial impact models, as outlined below.

Again with the exception of the coastal indicators, estimates of actual hazard occurrence up to 2016 are made by running the impact models with the CRU TS4 climatology time series from 1940 to 2016. Note that the projected future impacts are not influenced by the modelled time series of impacts to 2016.

Sea level rise scenarios were constructed from the projected temperature changes using an empirical relationship between accumulated temperature increase and sea level rise. This relationship is determined simply from temperature and sea level rise projections presented in the supplementary material to the sea level rise chapter in the IPCC Fifth Assessment Report (Church et al., 2013). For each emissions scenario, a central estimate of sea level rise is calculated from the time series of the median increase in temperature, and low and high sea level scenarios are calculated from the time series of the 10th and 90th percentile temperature changes.

For the agricultural indicators, it is assumed that the area of cropland and maize cropland remain constant through the 21st century. For the other indicators, exposure – in terms of numbers of people and gross domestic product (GDP) – is assumed to vary by socio-economic scenario. This assessment uses five Shared Socio-economic Pathways (SSPs; O'Neill et al., 2017), which are based on five different narrative storylines for the future development of societies, economies and governance. They are plausible projections, rather than predictions. National population projections, by age, for each SSP are described by KC & Lutz (2017), and this analysis uses the population projections downscaled to the 0.5 × 0.5° resolution by Jones & O'Neill (2016). The five SSPs differ in their assumptions about fertility and mortality, rates of urbanisation and international migration.

1.2.2 Heat extremes

There are many potential impacts of climate change through changes to the occurrence of hot and cold extremes. This report focuses on high temperatures, looking at a generic index related to health and at an index of the ability to sustain work.

High temperatures have a range of direct and indirect impacts on human health, and different aspects of temperature are relevant in different contexts. Some aspects of health are affected by high minimum (night-time) temperatures, whilst others are more affected by high maximum temperatures. The duration of ‘hot’ spells may be important, and for some health impacts humidity is also relevant. The critical temperature thresholds also vary for different health impacts. This report focuses on one heatwave indicator, and recognises that other indicators are available. The hazard indicator used is the annual likelihood of experiencing at least one heatwave, where a heatwave is defined as a period of four or more days with maximum daily temperature more than the 99th percentile maximum daily temperature calculated over the three-month warm season during the 1961–1990 reference period. The concentration on the warm season eliminates the apparent occurrence of ‘heatwaves’ in the cold season. The indicator is similar in principle to that used in the Lancet Countdown (Watts et al., 2017), although that uses a different reference period. Exposure is characterised by the number of people aged over 65, and potential impact is the average annual number of people over 65 experiencing at least one heatwave. Note that with large increases in temperature, many areas begin to experience more than one heatwave per year.

The capacity for physical labour is affected by temperature and humidity, and is typically assessed using the wet bulb globe temperature (WBGT). The hazard indicator is the average annual number of days that the WBGT exceeds 32°C, a widely used threshold of discomfort. Exposure is here represented by the number of people between 20 and 65 (an approximation to working age), and potential impact is characterised by the average annual proportion of working age people exposed to a period where it is impractical to undertake outdoor work. This is defined as a spell of at least 30 days with a WBGT greater than 36°C (Kjellstrom et al., 2015). In practice, only a relatively small proportion of working age people – those working outdoors – would be affected by climatic conditions, and this will vary between countries.

Each of these indicators is constructed from daily temperatures. The input climate data are provided at a monthly time step, and variability from day to day is added in a two-step process. First, the monthly input data are smoothed to produce what is effectively a daily time series of 31-day running means. Second, a time series of daily anomalies is added to this smooth running mean. The anomaly time series are calculated from the WATCH daily 1961–1990 time series (Weedon et al., 2011), and it is assumed that both the temporal sequencing of the anomalies and their magnitudes remain constant as climate changes (in other words, it is assumed that climate change does not alter the day-to-day variability in temperature around a running mean).

1.2.3 Water resources risks

There are two basic dimensions to water resources stress. One is the periodic occurrence of droughts, which has an indirect consequence for human wellbeing, industrial production and agricultural production. Droughts can occur in areas that normally have adequate water supplies. The second dimension is a more pervasive or persistent lack of water, even in ‘normal’ years, which challenges communities and limits agricultural or industrial development. This persistent lack of water can be managed through the development of a water supply infrastructure.

The risk of periodic water shortage is characterised by the frequency of occurrence of hydrological droughts. A hydrological drought is based on accumulated river flows. Here, flows are accumulated over 12 months and the standardised runoff index (SRI; Shukla & Wood, 2008) is calculated. A drought is defined as an accumulated runoff which has an SRI of less than −1.5 over a baseline reference climate period (1961–1990), which occurs approximately 6.5% of the time. A ‘significant’ drought is here defined as a period of at least six months with an SRI of less than −1.5, and the hazard indicator is the annual likelihood of experiencing a 'significant' drought. Exposure to drought is represented by the number of people living in 0.5 × 0.5° grid cells. Potential impact is characterised as the average annual number of people affected by 'significant' droughts. Note that the hazard and impact indicators are calculated even in areas with an abundance of water resources.

Persistent water shortage is represented by the water available in water-stressed watersheds. The indicator of physical hazard used here is the proportion of land with a 'significant' reduction in runoff, where 'significant' is defined as more than twice the standard deviation of 30-year mean runoff (which typically varies between 5 and 15%). Exposure to persistent water shortage is characterised by numbers of people, and potential impacts of climate change are represented by changes in the number of people living in water-stressed watersheds (with a runoff of less than 500m^3/capita/year; Gosling & Arnell, 2016).

The water resources indicators are based on river flows simulated using the global hydrological model MacPDM.09 (Gosling & Arnell, 2010; Arnell & Gosling, 2016). This simulates runoff on a daily resolution on a 0.5 × 0.5° grid. In the model, potential evaporation is estimated using the Penman–Monteith formula and snowfall and snowmelt are represented. The model performs similarly to other global-scale hydrological models (demonstrated in an intercomparison exercise; Haddeland et al., 2011), and in common with other global models tends to overestimate runoff in dry environments. This is primarily because the model does not incorporate the infiltration and subsequent evaporation of runoff (for example through transmission loss along river channels).

1.2.4 River flooding

This assessment distinguishes between risks from river flooding and risks from coastal floods. It does not consider floods caused by short-duration intense rainfall (pluvial flooding), for example in urban areas.

River flood hazard is characterised by the frequency of floods greater than the reference period (1961–1990) 50-year return period flood. Flood frequencies are estimated from river flows simulated by the global hydrological model MacPDM.09, at a spatial resolution of 0.5 × 0.5° (Arnell & Gosling, 2016). Exposure is defined as the number of people living in major floodplains (taken from the UNEP PREVIEW floodplain data base), and potential impact is calculated as the average annual number of people exposed to floods greater than the reference period 50-year flood. This is not the same as the number of people actually flooded, primarily because it does not take into account the extent of flood protection.

1.2.5 Coastal flooding

Coastal flood impacts are characterised by the average annual number of people in the coastal zone affected by coastal flooding, calculated using the flood module (Hinkel et al., 2014) within the DIVA modelling framework (version 2.0.1, database 32) (Hinkel, 2005; Vafeidis et al., 2008). DIVA estimates the change in frequency of coastal flood levels due to sea level rise along 12,000 segments, representing the world's coast. The flood frequency distribution for each segment incorporates local isostatic land movement and estimates of local subsidence in delta regions. In this analysis, it is assumed that the sea level rise due to climate change is globally uniform, and the effects of potential changes in the frequency, intensity and location of flood-generating storms and surges are not incorporated (i.e. storminess is considered stationary). The measure of physical hazard used here is the area of land which would be flooded in the estimated 100-year flood, ignoring the presence of coastal flood defences. The impact of coastal flooding is characterised by the average annual number of people affected by coastal flooding, assuming that coastal flood defences do not change from current levels. This is, of course, unrealistic as coastal flood defence levels will improve in many locations because of the increased value of assets and numbers of people exposed to flooding. The indicator therefore represents potential impact, rather than projected actual numbers of people flooded.

1.2.6 Agricultural risks

Two sets of indicators are constructed at a spatial resolution of 0.5 × 0.5°, looking first at crop production in general and second at maize in particular. In principle, it is possible to construct indicators based on estimated productivity as simulated by crop growth models. However, estimates of future productivity vary between crop models and are sensitive to assumptions about crop variety and agricultural practices. The indicators therefore focus on agri-climate proxies for crop growth.

The two indicators relating to crop production in general characterise the impacts of drought and flood. Drought is defined using the standardised precipitation evapotranspiration index (SPEI; Vicente-Serrano et al., 2010), which is based on the accumulated difference between precipitation and potential evaporation. Here, the accumulation is over six months, and agricultural droughts are defined in the same way as for hydrological droughts (SPEI less than or equal to −1.5 in 1961–1990). In the baseline 1961–1990 period agricultural droughts occur approximately 6.5% of the time. A ‘significant’ agricultural drought is defined as a period of three or more consecutive months with an SPEI less than −1.5, and the average annual frequency of ‘significant’ droughts calculated. The flood risk to cropland is defined in exactly the same way as flood risk to people, using the same estimated flood frequency distributions but using the reference period 30-year flood. In each case, exposure is characterised by the area of cropland (for the flood indicator, the area of cropland in major floodplains), and potential impacts are defined as the average annual area of cropland (Ramankutty et al., 2008) exposed to drought and to flood. The indicators are generalised, so droughts and floods do not necessarily occur during the crop growing season.

The second group of indicators are targeted more specifically at maize production (Challinor et al., 2016; Gourdji et al., 2013), and are all good proxies for maize yields. The four indicators are based on (i) the average temperature during the growing season; (ii) the time to accumulate the reference period accumulated thermal time (ATT); (iii) the frequency of hot spells; and (iv) accumulated rainfall. The first two are calculated over the growing season, and the other two are calculated over the shorter reproductive phase. The growing season and reproductive phase vary across the globe, and are here assumed to remain constant through time (although in practice they will change as climate changes). The start date of the growing season is taken from Sacks et al. (2010), and the reproductive season occurs a fixed proportion of time into the growing season.

Maize yield has been found to decrease once average growing season temperature exceeds 23°C (Lobell et al., 2011), or when there are at least five days with temperatures greater than 36°C during the reproductive season. The accumulation time is the time taken to accumulate the average ATT in the baseline (1961–1990) climate. The ATT is the sum of temperatures between 7 and 30°C over the growing season. A reduction in the time taken to accumulate this ATT is associated with reductions in yield (Challinor et al., 2016).

Exposure is represented by the area currently used for maize cultivation (Monfreda et al., 2008). Potential impact is characterised by the proportions of maize cropland with specific changes in hot spell frequency, rainfall, accumulation time and growing season temperature.

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Annex 2: China-scale climate risk indicators

2.1 Overall methodology

Direct risks for China are represented by indicators characterising the consequences of climate change for heat extremes, water resources, coastal flooding and agriculture. In each case, there are separate indicators for change in physical hazard and change in impact. All the projected changes in hazard and impact are based on scenarios constructed directly from the output from CMIP5 generation (Taylor et al., 2012) climate models run with RCP2.6 and RCP8.5 emissions scenarios. The details of the approach used vary between sectors, as outlined below.

2.2 Risk indicators

2.2.1 Heat extremes

Heat extremes are characterised by three indicators: the average annual maximum daily temperature, the average annual number of days with maximum temperature greater than 35°C, and the average annual number of heatwaves with at least five consecutive days with maximum temperature greater than 35°C (Xu et al., 2015). The threshold of 35°C is widely used in China to define a hot spell. The period 1986–2005 is used to define the reference climate.

Heat extremes were calculated from daily output from 20 CMIP5 climate models: each model's data were bias corrected to match observed mean climate over the period 1986–2005. The analysis presents the average change across the 20 models, together with the 10th to 90th percentile range across the models.

2.2.2 Water resources

2.2.2.1 Glacier runoff

The effects of climate change on glacier contributions to river flows are characterised by changes in total ice volume and the volume of ice melt. Glacier volume is calculated as a function of glacier surface area, and ice surface area is estimated from the Second Chinese Glacier Inventory. The general form of the volume and area scaling relationship is:

$$Da = c\, Sa^{\gamma - 1}$$

Where Sa and Da are glacier area and volume, and c and γ are scaling parameters. The scaling parameters are taken from Kraaijenbrink et al. (2017), and applied to the ice area and volume from the Second Chinese Glacier Inventory.

Glacier runoff is estimated using a degree-day model, calculating ice ablation from air temperature using a degree-day factor.

2.2.2.2 Water resource availability

Current and future water resource availability was estimated (Su et al., 2017) using a subset of the runoff projections made for the ISI-MIP assessment (Schewe et al., 2014). This subset consists of four global hydrological models (SWAT, SWIM, HBV and VIC), all driven by climate scenarios constructed from five climate models (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM and Nor-ESM1-M). This makes a total of 20 simulations for each emissions scenario. The analysis uses the average value across the 20 simulations, together with the 10th to 90th percentile range across the model combinations.

Water scarcity is here defined to occur when watershed average annual runoff falls below 500m^3/capita/year.

2.2.2.3 Drought

The standardised precipitation evapotranspiration index (SPEI; Vicente-Serrano et al., 2010), which describes the degree to which dry and wet conditions deviate from the long-term average by standardising the difference between potential evapotranspiration (PET) and precipitation, is applied to describe the droughts in the current study. The SPEI-12 used in this paper can reflect the long-term water loss process and indicate the inter-annual change in drought. The calculation of SPEI is briefly described as follows:

1) Estimation of PET using the Penman-Monteith method:

$$PET = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_a - e_d)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where PET is the daily PET (mm·d^{-1}); Δ is the slope of the saturation vapour pressure curve (kPa·°C^{-1}); T is the mean daily air temperature (°C); e_a is the saturation vapour pressure (kPa); R_n is the net radiation at the surface (MJ/(m^2·d)); e_d is the actual atmospheric water vapour pressure (kPa); G is the all-wave ground heat flux, (MJ/(m^2·d)); γ is the psychometric constant (kPa·°C^{-1}); and u_2 is the daily average wind speed at a height of 2m (m·s^{-1}). All the variables required for the calculation are from ISI-MIP data.

2) The accumulated difference between the precipitation and PET is normalised by the three-parameter log-logistic probability distribution:

$$F(X) = \left[1 + \left(\frac{\alpha}{X - \gamma}\right)^{\beta}\right]^{-1} \tag{2}$$

where *x* is the accumulated difference between the precipitation and PET; α, β and γ are scale, shape and position parameters, respectively; and p is the probability of a given *x*.

$$p = 1 - F(x) \tag{3}$$

If $p \leq 0.5$

$$w = \sqrt{-2\ln p} \tag{4}$$

$$SPEI = w - \frac{C_0+C_1w+C_2w^2}{1+d_1w+d_2w^2+d_3w^3} \tag{5}$$

If $p > 0.5$

$$w = \sqrt{-2\ln(1-p)} \tag{6}$$

$$SPEI = \frac{C_0+C_1w+C_2w^2}{1+d_1w+d_2w^2+d_3w^3} - w \tag{7}$$

where $C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, $d_3 = 0.001308$ (Vicente-Serrano et al., 2010).

−1<SPEI<1 denotes a near normal condition; SPEI≤−1, −1.5 and −2 denote a moderate, severe and extreme drought, respectively.

2.2.3 Coastal flooding

Sea level rise is projected in different regions: the China seas (100°E–135°E, 0°N–42°N), the Bohai and Yellow Sea (117°E–128°E, 32°N–42°N), the East China Sea (116°E–135°E, 23°N–32°N) and the South China Sea (100°E–121°E, 0°N–23°N). Sea level data from 21 CMIP5 models under three scenarios (RCP2.6, RCP4.5 and RCP8.5) and the trend in the steric sea level are used (Church et al., 2013). Sea level rise relative to the mean sea level between 1986 and 2005 are estimated for all regions (Figure 1 and Table 1), while the melting of glaciers and ice sheets in Greenland and the Antarctic, continental water, and the contribution of glacial isostatic adjustment to the regional seas are taken into account (Slangen et al., 2014). The low, medium and high levels of the sea level rise projection are the 5%, 50% and 95% uncertainty of the ensemble model projection, respectively.

The sea level in the China Seas will rise 0.26–1.09m by 2100 compared with the mean value from 1986–2005. The sea level in the Bohai and Yellow Sea, the East China Sea and the South China Sea will rise 0.20–1.14m, 0.26–1.22m and 0.27–1.09m respectively.

Figure 1: Sea level rise in the China Seas

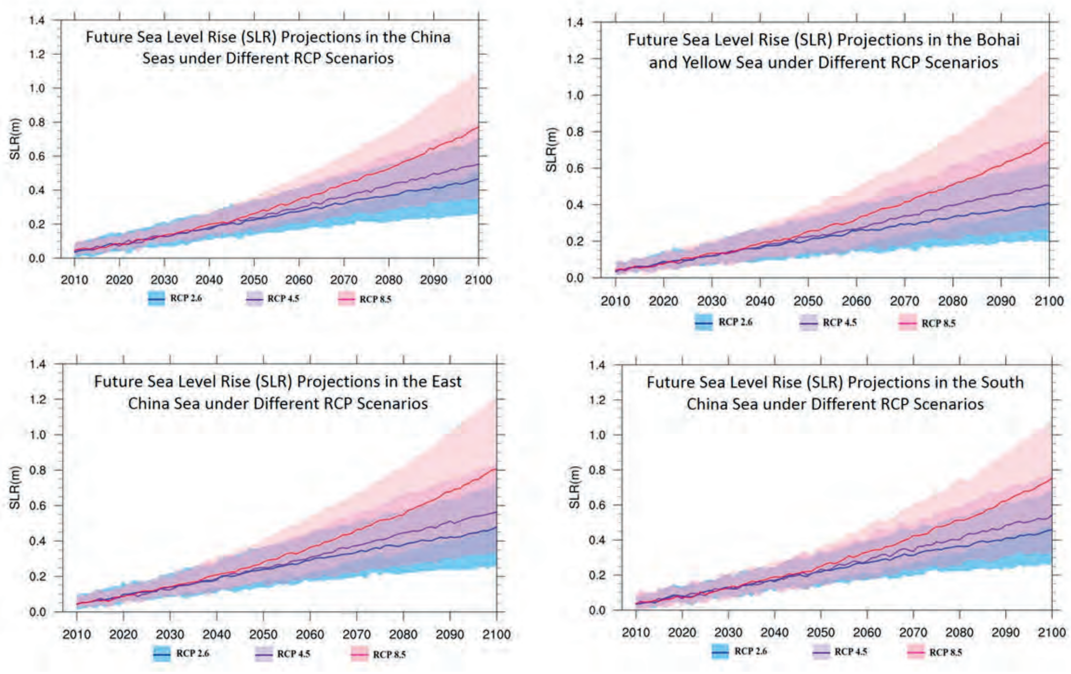

Table 1: Sea level rise in the China Seas

Time		**2050**			**2080**			**2100**		
Scenario		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Bohai & Yellow Sea	Low	0.10	0.13	0.15	0.18	0.21	0.28	0.20	0.26	0.41
	Medium	0.20	0.23	0.25	0.33	0.40	0.51	0.41	0.51	0.74
	High	0.33	0.34	0.39	0.53	0.62	0.78	0.65	0.79	1.14
East China Sea	Low	0.14	0.16	0.18	0.22	0.27	0.33	0.26	0.33	0.47
	Medium	0.25	0.26	0.28	0.38	0.45	0.55	0.48	0.56	0.80
	High	0.37	0.37	0.42	0.57	0.66	0.81	0.73	0.84	1.22
South China Sea	Low	0.13	0.15	0.16	0.22	0.26	0.32	0.27	0.34	0.49
	Medium	0.22	0.23	0.25	0.37	0.41	0.51	0.46	0.54	0.75
	High	0.33	0.35	0.37	0.54	0.59	0.75	0.68	0.79	1.09
China Seas	Low	0.13	0.16	0.19	0.21	0.29	0.36	0.26	0.35	0.52
	Medium	0.23	0.24	0.26	0.37	0.43	0.53	0.47	0.55	0.77
	High	0.34	0.36	0.38	0.55	0.60	0.74	0.70	0.80	1.09

The return periods of extreme sea levels along the Chinese coastline are estimated by fitting a Gumbel distribution (Extreme Value type 1) to tide gauge data from 1980 to 2016 (Table 2).

Table 2: Return periods of extreme sea levels along the Chinese coast (m)

Return period (years)	**1000**	**500**	**200**	**100**	**50**	**33**	**20**	**10**	**5**	**2**
Liaoning	3.42	3.33	3.21	3.11	3.02	2.96	2.89	2.80	2.66	2.54
Hebei	3.74	3.58	3.38	3.22	3.07	2.97	2.86	2.70	2.48	2.28
Tianjin	3.74	3.58	3.38	3.22	3.07	2.97	2.86	2.70	2.48	2.28
North of Shandong	2.94	2.81	2.63	2.50	2.37	2.28	2.19	2.06	1.87	1.70
South of Shandong	3.51	3.42	3.29	3.20	3.10	3.04	2.97	2.88	2.74	2.62
North of Jiangsu	4.13	4.00	3.84	3.71	3.59	3.50	3.42	3.29	3.10	2.94
South of Jiangsu	5.26	5.09	4.87	4.69	4.52	4.41	4.30	4.12	3.87	3.66
Shanghai	4.22	4.11	3.96	3.85	3.74	3.67	3.59	3.48	3.32	3.18
Zhejiang	4.23	4.11	3.96	3.85	3.74	3.66	3.59	3.47	3.31	3.16
Fujian	4.93	4.79	4.60	4.46	4.31	4.22	4.12	3.98	3.77	3.59
Guangdong	4.03	3.89	3.70	3.56	3.42	3.32	3.23	3.08	2.88	2.70
Guangxi	4.61	4.48	4.31	4.18	4.05	3.97	3.88	3.75	3.56	3.40
Hainan	4.00	3.79	3.50	3.29	3.07	2.93	2.79	2.56	2.25	1.98

The area under the 100-year return period level was estimated from the 1:1,000,000 geographic information provided by the Chinese Survey Department, at a spatial resolution of approximately 30m. Current and future population and GDP within the 100-year floodplain area was determined from high resolution socio-economic projections, based on SSPs (Jiang et al., 2017, 2018). Risk areas are calculated without considering coastal flood defences.

2.2.4 Agriculture

2.2.4.1 Climate scenarios

Climate risk to the production of rice and wheat was estimated using a series of agri-climate proxies for crop growth. Climate scenarios were constructed from 16 CMIP5 climate models.

2.2.4.2 Rice

Rice production – both single-cropping and double-cropping paddy rice – is mainly affected by heat damage. There are different thresholds for different degrees of damage, based on the number of days that the maximum daily temperature exceeds 35°C. Impacts are characterised by the likelihood that durations exceed these thresholds, and by the average annual proportion of the rice growing area that experiences these thresholds.

2.2.4.3 Wheat

Winter wheat production is mainly affected by waterlogging and drought. Waterlogging is particularly significant during the seedling and heading–filling phases, whilst drought is important during the jointing–tasseling and filling–maturity phases. Waterlogging is defined by a waterlogging index, which is calculated from precipitation and sunshine duration. Drought is characterised by precipitation anomalies during the relevant growth stage. Impacts are characterised by the likelihood that waterlogging or drought occur, and by the average annual proportion of winter wheat cropland that experiences waterlogging or drought.

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