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Climate change risk assessment 2021

The risks are compounding, and without immediate action the impacts will be devastating

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Summary

- If policy ambition, low-carbon technology deployment and investment follow current trends, 2.7°C of warming by the end of this century is likely, relative to pre-industrial temperatures. A plausible worst case of 3.5°C is possible (10 per cent chance). These projections assume Paris Agreement signatories meet their NDCs. If they fail to do so, the probability of extreme temperature increases is non-negligible.
- Any relapse or stasis in emissions reduction policies could lead to a plausible worst case of 7°C of warming by the end of the century (10 per cent chance).
- If emissions follow the trajectory set by current NDCs, there is a less than 5 per cent chance of keeping temperatures well below 2°C relative to pre-industrial levels, and less than 1 per cent chance of reaching the 1.5°C Paris Agreement target.
- There is currently a focus on net zero pledges, and an implicit assumption these targets will avert climate change. However, net zero pledges lack policy detail and delivery mechanisms, and the deficit between targets and the global carbon budget is widening every year.
- Unless NDCs are dramatically increased, and policy and delivery mechanisms are commensurately revised, many of the impacts described in this research paper are likely to be locked in by 2040 and become so severe they go beyond the limits of what nations can adapt to.
- The governments of highly emitting countries have an opportunity to accelerate emissions reductions through ambitious revisions of their NDCs, significantly enhancing policy delivery mechanisms, and incentivizing rapid large-scale investment in low-carbon technologies. This will lead to cheaper energy and avert the worst climate impacts.
- If emissions do not come down drastically before 2030, then by 2040 some 3.9 billion people are likely to experience major heatwaves, 12 times more than the historic average. By the 2030s, 400 million people globally each year are likely to be exposed to temperatures exceeding the workability threshold. Also by the 2030s, the number of people on the planet exposed to heat stress exceeding the survivability threshold is likely to surpass 10 million a year.
- To meet global demand, agriculture will need to produce almost 50 per cent more food by 2050. However, yields could decline by 30 per cent in the absence of dramatic emissions reductions. By 2040, the average proportion of global cropland affected by severe drought will likely rise to 32 per cent a year, more than three times the historic average.

- By the 2040s, the probability of a 10 per cent yield loss, or greater, within the top four maize producing countries (the US, China, Brazil and Argentina) rises to between 40 and 70 per cent. These countries currently account for 87 per cent of the world's maize exports. The probability of a synchronous, greater than 10 per cent crop failure across all four countries during the 2040s is just less than 50 per cent.
- Globally, on average, wheat and rice together account for 37 per cent of people's calorific intake. The central 2050 estimate indicates that more than 35 per cent of the global cropland used to grow both these critical crops could be subject to damaging hot spells. But this vulnerability could exceed 40 per cent in a plausible worst-case scenario. The central estimate for 2050 also indicates these same global cropland areas will be impacted by reductions in crop duration periods of at least 10 days, exceeding 60 per cent for winter wheat, 40 per cent for spring wheat, and 30 per cent for rice.
- By 2040, almost 700 million people a year are likely to be exposed to droughts of at least six months' duration, nearly double the global historic annual average. No region will be spared, but by 2040 East and South Asia will be most impacted – with, respectively, 125 million and 105 million people likely to experience prolonged drought. Across Africa, 152 million people each year are likely to be impacted.
- Cascading climate impacts can be expected to cause higher mortality rates, drive political instability and greater national insecurity, and fuel regional and international conflict. During an expert elicitation exercise conducted as part of the research for this paper, the cascading risks that participants identified greatest concern over were the interconnections between shifting weather patterns, resulting in changes to ecosystems and the rise of pests and diseases. Combined with heatwaves and drought, these impacts will likely drive unprecedented crop failure, food insecurity and migration. In turn, all will likely result in increased infectious diseases, and a negative feedback loop compounding each impact.

01 Introduction

Climate risks are increasing. Many of the impacts described in this research paper will be locked in by 2040, and become so severe they go beyond the limits of what many nations can adapt to.

In preparation for the UN Climate Change Conference (COP26), to be held in Glasgow in November 2021, signatories to the 2015 Paris Agreement on climate change are for the first time revising their climate mitigation plans, or nationally determined contributions (NDCs). The Paris Agreement set the common goal of limiting global average temperature increases (relative to pre-industrial levels) to 'well below' 2°C and 'pursuing efforts' to 1.5°C; and envisaged a five-year revision process to NDCs to encourage increasingly ambitious national pledges. However, the commitments made in line with current NDCs fall far short of limiting global temperature increases to 2°C above pre-industrial levels, let alone 1.5°C. By 2030, under current policies, the gap in annual emissions compared with a 2°C least-cost pathway will have reached 14–17.5 $GtCO_2$, equivalent to nearly half of current energy sector emissions.[1]

This research paper highlights the risks and likely impacts if the goals set under the Paris Agreement are not met, and the world follows an emissions pathway consistent with recent historical trends. Simply updating – i.e. without significantly enhancing – NDCs will not guarantee the Paris Agreement goals are met; nor will enhanced pledges without swift and decisive delivery of those pledges. The governments of highly emitting countries have an opportunity to accelerate emissions reductions through ambitious revisions of their NDCs, significantly enhancing policy delivery mechanisms, and incentivizing rapid large-scale investment in low-carbon technologies. This will lead to cheaper energy and avert the worst climate impacts.

The COVID-19 pandemic has underscored the interconnections and interdependences between nations, as well as the potential for cascading sectoral impacts with far-reaching consequences for society. This shows, too, the critical

1 Committee on Climate Change and China Expert Panel on Climate Change (2018), *UK-China Cooperation on Climate Change Risk Assessment: Developing Indicators of Climate Risk*, https://www.theccc.org.uk/publication/indicators-of-climate-risk-china-uk (accessed 13 Aug. 2021).

need to consider whether existing systems are sufficiently resilient, not only to domestic sectoral shocks but to global adverse trends and events. Climate change is among the greatest such risks.

Risk assessments are a critical tool in enabling decision-makers to allocate appropriate resources, within finite budgets, to the various challenges society faces. Climate change risks are increasing over time, and what might be a small risk in the near term could embody overwhelming impacts in the medium to long term. Risks can be defined by a probability of occurrence and severity of impact; climate risks are no different. This paper presents high-probability, high-impact climate risks as well as low-probability, high-impact climate risks, recognizing that a low-probability outcome may still correspond to a high risk if the impact is severe. Many of the impacts described are likely to be locked in by 2040, and become so severe they go beyond the limits of what many countries can adapt to.

The paper examines emissions risks, and the most significant direct and systemic risks in terms of societal impact, drawing on recent research of impact indicators. The assessment presents central estimates as well as plausible worst-case scenario impacts (see Box 1). A global emissions trajectory represents emissions risks (Chapter 2), under which direct risks are assessed (Chapter 3). Systemic cascading climate risks have been assessed via an expert elicitation process involving 70 climate scientists and sector risk experts (Chapter 4). It is these systemic cascading risks that are in general less well documented, principally as they emerge from the interdependences between various complex systems and as such require input from experts in multiple disciplines. For example, the 2007–08 and 2010–11 global food price spikes arose from relatively modest climate impacts interacting with other factors (e.g. biofuel policy diverting grain to ethanol, low stock transparency) that created a run on grain markets, leading to implementation of export bans and thus further amplifying the price shocks. The expert contributions that have informed this paper aim to go some way in addressing the gap in documenting cascading risks.

The paper builds on two previous phases of risk assessments,[2] and the guiding principle continues to be to ensure transparency regarding what we know, what we don't know, and what we think, when assessing climate risks.

This paper does not attempt to quantify transition risks; nor is its purpose to provide recommendations as to the climate mitigation policies that countries could implement to minimize the risks arising from climate change. This follows the principles of the previous phases of risk assessments, whereby best practice is to separate risk assessments and risk management strategies.

2 King, D., Schrag, D., Dadi, Z., Ye, Q. and Ghosh, A. (2017), *Climate Change: A Risk Assessment*. https://www.csap.cam.ac.uk/projects/climate-change-risk-assessment (accessed 13 Aug. 2021); Committee on Climate Change and China Expert Panel on Climate Change (2018), *UK-China Cooperation on Climate Change Risk Assessment: Developing Indicators of Climate Risk*.

02 Emissions trajectory and risks

If emissions follow the trajectory set by current NDCs, there is a less than 5 per cent chance of keeping temperatures well below 2°C above pre-industrial levels, and less than 1 per cent chance of reaching the 1.5°C Paris Agreement target.

Global efforts to reduce CO_2 emissions are dangerously off track. Current NDCs indicate a 1 per cent reduction in emissions globally by 2030, compared with 2010 levels.[3] Most countries are currently focusing on net zero pledges, with an implicit assumption these targets will avert climate change. However, net zero pledges lack policy detail and delivery mechanisms, and the deficit between targets and the global carbon budget is widening every year.

The global long-term average surface temperature and changes in climatic conditions are dependent on cumulative carbon dioxide equivalent (CO_2eq). As such, climate change risks are contingent on the emissions trajectory that the global community is likely to follow.[4] Given that around two-thirds of global CO_2eq emissions originate from the energy sector, the decarbonization of the energy sector will be a primary determinant of future emissions, and thus of the risks posed by emissions. The term *emissions risk* reflects the chance that the world is on a high emissions trajectory that will further increase the climate risks and their impacts on global and regional populations.

3 UNFCCC (2021), 'Greater Climate Ambition Urged as Initial NDC Synthesis Report Is Published', https://unfccc.int/news/greater-climate-ambition-urged-as-initial-ndc-synthesis-report-is-published (accessed 2 May 2021).
4 As well as the vulnerability and exposure of the population to a given climate change hazard.

Phase two of the UK-China Cooperation on Climate Change Risk Assessment project provided a robust assessment of the global energy sector's emissions trajectory.[5] We draw on this emissions trajectory assessment to define the emissions risks. The steps taken to assess the future emissions trajectory and risks under phase two can be summarized as:

— Twelve energy sector indicators were assessed to provide a granular examination of global progress towards decarbonization of the energy sector, as well as an assessment of future energy consumption.

— For each of the 12 indicators, historical time series data were used to compare development trends against International Energy Agency (IEA) scenarios, under the World Energy Outlook (WEO) 2017. These trends were then aggregated to forecast emissions from the energy sector and industrial processes to 2040, shown in Figure 1a.

— The extrapolated emissions trajectory was compared to emissions under IEA scenarios and Intergovernmental Panel on Climate Change (IPCC) representative concentration pathways (RCP8.5, 4.5 and 2.6), generated as part of the IPCC Fifth Assessment Report (AR5), and converted into probabilistic temperature rises, shown in Figure 1b.

Figure 1a. Energy sector and industrial process CO_2 emissions to 2040, based on indicator trends

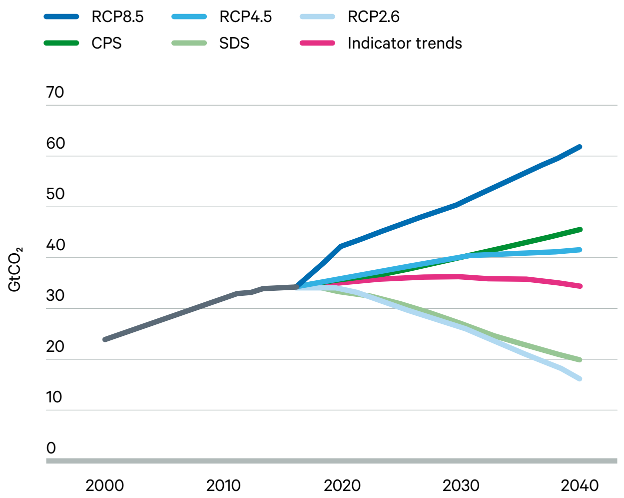
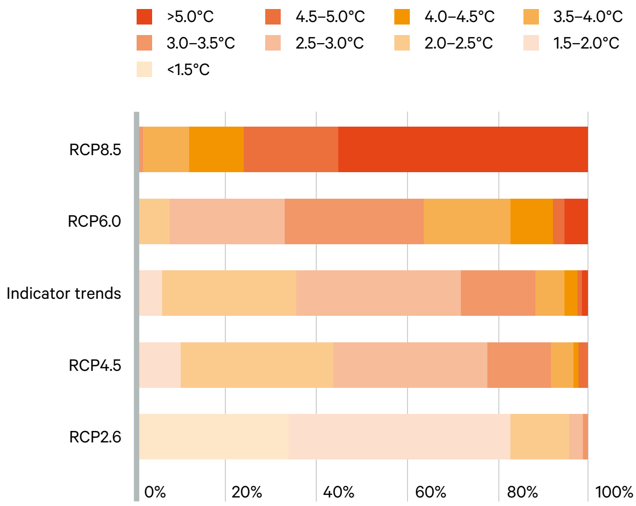


Figure 1b. Warming probability in different scenarios, in 2100



IEA: CPS = current policies scenario; SDS = sustainable development scenario
IPCC: RCP = representative concentration pathway

This emissions trajectory and risk assessment indicates that emissions are likely to continue to rise slowly until the late 2020s, and subsequently decline very gradually to around 35 Gt in 2040, around 6 per cent higher than in 2019, reaching just under 25 $GtCO_2$ in 2100, around a third lower than 2019. The trajectory most closely tracks RCP4.5 and is significantly below RCP8.5, but is also much higher than

5 Committee on Climate Change and China Expert Panel on Climate Change (2018), *UK-China Cooperation on Climate Change Risk Assessment*.

the sustainable development scenario (SDS), which tracks RCP2.6. It is important to note that this trajectory assessment relies on climate mitigation policy ambition continually expanding, but does not account for the impacts of the COVID-19 pandemic or future similar events. Taking account of the economic rebound in the current pandemic, the IEA anticipates that 2021 will see the second largest increase in CO_2 emissions in history. (The biggest was in 2010, in the context of the recovery from the global financial crisis.)[6]

As Figure 1b illustrates, the median temperature rise (relative to pre-industrial temperatures) in 2100 of this RCP4.5-like trajectory is around 2.7°C (with a 10–90 per cent range of 2.1–3.5°C), and a plausible worst case of 3.5°C (10 per cent chance). Without continued expansion of decarbonization policies, emissions could continue to rise in line with the current policies scenario (CPS), or even RCP8.5, resulting in a near 90 per cent chance that temperatures in 2100 will exceed 4°C relative to pre-industrial levels, with the median temperature rise in 2100 exceeding 5°C, and a plausible worst-case increase of 7°C (10 per cent chance). If emissions follow the trajectory set by current NDCs, there is less than 5 per cent chance of keeping temperatures well below 2°C, and less than 1 per cent chance of reaching the 1.5°C Paris Agreement target.[7]

Box 1. A plausible worst-case scenario

The very nature of risks means their impacts are uncertain. At the same time, decision-makers require an evaluation of the worst-case scenario – i.e. the most severe outcome that might plausibly occur. Such scenarios are integral for policy planning and when taking decisions on infrastructure investment to mitigate and adapt to such risks.

The identified emissions trajectory indicates a climate forcing scenario similar to RCP4.5, which has subsequently been used to characterize direct risk impacts. As such, the plausible worst-case outcome under this scenario is the upper end of an estimated distribution of potential impacts (the 90th percentile). For the impacts set out in Chapter 3, the central, or median, estimate is generally discussed within the text, with the plausible worst-case scenario represented in the associated figures. Where appropriate, the upper estimate, or plausible worst-case outcome, is highlighted within the text. In most instances, however, the impacts are so severe under the central estimate that in many instances stating the worst-case scenario does not add significant value.

It should be noted that the emissions trajectory identified determines the quantification of direct risks and impacts. However, if decarbonization policies stagnate or reverse, it is more than conceivable that the worst-case emissions scenario results in climate forcing more similar to RCP8.5 than the modelled RCP4.5. This would result in the plausible (10 per cent chance) worst-case global mean temperature scenario increasing from 3.5°C to 7°C. Consequently, the direct risk impacts presented in Chapter 3 would significantly increase in severity of impact, as well as probability of occurrence.

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6 International Energy Agency (2021), *Global Energy Review 2021*, Paris: International Energy Agency, https://www.iea.org/reports/global-energy-review-2021 (accessed 2 May 2021).
7 Committee on Climate Change and China Expert Panel on Climate Change (2018), *UK-China Cooperation on Climate Change Risk Assessment.*

03 Direct climate impacts

Unless emissions are dramatically reduced, many of the direct impacts of climate change will likely be locked in by 2040, and could become so severe they go beyond the limits of what many countries can adapt to.

3.1 Approach: how to understand the impacts presented

This chapter presents impact indicators of the most significant global and regional direct risks of climate change, under the RCP4.5 GHG concentration trajectory, which approximately maps to the emissions trajectory identified in Chapter 2. The quantitative analysis of each direct risk and associated impact (Figures 3–18) is entirely sourced from Nigel Arnell and colleagues (2019).[8] Whereas they present the major climate hazards as a function of time, with the associated climate impacts illustrated at discrete time horizons (2050 and 2100), in this paper we draw on their decadal data to present – for the first time – these climate risk impacts as function of time.[9]

The approach of presenting the major climate risk impacts as a function of time partially follows the approach laid out by Simon Sharpe (2019):

> The risks of climate change can be understood more clearly when research starts by identifying what it is that we most wish to avoid and then assesses its likelihood

8 Arnell, N. W., Lowe, J. A., Bernie, D., Nicholls, R. J., Brown, S., Challinor, A. J. and Osborn, T. J. (2019), 'The global and regional impacts of climate change under representative concentration pathway forcings and shared socioeconomic pathway socioeconomic scenarios', *Environmental Research Letters*, 14(8), 084046, doi:10.1088/1748-9326/ab35a6 (accessed 13 Aug. 2021).
9 For greater detail on the uncertainty associated with the direct risk impacts, as well as definitions of thresholds of impact, see Arnell et al. (2019).

> as a function of time. By providing a clearer picture of the overall scale of the risks of climate change, such assessments could help inform the most important decision of all: how much effort to put into reducing emissions.[10]

The difference between Sharpe's approach and the one used in this paper pertains to the thresholds applied to a given climate impact. Defining 'what it is that we most wish to avoid' requires geographically specific thresholds of concern/impact, as societies across different regions do not necessarily have equivalent vulnerabilities to a given climate hazard. For instance, an equivalent temperature in two regions could be defined as a severe heatwave in one while having little impact in another. As such, thresholds of concern/impact need to be defined by stakeholders in each region to enable an assessment of what it is we wish to avoid, and subsequently its likelihood over time. This bottom-up approach to assessing climate risks and impacts requires significant stakeholder engagement across all regions of the world, to then work backwards and identify the climatic conditions that would bring them about.

For this paper, a top-down approach to assessing direct climate impacts is followed, with standardized thresholds applied across all regions. For instance, the threshold for defining a major heatwave requires the temperature of a given region to exceed the 99th percentile of the reference period for four or more consecutive days in one year. As such, the **direct risks and associated impacts in this chapter should be treated as indicators of impact**. As highlighted by Sharpe (2019), it is integral to define what we wish to avoid in assessing the risks of climate change. The thresholds of impact for each indicator are described in the coming sections, as each impact is presented, but for fuller detail see the work of Arnell and colleagues (2019).[11]

The risks of climate change can be understood more clearly when research starts by identifying what it is that we most wish to avoid and then assesses its likelihood as a function of time (Sharpe, 2019).

There is a clear need for subsequent research to engage stakeholders in all regions of the globe to define geographically specific thresholds of concern/impact. However, the top-down approach used here does enable impact indicators to be assessed under a common emissions scenario (as described in Chapter 2).

Climate hazards do not translate neatly into impacts. Impacts require exposure and vulnerability to be defined in order to quantify the impact of any given hazard. Shifts in population, innovation, advances in healthcare, and infrastructure will all alter the vulnerability and exposure of societies to a given climate hazard. Exposure

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10 Sharpe, S. (2019), 'Telling the boiling frog what he needs to know: why climate change risks should be plotted as probability over time, *Geoscience Communication*, 2(1), pp. 95–100, doi:10.5194/gc-2-95-2019 (accessed 13 Aug. 2021).
11 Arnell et al. (2019), 'The global and regional impacts of climate change under representative concentration pathway forcings and shared socioeconomic pathway socioeconomic scenarios'.

is represented by shared socio-economic pathway 2 (SSP2).[12] While five SSPs are commonly used,[13] SSP2 has been selected on the basis that: (a) it represents a similar trend in decarbonization action that the emissions trajectory indicates; (b) it represents a middle ground along the spectrum of challenges for mitigation and adaptation. Just as with the selection of RCP4.5, using SSP2 to quantify climate impacts does not represent a prediction, but rather a plausible projection. SSP2 is characterized in full by O'Neill and colleagues (2017), but is summarized as:

> The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations … Even though fossil fuel dependency decreases slowly, there is no reluctance to use unconventional fossil resources. Global population growth is moderate and levels off in the second half of the century.[14]

While direct risk impacts are graphically represented (Figures 3–18) at a given indicator threshold of impact, plotting their likelihood as a function of time, the 2040–50 time horizon is generally used to highlight the impact within the text. This allows readers to make a comparative assessment of risks between geographies and impact types.

The uncertainty associated with the following impacts of direct climate risks (under RCP4.5) set out in this chapter has two principal sources: (1) the change in global mean temperature, which in turn is a function of equilibrium climate sensitivity, ocean diffusivity and carbon cycle feedback; and (2) the spatial pattern of change in temperature and precipitation. The total uncertainty is represented by the shaded areas in Figures 3–18, with the lower and upper bounds of that area indicating the 10th and 90th percentiles of the distribution of impacts in each year. These bounds can be regarded as the low and high estimates of the given impact, with the solid line representing the median, or central, estimate. As discussed in Box 1, the high or upper estimate represents the plausible worst-case scenario (under RCP4.5). However, these do not capture the behaviour of the tails of the probability distribution – e.g. what is the maximum plausible number of days of heatwaves – and so almost certainly under-represent the plausible worst case.

Whereas a wide range of hazards and impacts were assessed by Arnell and colleagues (2019), both at the continental and regional levels, this paper presents the impacts to which the greatest number of people or cropland are exposed. It also takes into consideration impacts with the greatest increases relative to historic baselines, and where the avoidance of climate change significantly reduces a given impact.

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12 Arnell et al. (2019) use SSP population projections downscaled to the 0.5°×0.5° resolution by Jones and O'Neill (2016), as well as country GDP projections from Dellink et al. (2017), downscaled to the same resolution in order to quantify exposure. For more details see Arnell et al. (2019).
13 O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M. and Solecki, W. (2017). 'The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century', *Global Environmental Change*, 42: pp. 169–180, doi:10.1016/j.gloenvcha.2015.01.004 (accessed 13 Aug. 2021).
14 Ibid.

Box 2. Tipping points

The study by Arnell and colleagues (2019) is robust, based on current climate science, with 23 CMIP5[15] climate models used to characterize uncertainty in the regional patterns of climate change. However, there are growing concerns that many climate models may under-represent the influence of tipping points on global mean temperature, which climate science is increasingly indicating could be a key determinant of future temperatures even at low levels of climate forcing.[16]

Tipping points can be thought of as large discontinuities, or abrupt changes, occurring as a critical earth system threshold is passed. One such instance is the melting of the permafrost in the Arctic leading to the release of methane, which is 30 times more potent than CO_2. Many tipping points additionally have feedback or cascading effects on the rate of climate change. As such, passing the threshold of one tipping point can increase the risk of passing the threshold of triggering another.

Critically, certain thresholds could be reached at lower levels of temperature increase than previously thought. The latest IPCC climate models show a cluster of such abrupt shifts between 1.5°C and 2°C.[17] Therefore the risk is that around this level of temperature rise, a cascade of tipping points could be triggered, vastly accelerating climate change and generating catastrophic impacts. Indeed, some initial results from the latest climate models, part of the IPCC's ongoing Sixth Assessment Report cycle, demonstrate greater climate sensitivity (temperature response to a doubling of atmospheric CO_2) than shown in earlier models.[18]

Global temperatures can rise significantly beyond those described in the previous chapters. Current atmospheric CO_2 concentration is around 420 parts per million (ppm). Around 3 million years ago, atmospheric CO_2 was between 350 and 450 ppm, and global mean surface temperatures were between 1.9° and 3.6°C higher than the pre-industrial climate. However, global temperatures have been much higher: around 50 million years ago, atmospheric CO_2 exceeded 1,000 ppm, while global mean surface temperatures were 9° to 14°C.[19]

Ice sheets are crucial for the stability of the climate system as a whole, and are already at risk of transgressing their temperature thresholds within the Paris range of 1.5°–2°C.[20] A domino-like effect has recently been identified between various tipping points, which can lead to abrupt non-linear responses. Tipping point cascades (two or more tipping points being initiated for a given temperature level) have been identified in more

15 Coupled Model Intercomparison Project Phase 5.
16 Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W. and Schellnhuber, H. J. (2019), 'Climate tipping points – too risky to bet against', *Nature*, 575(7784): pp. 592–595, doi:10.1038/d41586-019-03595-0 (accessed 13 Aug. 2021).
17 Drijfhout, S., Bathiany, S., Beaulieu, C., Brovkin, V., Claussen, M., Huntingford, C., Scheffer, M., Sgubin, G. and Swingedouw, D. (2015), 'Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models', *Proceedings of the National Academy of Sciences*, 112(43): pp. E5777–E5786, doi:10.1073/pnas.1511451112 (accessed 13 Aug. 2021).
18 Lenton et al. (2019), 'Climate tipping points – too risky to bet against'.
19 IPCC (2013), *Climate Change 2013: The Physical Science Basis*, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge and New York: Cambridge University Press.
20 Wunderling, N., Donges, J. F., Kurths, J. and Winkelmann, R. (2021), 'Interacting tipping elements increase risk of climate domino effects under global warming', *Earth System Dynamics*, 12(2), pp. 601–619, doi:10.5194/esd-12-601-2021 (accessed 13 Aug. 2021).

than 60 per cent of simulations, for which the initial trigger is likely to be polar ice sheet melting, with the Atlantic Meridional Overturning Circulation (AMOC) acting as a mediator transmitting cascades.[21]

The implications for this risk assessment are clear. If cascading tipping points are indeed reached at lower temperatures, for the same emissions trajectory, most of the impacts presented in chapters 3 and 4 are likely to under-represent the effects on people and cropland, with impacts occurring with a higher probability sooner in time. Furthermore, the severity and frequency of the impacts will be far more extreme, which in turn will greatly reduce the capacity of societies the world over to adapt, compounding the impacts.

Examples of tipping points include:

— Greenland and West Antarctic ice sheet disintegration: Melting of ice reduces reflection of sunlight back into space, resulting in accelerated warming and increased sea level rise.

— Permafrost loss: Abrupt increase in emissions of CO_2 and methane through the thawing of frozen carbon-rich soils. Methane is a more potent greenhouse gas than CO_2, resulting in accelerated warming.

— AMOC breakdown: Shutdown of the AMOC caused by an increased influx of freshwater into the North Atlantic, reducing the ability of oceans to disperse heat around the globe and thus impairing oceans' ability to provide cooling.

— Boreal forest shift: Dieback of boreal forests potentially turning some regions from a carbon sink to a carbon source as pests and wildfires create large-scale disturbances.

— Amazon rainforest dieback: Dieback of the rainforest and a shift towards savannah, resulting in large release of CO_2 from that stored within the forests.

3.2 Heat, productivity and health

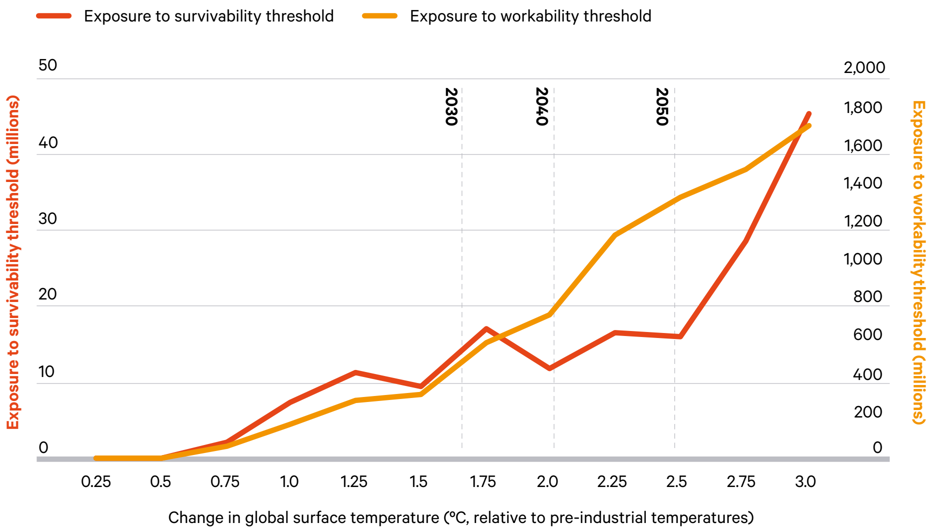
Increased temperatures and heatwaves are increasingly limiting labour productivity and causing heat-stress-related mortality. In 2019 a potential 302 billion working hours were lost due to temperature increases globally, 52 per cent more than in 2000.[22] To put this in context, COVID-19 resulted in around 580 billion lost working hours globally in 2020;[23] hence temperature increases are already resulting in the equivalent of more than half of COVID-19-induced lost working hours. India's agricultural sector accounted for 39 per cent of the heat-related lost working hours

21 Ibid.
22 Watts, N. et al. (2021), 'The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises', *The Lancet*, 397(10269): pp. 129–170, doi:10.1016/S0140-6736(20)32290-X (accessed 13 Aug. 2021).
23 International Labour Organization (2021), 'ILO Monitor: COVID-19 and the world of work. Seventh edition', ILO Data Explorer, https://www.ilo.org/shinyapps/bulkexplorer39/?lang=en&segment=indicator&id=HOW_2LSS_NOC_RT_A (accessed 1 May 2021).

in 2019. In southern areas of the US, 15–20 per cent of daylight working hours were lost during the hottest month of 2018.[24] Globally, heat-related mortality among people aged over 65 increased by nearly 54 per cent over the period 2000–18, reaching 296,000 deaths in 2018. Of heat-related deaths in the latter year, 62,000 were in China, 31,000 in India, and 104,000 across Europe.[25]

By the 2030s, more than 400 million people globally each year are likely to be exposed to temperatures exceeding the workability threshold.[26] Also by the 2030s, the number of people exposed to heat stress exceeding the survivability threshold[27] is likely to surpass 10 million each year.[28,29]

Figure 2. Number of people exposed to heat stress above the risks to workability and survivability thresholds at a given change in global mean surface temperature relative to pre-industrial levels



Source: Adapted from Andrews et al. (2018).

Globally, the central estimate indicates that over 8.2 billion people will experience a heatwave of two or more consecutive days per year by 2050 (Figure 3a), equivalent to 90 per cent of the global population.[30] This climate risk impacts a far greater proportion of the global population than any other direct risk assessed.

24 Watts, N. et al. (2019), 'The 2019 report of The Lancet Countdown on health and climate change: ensuring that the health of a child born today is not defined by a changing climate', *The Lancet*, 394(10211): pp. 1836–1878, doi:10.1016/S0140-6736(19)32596-6 (accessed 13 Aug. 2021).
25 Watts et al. (2021), 'The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises'.
26 Workability threshold: the monthly mean of daily maximum wet-bulb globe temperature exceeds 34°C.
27 Survivability threshold: the maximum daily wet-bulb globe temperature exceeds 40°C for three consecutive days.
28 Andrews, O., Le Quéré, C., Kjellstrom, T., Lemke, B. and Haines, A. (2018), 'Implications for workability and survivability in populations exposed to extreme heat under climate change: a modelling study', *The Lancet Planetary Health*, 2(12), pp. e540–e547, doi:10.1016/s2542-5196(18)30240-7 (accessed 13 Aug. 2021).
29 Converted Andrews et al. (2018) temperature thresholds to timeframes, based on RCP4.5 passing relevant temperature thresholds, based on CMIP6 climate models. See https://esd.copernicus.org/articles/12/253/2021/esd-12-253-2021-discussion.html and https://www.carbonbrief.org/analysis-when-might-the-world-exceed-1-5c-and-2c-of-global-warming.
30 Arnell et al. (2019), 'The global and regional impacts of climate change under representative concentration pathway forcings and shared socioeconomic pathway socioeconomic scenarios'.

Protecting citizens from the consequences of heatwaves will be challenging for all governments. More worryingly, some 5.2 billion people – just over half the world's population – are expected to be subjected to major heatwaves of at least four consecutive days per year under the central estimate; this exposure extends to more than 95 per cent of the global population under the plausible worst-case scenario. Clearly, all things being equal, the larger the population size in 2050, the larger the number of people exposed to heatwaves. However, if climate change were averted completely, fewer than 0.5 billion people would experience major heatwaves, over 90 per cent below the central estimate. By 2040, 3.9 billion people are likely to experience major heatwaves, 12 times more than the historic average. While major heatwaves are defined as being at least twice as long as heatwaves, the temperatures experienced by people are also greater.[31]

By 2040, 3.9 billion people are likely to experience major heatwaves, 12 times more than the historic average.

As well as considering heatwaves in terms of the number of people experiencing a minimum number of consecutive days of a given severity of temperature, it is important to consider the duration of heatwaves. The central estimate indicates that 135 billion person days per year in 2050 will exceed the 98th percentile of warm season temperatures, within the reference period. Hence, the average person globally in 2050 will experience 14.6 days of heatwaves per year, compared with 1.1 days if climate change were averted.

Figure 3a. Global population experiencing a heatwave that exceeds the 98th percentile of the reference period (1981–2010) for two or more consecutive days per year

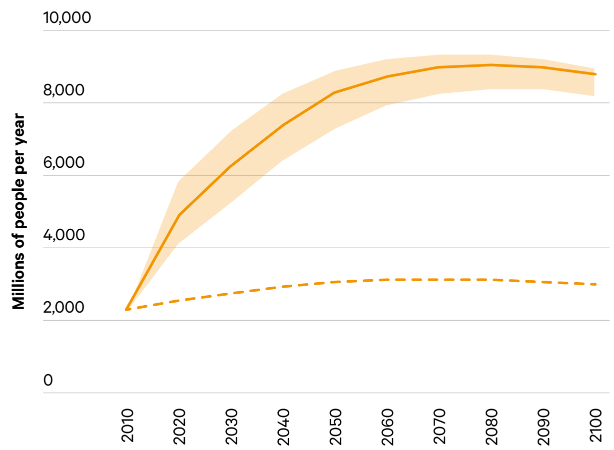
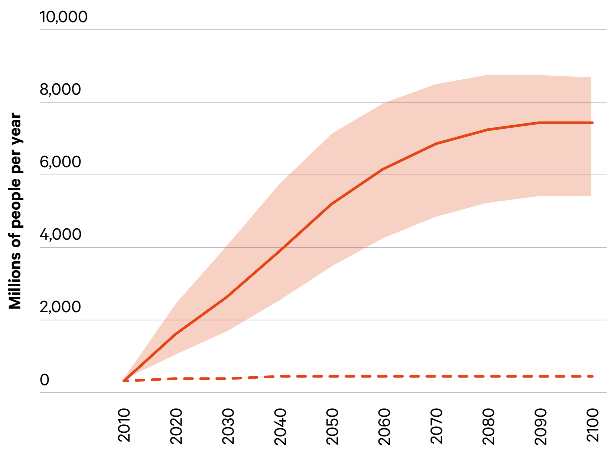


Figure 3b. Global population experiencing a major heatwave that exceeds the 99th percentile of the reference period (1981–2010) for four or more consecutive days per year



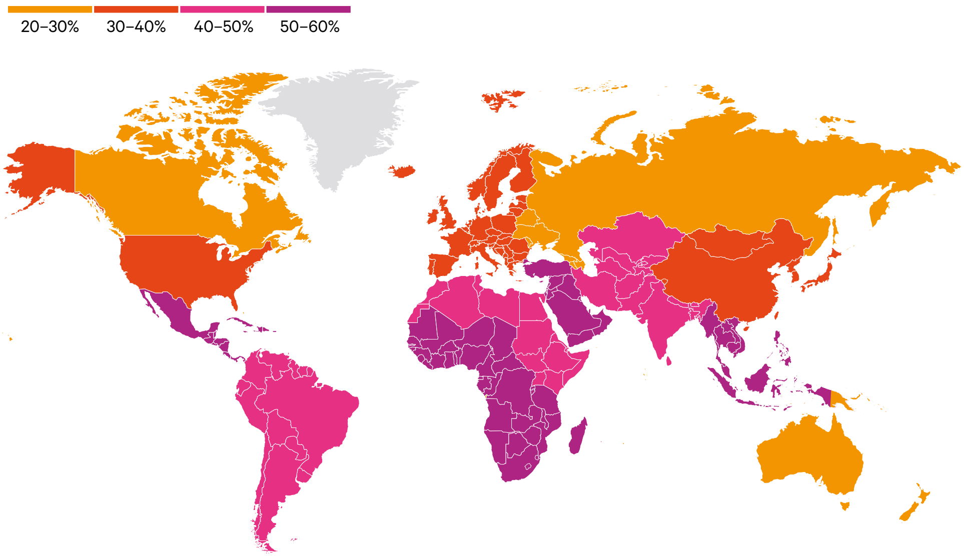
Shaded areas represent the lower and upper estimates of the given impact. Solid lines represent the central estimate. Dashed lines represent no additional climate change. Source: Adapted from Arnell et al. (2019).

31 By definition, a heatwave requires the temperature to exceed the 98th percentile of the historic reference period (1981–2010); a major heatwave exceeds the 99th percentile.

Regional heatwaves

No region will be spared. By 2040, major heatwaves will be experienced by 50 per cent or more of the populations in West, Central, East and Southern Africa, the Middle East, South and Southeast Asia, as well as Central America and Brazil (Figure 4). By 2050, more than 70 per cent of people in every region will experience heatwaves.[32] Urban areas will experience the greatest challenges of workability and survivability,[33] due to urban heat island effects.

Figure 4. Proportion of regional populations experiencing major heatwaves, in 2040



Source: Adapted from Arnell et al. (2019).

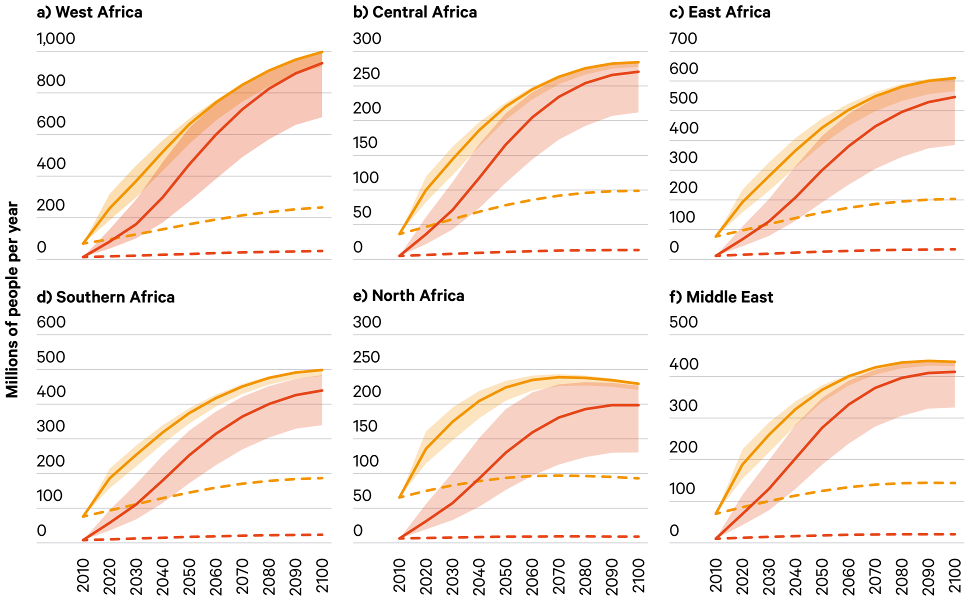
Africa and the Middle East

Across Africa and the Middle East, the projection under the central estimate is that more than 2.25 billion people will likely experience at least one heatwave of two or more consecutive days per year by 2050, exceeding 90 per cent of the population in all regions illustrated in Figure 5a–f. Major heatwaves of four consecutive days or more will be experienced across these regions, impacting more than 1.5 billion people – around two thirds of the population. For all these regions, major heatwaves will likely impact at least 10 times more people than if climate change were averted. West Africa is likely to be particularly impacted, with nearly half a billion people experiencing major heatwaves, 17 times more than if climate change were averted. Heatwaves in all these regions will also be felt over an increasing number of days

32 Arnell et al. (2019), 'The global and regional impacts of climate change under representative concentration pathway forcings and shared socioeconomic pathway socioeconomic scenarios'.
33 Andrews et al. (2018), 'Implications for workability and survivability in populations exposed to extreme heat under climate change: a modelling study'.

per year. By 2050, North Africa is projected to be the least impacted, with 13 days per year of heatwaves; and Central Africa the most impacted, with 26 days. However, by 2100 the duration of heatwaves in Central Africa increases to over two months of the year for the central estimate, and almost seven months of the year for the high range of the estimate.

Figure 5. Populations within African regions and the Middle East experiencing heatwaves and major heatwaves



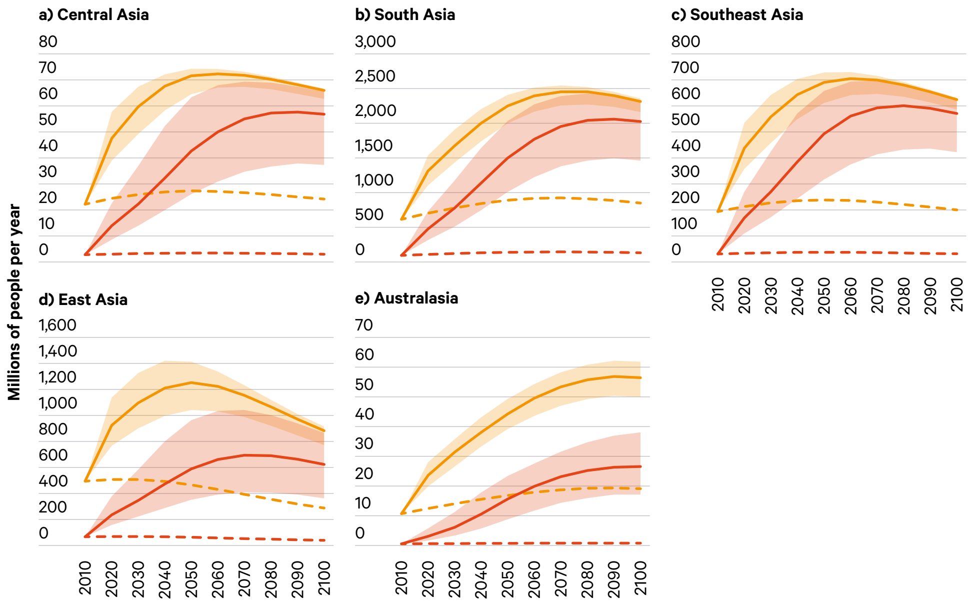
Orange lines and areas represent heatwaves; red lines and areas represent major heatwaves. Shaded areas represent the lower and upper estimates of the given impact. Solid lines represent the central estimate. Dashed lines represent no additional climate change.
Source: Adapted from Arnell et al. (2019).

Asia and Australasia[34]

Across Asia (Figure 6a–d), the central estimate indicates that in excess of 4.2 billion people will likely experience heatwaves by 2050, equivalent to 90 per cent of the population. Across the most populous regions of South and East Asia, the central estimate indicates major heatwaves will impact more than 2 billion people in aggregate, around 60 per cent and 40 per cent of the population respectively. Relative to a scenario in which climate change is averted, Southeast Asia is projected to be most impacted, with over 13 times more people likely to experience major heatwaves. The duration of heatwaves also impacts Southeast Asia most heavily, with the central estimate indicating more than 25 days of heatwaves per year.

34 Australasia is defined in the source analysis (Arnell et al., 2019) as including Australia, New Zealand, Papua New Guinea and the Pacific islands.

Figure 6. Populations within Asia and Australasia experiencing heatwaves and major heatwaves



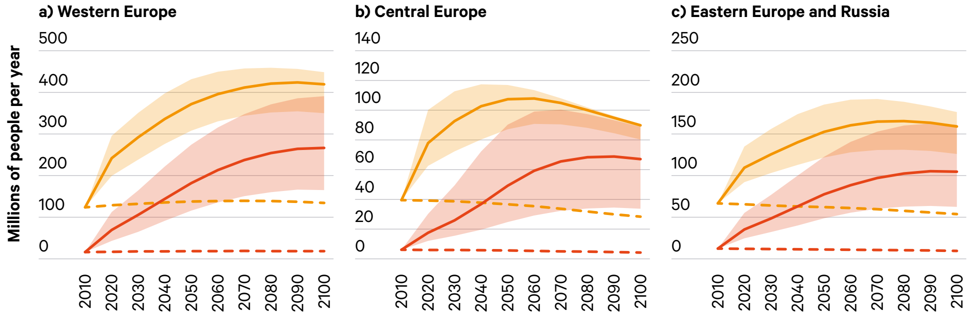
Orange lines and areas represent heatwaves; red lines and areas represent major heatwaves. Shaded areas represent the lower and upper estimates of the given impact. Solid lines represent the central estimate. Dashed lines represent no additional climate change.
Source: Adapted from Arnell et al. (2019).

The central estimate indicates more than 40 million people in Australasia (Figure 6e) are likely to experience heatwaves by 2050, equivalent to 80 per cent of the population. Major heatwaves are likely to impact over 22 times more people in 2050 than if climate change were averted, with over 10 days of heatwaves per year.

Europe

In Europe, as for Australasia, the impacts of heatwaves are felt by a relatively smaller proportion of the population compared with other regions. However, the central estimate for 2050 still indicates that more than 80 per cent of the population – i.e. over 0.6 billion people – are likely to experience heatwaves. Central Europe will be the most impacted (Figure 7b), with more than 90 per cent of the 2050 population, or just over 100 million people, experiencing heatwaves. Major heatwaves are most likely to impact the population of Western Europe (Figure 7a), with the central estimate indicating over 180 million people, 11 times more than if climate change were averted. By 2100, the central estimate indicates almost 16 days of heatwaves per year, but this could extend to as many as 35 days.

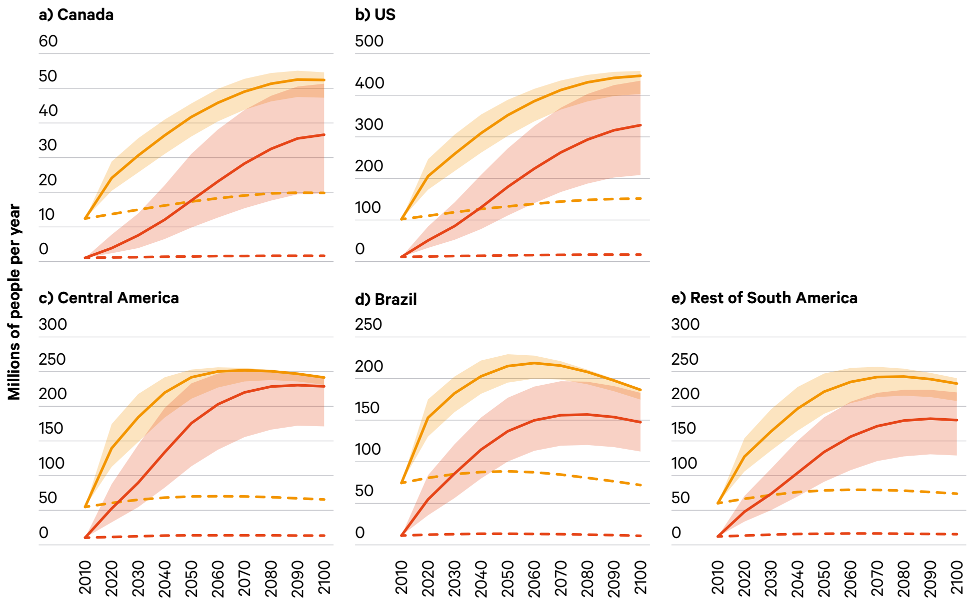
Figure 7. Populations within Europe experiencing heatwaves and major heatwaves



Orange lines and areas represent heatwaves; red lines and areas represent major heatwaves. Shaded areas represent the lower and upper estimates of the given impact. Solid lines represent the central estimate. Dashed lines represent no additional climate change.
Source: Adapted from Arnell et al. (2019).

North, Central and South America[35]

Figure 8. Populations within North, Central and South America experiencing heatwaves and major heatwaves



Orange lines and areas represent heatwaves; red lines and areas represent major heatwaves. Shaded areas represent the lower and upper estimates of the given impact. Solid lines represent the central estimate. Dashed lines represent no additional climate change.
Source: Adapted from Arnell et al. (2019).

In North America, under the central estimate, more than 350 million and 40 million people across the US and Canada, respectively, are likely to experience heatwaves by 2050, respectively (Figure 8a&b), representing more than 85 per cent of the population of each country. The US is likely to be more severely impacted

35 Mexico and the Caribbean islands are included in the source analysis (Arnell et al., 2019) as part of Central America.

by major heatwaves, with 44 per cent of the population experiencing such events, as against 36 per cent in Canada. Compared to a scenario in which climate change is averted, both countries are likely to experience around 12 times more major heatwaves in 2050, with more than 13 per days per year of heatwaves in Canada, and over 20 days per year in the US.

Central America and Brazil (Figure 8c&d) are likely to be two of the most impacted regions, with the central estimate indicating that 95 per cent and 93 per cent of their respective populations will experience heatwaves by 2050. Across the whole of Central and South America, more than 670 million people will likely experience heatwaves, and in excess of 440 million – or 60 per cent of the population – are projected to experience major heatwaves. Across South and Central America, major heatwaves are likely to impact 10 times more people than if climate change were averted. Across Central and South America, by 2050, there are likely to be in excess of 20 days of heatwaves per year.

3.3 Food security

To meet global demand, agriculture will need to produce almost 50 per cent more food by 2050. However, yields could decline by 30 per cent in the absence of dramatic reductions in emissions.[36] Between 1980 and 2019, global average crop yield potentials[37] for maize, winter wheat, soybeans and rice have declined, with reductions of 5.6 per cent, 2.1 per cent, 4.8 per cent and 1.8 per cent, respectively.[38] In recent years, regional drought and heatwaves have caused 20–50 per cent losses in crop harvests. In Australia, severe drought caused a 50 per cent collapse of wheat harvests two years in a row (2006 and 2007).[39] In Europe, the 2018 heatwave led to multiple crop failures and yield losses of up to 50 per cent in Central and Northern Europe.[40] During this period, Central Europe experienced severe drought across 52 per cent of the cropland area, where the threshold of severe drought is equivalent to the threshold of severe drought used here (Figure 9a&b and Figure 12). And in China, in Liaoning Province, drought years led to 20–25 per cent reductions in maize harvests.[41] The global food crisis of 2007–08, caused by a conjunction of depleted grain stores, Australian drought and regional crop failures,

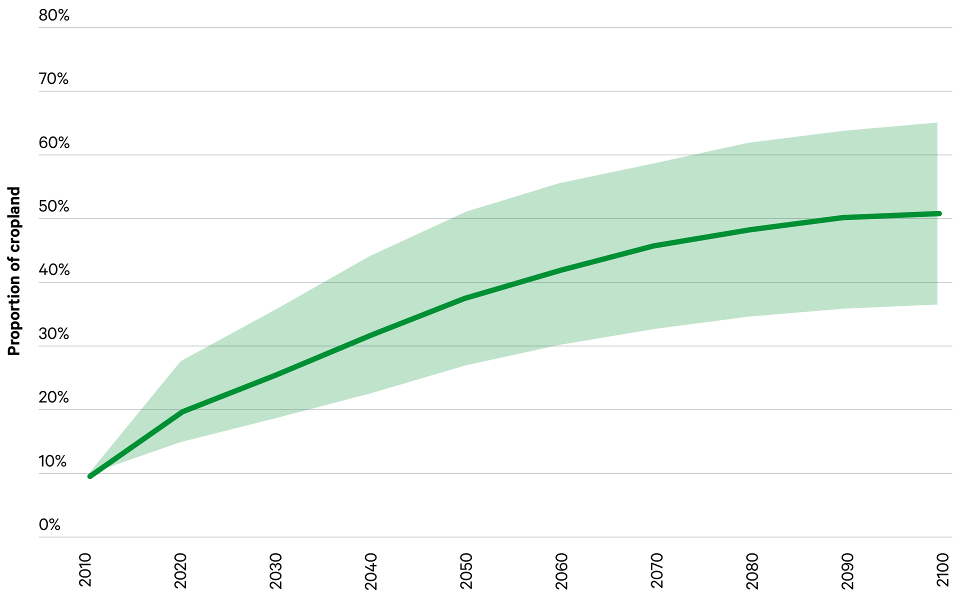
36 Global Commission on Adaptation (2019), *Adapt Now: A Global Call For Leadership On Climate Resilience*, Rotterdam: Global Commission on Adaptation, https://gca.org/reports/adapt-now-a-global-call-for-leadership-on-climate-resilience (accessed 13 Aug. 2021).
37 Crop yield potential is characterized by 'crop growth duration' (the time taken to reach a target sum of accumulated temperatures) over its growing season. If this sum is reached early, the crop matures too quickly and yields are lower than average, with a reduction in crop growth duration therefore representing a reduction in yield potential.
38 Watts et al. (2021), 'The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises'.
39 Index Mundi (2021), 'Australia Wheat Production by Year', https://www.indexmundi.com/agriculture/?country=au&commodity=wheat&graph=production (accessed 13 Jun. 2021).
40 Beillouin, D., Schauberger, B., Bastos, A., Ciais, P. and Makowski, D. (2020), 'Impact of extreme weather conditions on European crop production in 2018', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 375(1810): p.20190510, doi:10.1098/rstb.2019.0510 (accessed 13 Aug. 2021). Toreti, A., Belward, A., Perez-Dominguez, I., Naumann, G., Luterbacher, J., Cronie, O., Seguini, L., Manfron, G., Lopez-Lozano, R., Baruth, B., Berg, M., Dentener, F., Ceglar, A., Chatzopoulos, T. and Zampieri, M. (2019), 'The Exceptional 2018 European Water Seesaw Calls for Action on Adaptation', *Earth's Future*, 7(6): pp. 652–663, doi:10.1029/2019ef001170 (accessed 13 Aug. 2021).
41 Chen, T., Xia, G., Liu, T., Chen, W. and Chi, D. (2016), 'Assessment of Drought Impact on Main Cereal Crops Using a Standardized Precipitation Evapotranspiration Index in Liaoning Province, China', *Sustainability*, 8(10): p. 1069, doi:10.3390/su8101069 (accessed 13 Aug. 2021).

led to a doubling of global food prices, export bans, food insecurity for importers, social unrest, and mass protests in at least 13 countries, including Cameroon, Egypt, Indonesia, Mexico, Morocco, Nepal, Peru, Senegal and Yemen.[42, 43]

By 2050 the central estimate indicates that nearly 40 per cent of global cropland area will be exposed to severe drought for three months or more each year.

Agricultural drought is a major cause of crop failure. Assuming global cropland remains constant at 14.7 million square kilometres, by 2050 the central estimate indicates that nearly 40 per cent of that area will be exposed to severe drought for three months or more each year;[44] however, this could reach just over 50 per cent under the plausible worst-case scenario (Figure 9a). This vast area of stressed cropland is far higher than the 9 per cent of global cropland historically exposed to drought (1981–2010). Even by 2040, the average proportion of global cropland affected by severe drought will likely rise to 32 per cent each year, more than three times higher than the historic average.

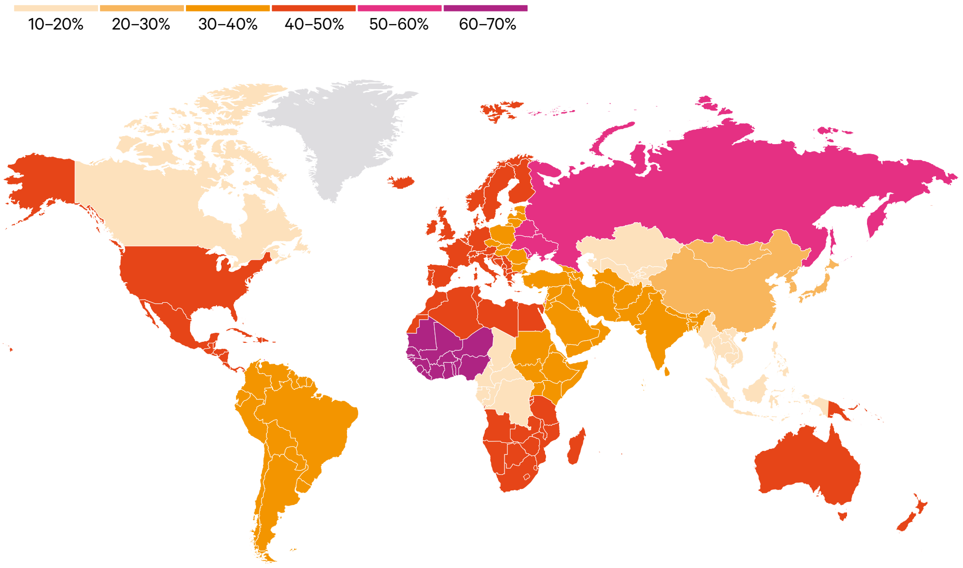
Figure 9a. Proportion of global cropland experiencing severe drought of three months or more per year



Shaded area represents the lower and upper estimates of the given impact. Solid line represents the central estimate.
Source: Adapted from Arnell et al. (2019).

42 Wright, B. D. (2011), 'The Economics of Grain Price Volatility', *Applied Economic Perspectives and Policy*, 33(1): pp. 32–58, doi:10.1093/aepp/ppq033 (accessed 13 Aug. 2021). Spiegel International (2008), 'Global Food Crisis: The Fury of the Poor', 14 April 2008, https://www.spiegel.de/international/world/global-food-crisis-the-fury-of-the-poor-a-547198.html (accessed 13 Jun. 2021).
43 United Nations (2012), *Report on the World Social Situation 2011: The Global Social Crisis*, New York: United Nations, pp. 61–74, https://www.un-ilibrary.org/content/books/9789210552226 (accessed 13 Aug. 2021).
44 A severe drought is a period of at least three months with a SPEI-6 less than -1.5. SPEI: Standardised Precipitation-Evapotranspiration Index (SPEI: Vicente-Serrano et al., 2010).

Figure 9b. Proportion of regional cropland exposed to severe drought, in 2050



Source: Adapted from Arnell et al. (2019).

Farmers in the worst-affected areas (Figure 9b), including the critical breadbasket regions of southern Russia and the US, are likely to experience agricultural drought impacting 40 per cent or more of their cropland area every year. By the 2040s, the probability of a 10 per cent yield loss, or greater, within the top four maize producing countries (the US, China, Brazil and Argentina) rises to 40–70 per cent. These countries together account for some 87 per cent of the world's maize exports. The probability of a synchronous, greater than 10 per cent crop failure across all four countries is currently near zero, but this rises to around 6.1 per cent each year in the 2040s. The probability of a synchronous crop failure of this order during the decade of the 2040s is just less than 50 per cent.[45,46]

The probability of a synchronous, greater than 10 per cent crop failure across all of the top four maize producing countries is currently near zero, but this rises to around 6.1 per cent each year in the 2040s. The probability of a synchronous crop failure of this order during the decade of the 2040s is just less than 50 per cent.

45 Tigchelaar, M., Battisti, D. S., Naylor, R. L. and Ray, D. K. (2018), 'Future warming increases probability of globally synchronized maize production shocks', *Proceedings of the National Academy of Sciences*, 115(26): pp. 6644–6649, doi:10.1073/pnas.1718031115 (accessed 13 Aug. 2021).
46 Converted Tigchelaar et al. (2018) temperature thresholds to timeframes, based on RCP4.5 passing relevant temperature thresholds, based on CMIP6 climate models. See https://esd.copernicus.org/articles/12/253/2021/esd-12-253-2021-discussion.html and https://www.carbonbrief.org/analysis-when-might-the-world-exceed-1-5c-and-2c-of-global-warming. Further, converted annual likelihood of 6.1 per cent to probability decadal probability of occurrence.

Wheat and rice form a major component of people's diets, together comprising 37 per cent of average calorific intake per head globally.[47] The central 2050 estimate (Figure 10a&b) indicates that more than 35 per cent of the global cropland used to grow both these critical crops will be subject to at least five days of damaging hot spells[48] over their 30-day reproductive phase; but this could exceed 40 per cent in a plausible worst-case scenario. For comparison, 20 per cent and 27 per cent of winter wheat and rice areas, respectively, are currently under the same damaging hot spells.

As well as damaging hot spells of at least five days, agricultural crops will also have to deal with a reduction in crop duration periods.[49] Damaging hot spells and reductions in crop duration periods can both reduce yields. The central estimate for 2050 indicates that significant proportions of global crop areas will be impacted by reductions in crop duration periods of at least 10 days, exceeding 45 per cent for maize, 50 per cent for soybeans, 60 per cent for winter wheat, 40 per cent for spring wheat, and 30 per cent for rice. Figure 11 indicates how the proportion of these croplands is impacted over time. It is important to note that, across these critical crops, the current global cropland area subject to reductions in crop duration periods is 5 per cent or less in all but one case; the exception is soybeans, currently around 7 per cent.

Figure 10a. Proportion of global winter wheat crop area experiencing damaging hot spells

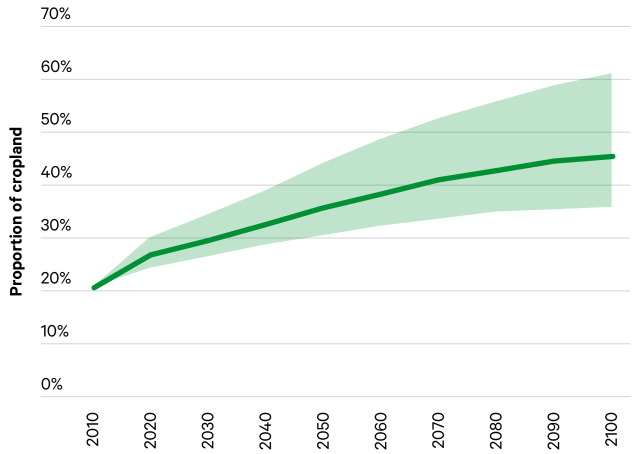
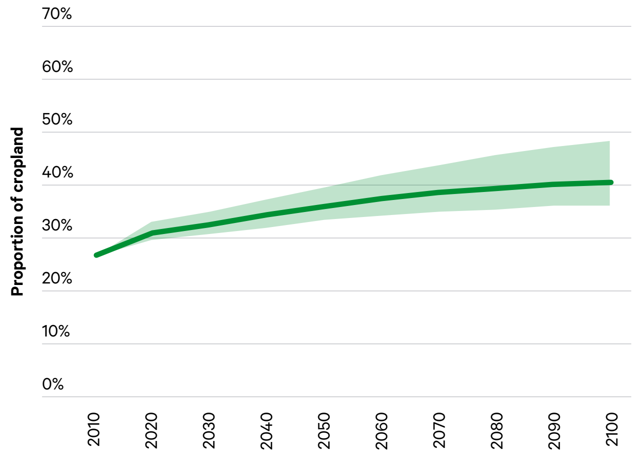


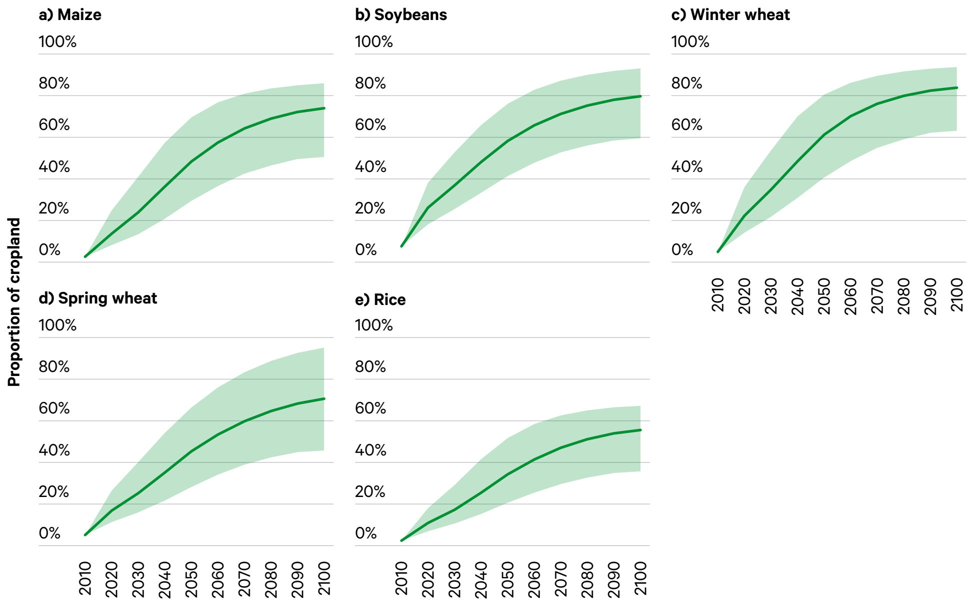
Figure 10b. Proportion of global rice crop area experiencing damaging hot spells



Shaded areas represent the lower and upper estimates of the given impact. Solid lines represent the central estimate.
Source: Adapted from Arnell et al. (2019).

47 FAO (2017), FAOSTAT data, http://www.fao.org/faostat/en/#home (accessed 14 Aug. 2021).
48 A hot spell consists of at least five days above a heat stress threshold (Table S1) during the 30-day reproductive phase of the crop, with the heat stress thresholds taken from Gourdji et al., 2013. The reproductive season is based on planting dates (Sacks et al., 2010) which are assumed not to change over time.
49 This is defined (following Challinor et al., 2016) on the basis of the accumulated thermal time (ATT) over the growing season, where the ATT is the sum of temperatures above a minimum temperature and capped at an optimum temperature.

Figure 11. Proportion of global crop areas with reductions in crop duration periods of at least 10 days, by crop type



Shaded areas represent the lower and upper estimates of the given impact. Solid lines represent the central estimate.
Source: Adapted from Arnell et al. (2019).

Continental agricultural impacts

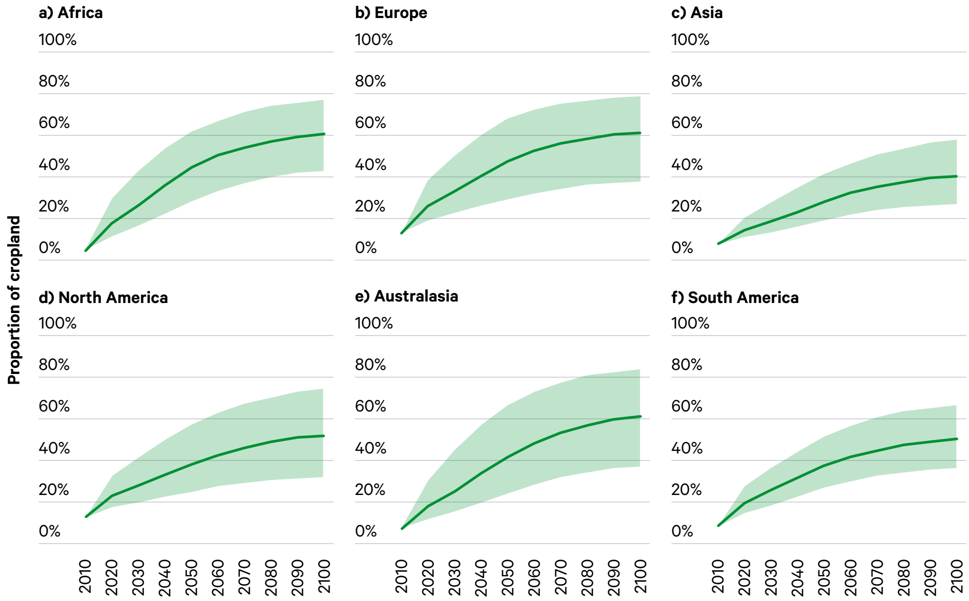
Crop drought

As already highlighted, by 2050 the central estimate indicates that almost 40 per cent of global cropland will likely be exposed to severe drought each year.[50] However, as the Asian continent contains 37 per cent of global cropland and a relatively low proportion of Asian cropland is subject to severe drought (just less than 30 per cent by 2050), it is crucial to investigate the continental impacts (Figure 12).

Europe has the second largest cropland area (20 per cent of the global total), and is likely to experience the largest increase in area affected by agricultural drought, with the central estimate indicating that nearly half the cropland area will experience severe periods of drought by 2050. Africa and North America have similar land areas dedicated to cropland: respectively 14 per cent and 15 per cent of the global total. However, Africa is likely to be more impacted, with almost 44 per cent of cropland projected to suffer severe drought, compared with 38 per cent for North America. Australasia is likely to be impacted to a similar extent as Europe, but only represents 2 per cent of global cropland.

50 Cropland areas are assumed to remain constant.

Figure 12. Proportion of continental cropland experiencing severe drought of three months or more



Shaded areas represent the lower and upper estimates of the given impact. Solid lines represent the central estimate.
Source: Adapted from Arnell et al. (2019).

Crop heat stress and duration reductions

At the global level, to 2050, damaging hot spells increase across winter wheat and rice croplands. However, relative to historic baselines, the cropland area impacted by reductions in crop duration periods is likely to be greater than the area impacted by increases in damaging hot spells. The same is true at the continental level, and is illustrated in Figure 13a–l. Across the six continents and five crop types shown in Table 1, this section focuses on those crop–continent combinations illustrated in Figure 13a–l that (a) in aggregate represent at least 10 per cent of a given continent's cropland area; and (b) in aggregate represent at least 70 per cent of the global total of a given crop area.

Of those crop–continent combinations selected, shown in Table 1 and illustrated in Figure 13a–l, the predominant crops, by area, in Africa and Europe are maize (10 per cent) and winter wheat (16 per cent) respectively. Under the central estimate, more than 40 per cent of African maize growing areas are likely to be subject to reductions in crop duration periods of at least 10 days by 2050, up from 0.3 per cent historically (Figure 13i), while nearly 75 per cent of European winter wheat is subject to equally yield-reducing conditions (reductions in crop duration periods), up from almost 6 per cent historically.

Table 1. Cropland areas across crop types and continents. Highlighted entries are shown in Figure 13.

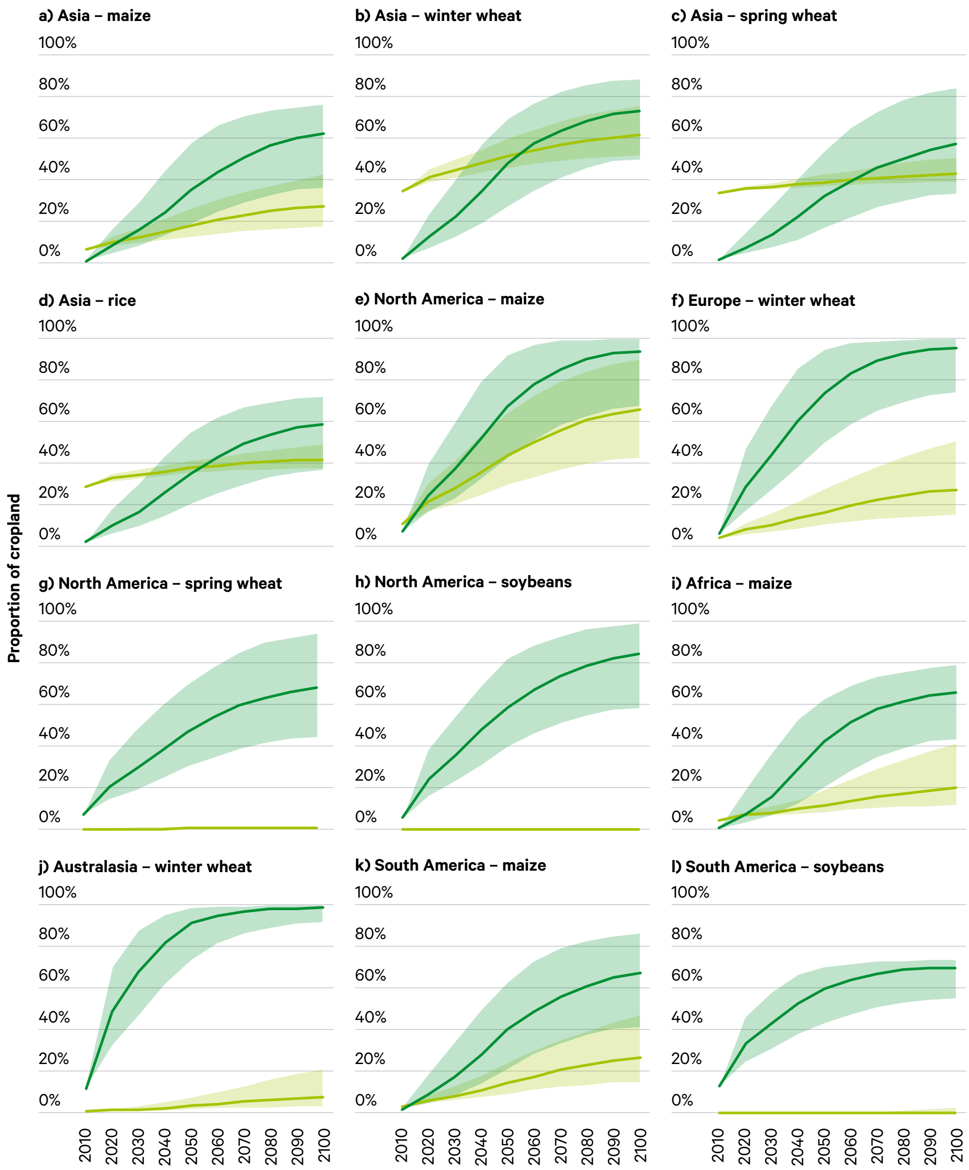
	Cropland areas, in thousand km²						
	Maize	**Winter wheat**	**Spring wheat**	**Rice**	**Soybeans**	**Total**	**Selection (% continent (a))**
Global	1,335	1,721	415	788	744	**14,719**	–
Africa	219	64	14	54	9	**2,124**	10%
Asia	419	818	175	667	171	**5,513**	38%
Europe	136	491	36	4	11	**3,009**	16%
North America	302	150	180	13	306	**2,185**	36%
South America	259	81	10	50	247	**1,573**	32%
Australasia	1	118	0	1	0	**315**	38%
Selection (% global (b))	90%	83%	86%	85%	74%	**–**	–

(a) In aggregate representing at least 10 per cent of continent's cropland area.
(b) In aggregate representing at least 70 per cent of the global total of crop area.

Maize, winter wheat and spring wheat make up around 38 per cent of Asian croplands. Figure 13a–d illustrates the reductions in crop duration periods across these crops. In aggregate, 40 per cent of the growing area is likely to be subject to reductions in crop duration periods of at least 10 days by 2050, with winter wheat the most impacted (over 50 per cent) under the central estimate. Similarly, in aggregate, just less than 60 per cent of North American maize, spring wheat and soybeans are likely to be subject to such yield reducing conditions (Figure 13e, g&h), with these crops making up 36 per cent of North American cropland areas.

Turning to South America, in aggregate, just less than half of maize and soybean croplands are likely to suffer reduced crop duration periods (Figure 13k&l) by 2050, with these crops accounting for 32 per cent of South American cropland areas. Finally, in Australasia, again under the central estimate, more than 90 per cent of winter wheat growing areas will be to be subject to reductions in crop duration periods (Figure 13j), with winter wheat representing 38 per cent of Australasian cropland.

Figure 13. Proportion of the largest areas, for different crops per continent (across five crop types), with reductions in crop duration periods of at least 10 days, and experiencing damaging hot spells



Dark green lines and areas represent hot spells; bright green represent reductions in crop duration periods. Shaded areas represent the lower and upper estimates of the given impact. Solid lines represent the central estimate.
Source: Adapted from Arnell et al. (2019).

Agricultural yields

Crop yields are likely to be reduced by the conditions represented by the three impact indicators of agricultural drought, shorter crop durations[51] and heat stress,[52] presented in the previous sections. The thresholds of impact for these crop impact indicators are set at a level where crossing these thresholds is damaging to crop yields.[53] The dramatic increase in frequency and probability of these extreme events in all regions even under the central estimate – let alone under the plausible worst-case scenario – indicates that yields could be dramatically reduced. While probabilistic estimates for crop yields are not made directly here, it remains plausible that multiple breadbaskets may suffer simultaneous effects, with the potential to drive significant reduction in yields at global as well as regional levels.

It remains plausible that multiple breadbaskets may suffer simultaneous effects, with the potential to drive significant reduction in yields at global as well as regional levels.

The 2007–08 and 2010–11 food price spikes arose from relatively modest climate impacts interacting with other factors (e.g. biofuel policy diverting grain to ethanol, low stock transparency), which created a run on grain markets, in turn leading to the implementation of export bans, and thus further amplifying the price effect. The consequences for global food prices, availability and associated food riots around the world is well known. The impacts of climate change will likely compound these risks in the average year of the coming decades. It should be noted, too, that the impact indicators of the previous sections are not representative of extreme outlier events, such as megadroughts, nor of the impacts of interacting or compounding risks that are likely to occur as multiple risks interact.

3.4 Water security

Hydrological drought poses a significant risk on the global scale (Figure 14a). Long droughts are one of the most significant environmental causes of premature mortality, impacting sanitation and hygiene, increasing malnutrition, and reducing crop yields.[54] Over twice the global land area was affected by drought in 2019, compared with the historic baseline. In the Sahel in 2020, some 13.4 million

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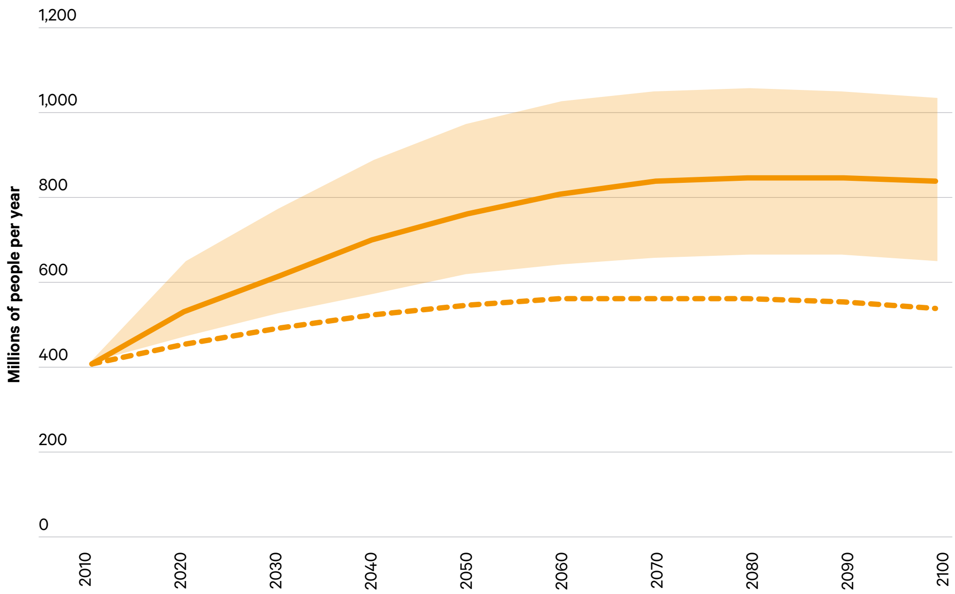
51 Challinor, A. J., Koehler, A.-K., Ramirez-Villegas, J., Whitfield, S. and Das, B. (2016), 'Current warming will reduce yields unless maize breeding and seed systems adapt immediately', *Nature Climate Change*, 6(10): pp. 954–958, doi:10.1038/nclimate3061 (accessed 13 Aug. 2021).
52 Gourdji, S. M., Sibley, A. M. and Lobell, D. B. (2013), 'Global crop exposure to critical high temperatures in the reproductive period: historical trends and future projections', *Environmental Research Letters*, 8(2): 024041, doi:10.1088/1748-9326/8/2/024041 (accessed 13 Aug. 2021).
53 See Arnell et al. (2019) for further details on these thresholds as well as the previous section descriptions of these thresholds.
54 Smith, K. R., Woodward, A., Campbell-Lendrum, D., Chadee, D. D., Honda, Y., Liu, Q., Olwoch, J. M., Revich, B. and Sauerborn, R. (2014), 'Human Health: Impacts, Adaptation, and Co-Benefits', in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge and New York: Cambridge University Press.

people in Mali, Niger and Burkina Faso were reported as being affected by drought, and in need of humanitarian assistance; and the region's security crisis, in part driven by shocks related to climate change, has caused some 2.7 million people to flee their homes.[55] In the US drought of 2012, natural disasters were declared in 71 per cent of the country's counties, and a reduction in GDP growth of 0.5–1 percentage point was forecast.[56] In China's Yunnan Province, the 2020 drought affected 1.5 million people. 180 reservoirs in the province dried up, 100 rivers were cut off, and 140 irrigation wells lacked sufficient water supply.[57]

Figure 14a. Global population experiencing a drought of at least six months with 12-month accumulated Standardized Runoff Index of less than -1.5



Shaded area represents the lower and upper estimates of the given impact. Solid line represents the central estimate. Dashed line represents no additional climate change.
Source: Adapted from Arnell et al. (2019).

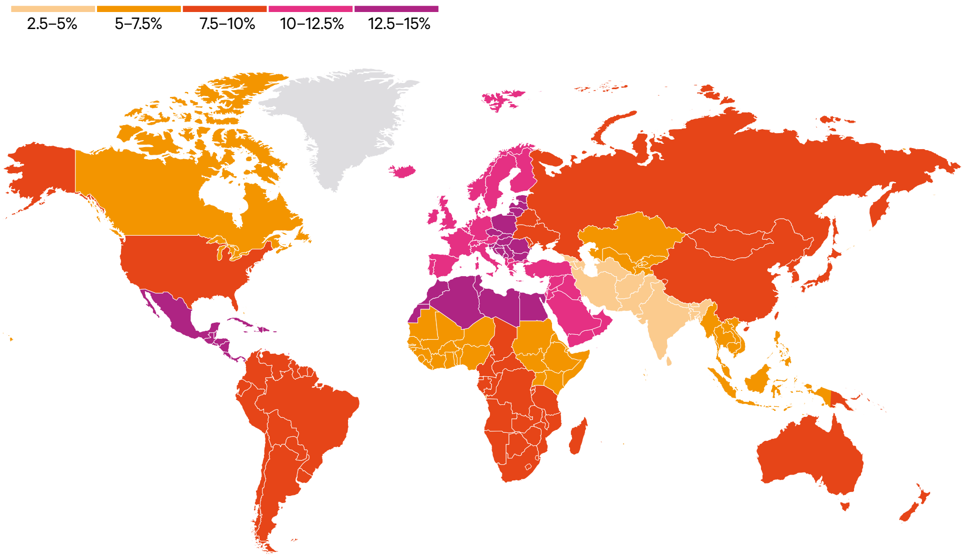
By 2040, the central estimate indicates almost 700 million people each year will be exposed to hydrological droughts of at least six months' duration.[58] This represents a near doubling of the historic annual average of 408 million people subjected to long periods of drought. The severity and length of these future droughts

55 Watts et al. (2021), 'The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises'. UNHCR (2020), 'Sahel Crisis Explained', https://www.unrefugees.org/news/sahel-crisis-explained (accessed 11 Jun. 2021). CRED and UNDRR (2020), The Non-COVID Year in Disasters, Brussels: CRED, https://reliefweb.int/report/world/2020-non-covid-year-disasters-global-trends-and-perspectives (accessed 11 Jun. 2021).
56 Richter, J. (2012), 'U.S. Drought May Cut GDP by 1 Percentage Point, Deutsche Says', Bloomberg, 12 November 2012, https://www.bloomberg.com/news/articles/2012-11-12/u-s-drought-may-cut-gdp-by-one-percentage-point-deutsche-says (accessed 11 Jun. 2021). USDA (2013), 'USDA Designates 597 Counties in 2013 as Disaster Areas Due to Drought', U.S. Department of Agriculture, 9 January 2013, https://www.usda.gov/media/press-releases/2013/01/09/usda-designates-597-counties-2013-disaster-areas-due-drought (accessed 1 May 2021).
57 CGTN (2020), 'Chinese plateau province sees worst drought in 10 years', China Global Television Network, 18 April 2020, https://news.cgtn.com/news/2020-04-18/Chinese-plateau-province-sees-worst-drought-in-10-years-PMGdSN543e/index.html (accessed 1 May 2021).
58 Hydrological drought: a period of at least six months with 12-month accumulated Standardized Runoff Index (SRI) of less than -1.5. (SRI: Shukla and Wood 2008.)

are projected to be at least as bad as the first wave (1934) of the US Midwest 'dust bowl' drought of the 1930s.[59]

It should be noted that this paper does not present a quantification of the likelihood of megadroughts. One recent study has shown such a multi-decadal drought in southwestern North America in 2000–18 was the most severe since medieval megadroughts (late 1500s), and the second driest 19-year period since 800 CE.[60]

Figure 14b. Proportion of regional populations experiencing drought, in 2040



Source: Adapted from Arnell et al. (2019).

Continental and regional drought

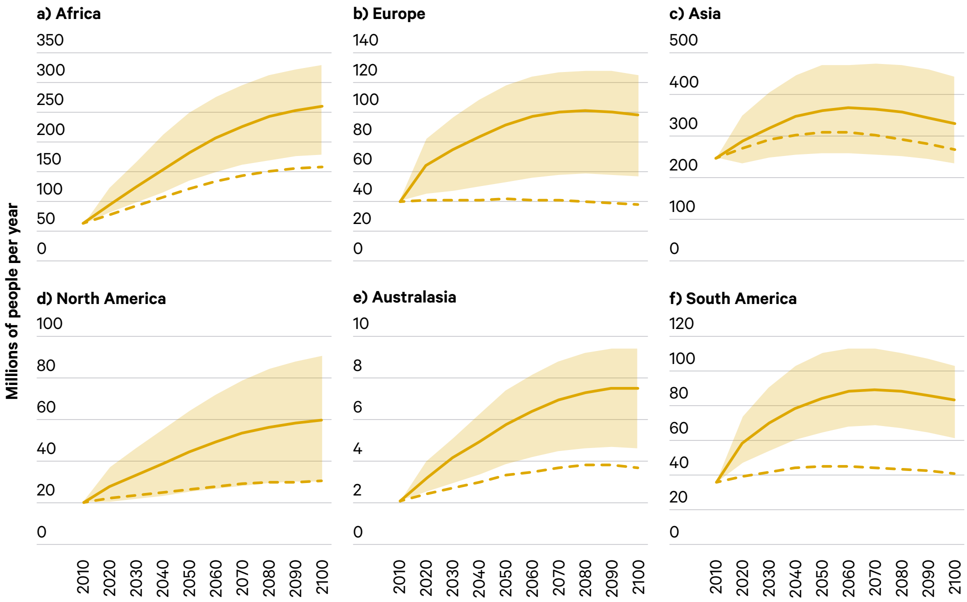
Heatwaves and increased temperatures place greater stress on the availability of water regionally. No region will be spared, but by 2040 East and South Asia will be most impacted, with 125 million and 105 million people respectively experiencing prolonged hydrological drought. In Africa, 152 million people each year will be impacted. As Figure 14b shows, more than 10 per cent of the populations of North Africa, the Middle East, Western and Central Europe, and Central America will all be impacted by prolonged drought.

Figure 15 illustrates the populations, by continent, likely to experience droughts of at least six months' duration to the end of this century. Whereas by 2050 the population of Asia is likely to be most impacted, with more than 360 million people affected, this is a relatively low (although nonetheless troubling) 17 per cent increase relative

59 Mishra, V., Cherkauer, K. A. and Shukla, S. (2010), 'Assessment of Drought due to Historic Climate Variability and Projected Future Climate Change in the Midwestern United States', *Journal of Hydrometeorology*, 11(1): pp. 46–68, doi:10.1175/2009jhm1156.1 (accessed 13 August 2021).
60 Williams, A. P., Cook, E. R., Smerdon, J. E., Cook, B. I., Abatzoglou, J. T., Bolles, K., Baek, S. H., Badger, A. M. and Livneh, B. (2020), 'Large contribution from anthropogenic warming to an emerging North American megadrought', *Science*, 368(6488): pp. 314–318, doi:10.1126/science.aaz9600 (accessed 13 Aug. 2021).

to a scenario in which climate change is averted. Europe and South America are likely to see the greatest increase in this regard by 2050, at more than 120 per cent and nearly 90 per cent respectively. Setting Asia aside, the continent with the greatest number of people likely to be impacted by hydrological drought is Africa, exceeding 180 million by 2050 under the central estimate. Africa is also likely to suffer the greatest increase of people experiencing drought relative to the historic baseline (1981–2010), by 290 per cent from just below 63 million. This increase relative to the historic baseline is similar across all regions of the African continent. At regional level, the Middle East and Central America will each likely experience increases exceeding 300 per cent relative to the past under the central estimate, and in absolute terms affecting over 40 and 35 million people by 2050, respectively.

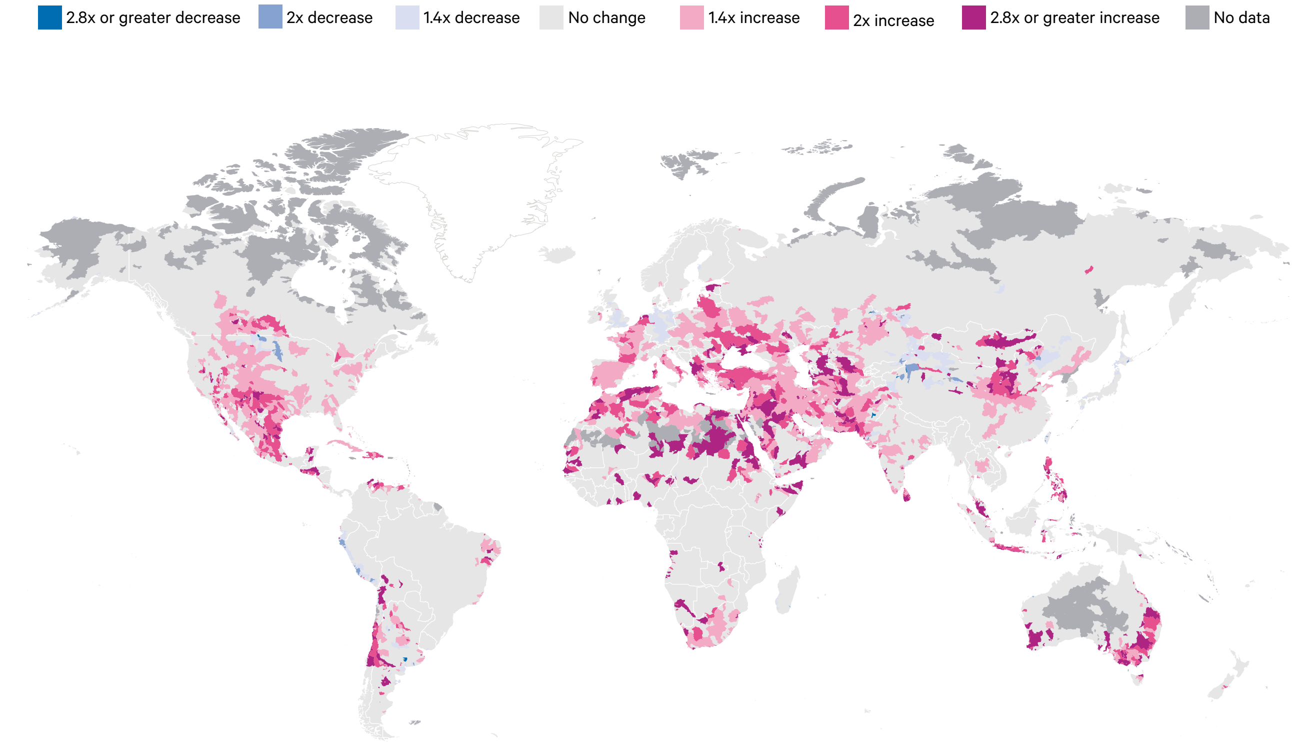
Figure 15. Populations experiencing a drought of at least six months with 12-month accumulated Standardized Runoff Index of less than -1.5, by continent



Shaded areas represent the lower and upper estimates of the given impact. Solid lines represent the central estimate. Dashed lines represent no additional climate change.
Source: Adapted from Arnell et al. (2019).

Drought is a relative measure of water availability, and does not necessarily relate to the absolute amount of water per person. As such, it is useful also to consider water stress. North Africa and the Middle East are likely to have the greatest proportion of their populations experiencing severe water stress (i.e. availability of less than 500 cubic metres per head per year), at 17 per cent and 14 per cent, respectively, in 2050. As Figure 16 illustrates, many regions of the world are likely to see 40 per cent or greater increases in the difference between supply and demand of water by 2040, relative to the historic baseline.

Figure 16. Regions of increasing water stress (demand relative to supply) in 2040, relative to 2019



Source: World Resources Institute, Aqueduct Water Risk Atlas.

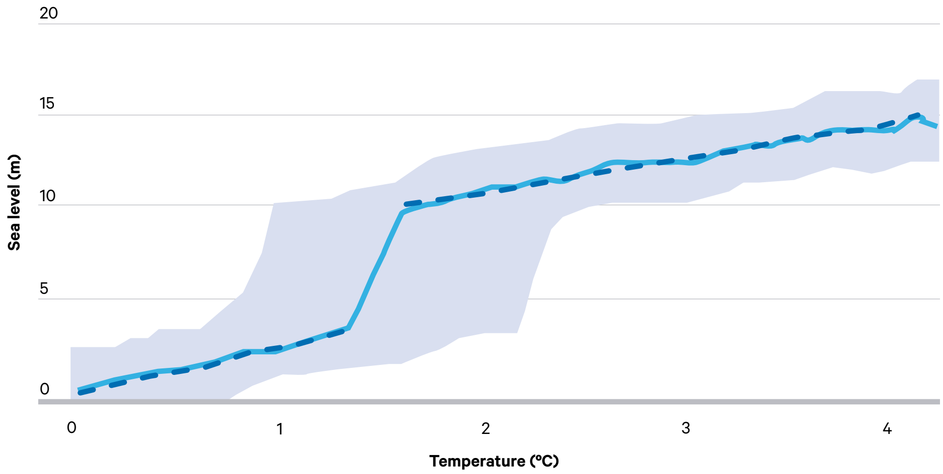
Regional coastal and river flooding

In 2020, there were 23 per cent more floods recorded than the annual average of 163 events in 2000–19, and 18 per cent more flood deaths than the annual average of 5,233.[61] One billion people are now living on land less than 10 metres above current high tide lines, with 230 million of these on land below 1 metre.[62]

The impacts of coastal flooding are likely to occur over a longer time horizon than many other climate risks. The long-term central estimate of committed sea level rise is around 12 metres, if temperatures are held at 2°C. The timeframes are extremely uncertain: this could occur over 500 years or 10,000 years.[63] A 1 metre rise in relative sea level increases the probability of current 100-year flood events by around 40 times in Shanghai, around 200 times in New York, and around 1,000 times in Kolkata.[64]

61 CRED (2021), 'CRED Crunch Newsletter, Issue No. 62 (May 2021) – Disaster Year in Review 2020: Global Trends and Perspectives', https://reliefweb.int/report/world/cred-crunch-newsletter-issue-no-62-may-2021-disaster-year-review-2020-global-trends-and (accessed 7 Jun. 2021).
62 Kulp, S. A. and Strauss, B. H. (2019), 'New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding', *Nature Communications*, 10(1), doi:10.1038/s41467-019-12808-z (accessed 13 Aug. 2021).
63 King, D. et al. (2017), *Climate Change: A Risk Assessment*.
64 Ibid.

Figure 17. Committed sea level rise as a function of long-term global temperature increase

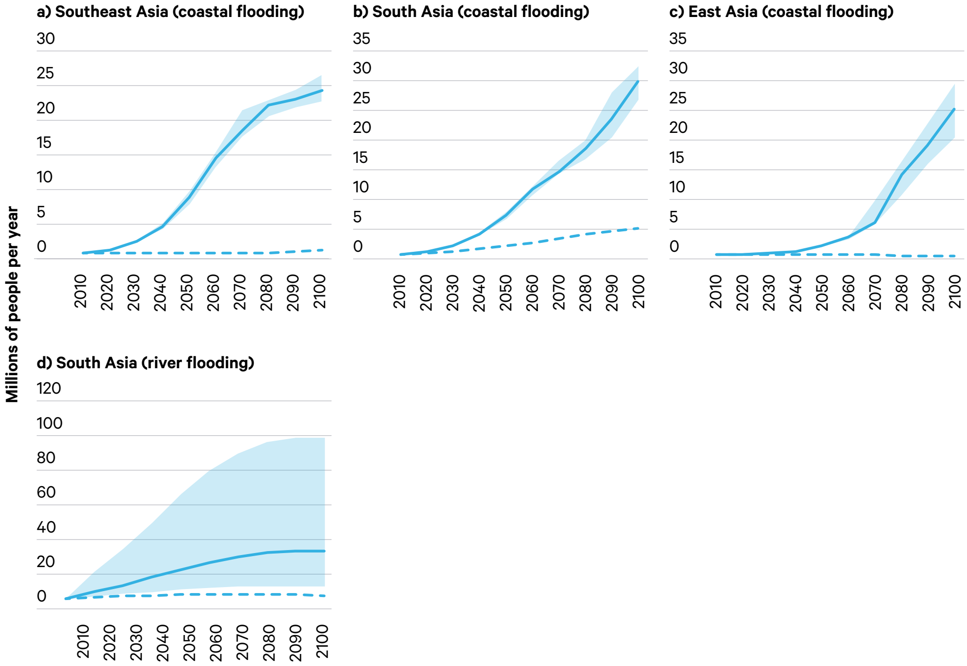


Source: Adapted from Fig. 13.14 from IPCC (2013).[65]

Given current understanding, the central estimate suggests that by 2100 nearly 200 million people worldwide will be living below the 100-year flood level. However, if the rate of Antarctic ice melt continues at the accelerated rate of recent years, this is likely to be an underestimate (the rate of ice loss from Antarctica has tripled since 2012, relative to the previous two decades).[66] The impacts of coastal flooding are most likely to be suffered by populations in Asia. Figure 18a–c illustrates the annual number of people likely to be impacted, where it is assumed that coastal flood defences are designed to cope with sea levels of the period 1986–2005. By 2100, 30 million per year are projected to be impacted in South Asia, 25 million in East Asia and more than 20 million in Southeast Asia. In aggregate, across these three regions, around 11 times more people will be impacted by coastal flooding than under a scenario in which climate change is averted. River flooding also poses a risk in South Asia, with the central estimate indicating around 33 million people are likely to be impacted; however, as many as 86 million could be affected in a worst-case scenario.[67] It should be noted that this assumes no river flood defences are built, where the threshold of impact indicator is a river flood greater than the historic baseline (once in 50 years) flooding.

65 IPCC (2013), *Climate Change 2013: The Physical Science Basis*.
66 Slater, T., Lawrence, I. R., Otosaka, I. N., Shepherd, A., Gourmelen, N., Jakob, L., Tepes, P., Gilbert, L. and Nienow, P. (2021), 'Review article: Earth's ice imbalance', *Cryosphere*, 15(1): pp. 233–246, doi:10.5194/tc-15-233-2021 (accessed 13 Aug. 2021).
67 Average annual number of people exposed to a river flood greater than the reference period 50-year flood (1981–2010).

Figure 18. Populations in selected regions likely to experience coastal and river flooding



Shaded areas represent the lower and upper estimates of the given impact. Solid lines represent the central estimate. Dashed lines represent no additional climate change.
Source: Adapted from Arnell et al. (2019).

04 Cascading systemic risks

A negative and compounding feedback loop is likely, involving shifting weather patterns and ecosystems, increased pests and diseases, heatwaves and drought, driving unprecedented food insecurity and migration – all with far reaching consequences.

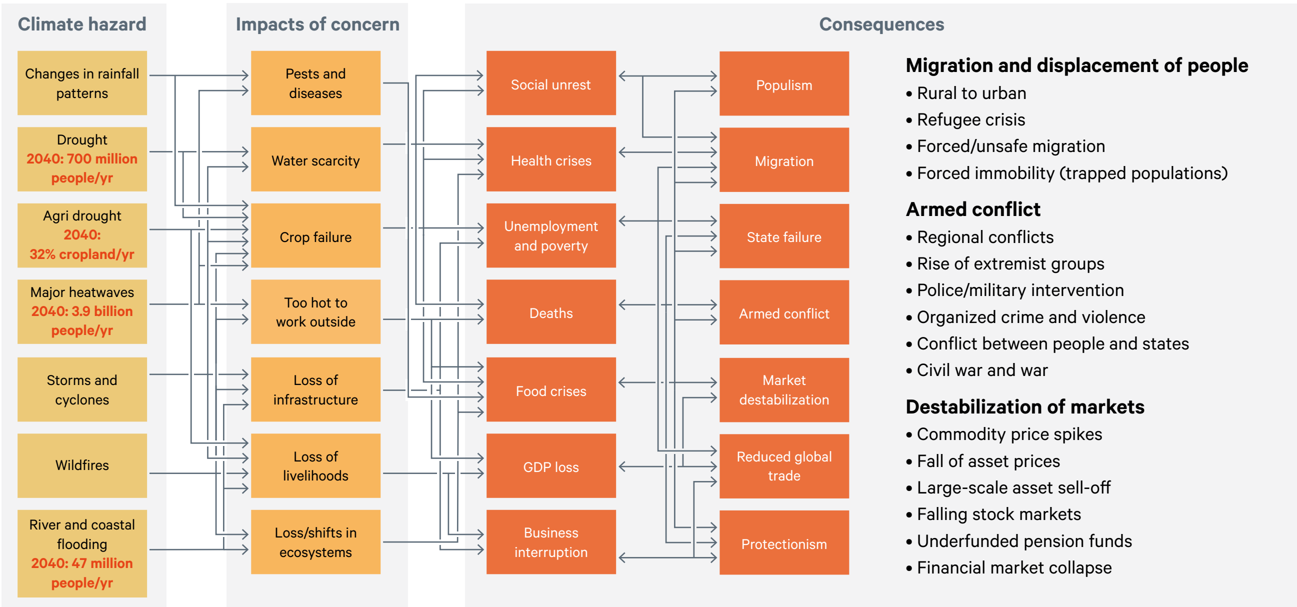
The direct risks and impacts described in the previous chapters are the initial physical and socio-economic consequences of changes in climate. Systemic risks stem from the consequence of those direct impacts – materializing as a chain, or cascade, of impacts – compounding to impact a whole system, including people, infrastructure, the economy, societal systems and ecosystems. Quantifying the probability and severity of systemic risks is not possible due to their complex nature. However, an elicitation exercise[68] was conducted with 70 experts to capture the major dynamics and impacts that climate scientists and sector risk experts are concerned will occur as direct climate impacts increase in prevalence and severity. A diverse range of experts were invited to participate, each working within their domain of risk specialism, and the aggregated diagrams within each risk domain were tested with the experts in workshops. Figure 19 summarizes the central estimates of the major global direct impacts of climate change in 2040, and how

68 The expert elicitation exercise consisted of using semi structured interviews and a template systemic risk diagram. Experts were asked to identify the exposures and vulnerabilities, direct hazards and impacts that could initiate and mediate a cascade of systemic risks, as well as the human and natural systems that could transmit and amplify the impacts. Through the exercise, 70 experts contributed 44 diagrams, ranging from regionally specific to global in scope, which have been aggregated in the six discrete systemic risk category diagrams presented in this chapter.

they could initiate cascading systemic impacts. The same figure also summarizes the six detailed risk cascades of the following sections:

- National and international security
- Economic and trade disruption
- Migration pressures
- Food security
- Health crises
- Energy security

Figure 19. Summary diagram of the major systemic risk dynamics identified by an expert elicitation process



Cascading risks will ultimately cause higher mortality rates, drive political instability and greater national insecurity, and fuel regional and international conflict. The cascading risks over which the participating experts expressed greatest concern were the interconnections between shifting weather patterns, resulting in changes to ecosystems, and the rise of pests and diseases, which, combined with heatwaves and drought, will likely drive unprecedented crop failure, food insecurity and migration of people. Subsequently, these impacts will likely result in increased infectious diseases (greater prevalence of current infectious diseases, as well as novel variants), and a negative feedback loop compounding and amplifying each of these impacts.

Box 3. Extreme weather events often trigger cascading impacts

Extreme weather events often set off compounding secondary events and risks,[69] such as cascading impacts across borders affecting global supply chains.[70] Since 2012, the American Meteorological Society has published an annual assessment of extreme weather events. Of 146 research findings, a substantial link between an extreme weather event and climate change was identified in 70 per cent of instances between 2011 and 2018.[71,72]

An assessment published by GermanWatch in 2020 determined that between 1999 and 2018 nearly half a million people worldwide died as a direct result of over 12,000 extreme weather events, with losses amounting to some $3.54 trillion (at purchasing power parity).[73] It is important to note that almost all economic losses from extreme weather events in low-income countries are uninsured, further compounding the impacts on those populations.[74]

Climate change contributes to the creation of conditions that are more susceptible to wildfires, principally via hotter and drier conditions. In the period 2015–18, measured against 2001–14, 77 per cent of countries saw an increase in daily population exposure to wildfires, with India and China witnessing 21 million and 12 million exposures respectively.[75] California experienced a fivefold increase in annual burned area between 1972 and 2018. There, average daytime temperatures of warm-season days have increased by around 1.4°C since the early 1970s, increasing the conditions for fires, and consistent with trends simulated by climate models.[76] Observations show that during the devastating Australian bushfires of 2019–20, a heatwave 1–2°C warmer than at the beginning of the 20th century was a contributing factor. Property and economic damage resulting from the disaster is estimated to have totalled some US $70 billion.[77,78] Such heatwaves are now around 10 times more likely than at the beginning of the last century. Projecting forward, similar bushfires are around eight times more likely with 2°C of global

69 Committee on Climate Change and China Expert Panel on Climate Change (2018), *UK-China Cooperation on Climate Change Risk Assessment: Developing Indicators of Climate Risk*.
70 Challinor, A. J., Adger, W. N., Benton, T. G., Conway, D., Joshi, M. and Frame, D. (2018), 'Transmission of climate risks across sectors and borders', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376(2121): 20170301, doi:10.1098/rsta.2017.0301 (accessed 13 Aug. 2021).
71 Herring, S. C., Christidis, N., Hoell, A., Kossin, J. P., Schreck, C. J. and Stott, P. A. (2018), 'Explaining Extreme Events of 2016 from a Climate Perspective', *Bulletin of the American Meteorological Society*, 99(1): pp. S1–S157, doi:10.1175/bams-explainingextremeevents2016.1 (accessed 13 Aug. 2021).
72 Eckstein, D., Kunzel, V., Schafer, L. and Winges, M. (2020), *Global Climate Risk Index 2020. Who Suffers Most from Extreme Weather Events?*, Bonn: Germanwatch, https://germanwatch.org/en/17307 (accessed 13 Aug. 2021).
73 Ibid.
74 Watts et al. (2019), 'The 2019 report of The Lancet Countdown on health and climate change: ensuring that the health of a child born today is not defined by a changing climate'.
75 Ibid.
76 Williams, A. P., Abatzoglou, J. T., Gershunov, A., Guzman-Morales, J., Bishop, D. A., Balch, J. K. and Lettenmaier, D. P. (2019), 'Observed Impacts of Anthropogenic Climate Change on Wildfire in California', *Earth's Future*, 7(8): pp. 892–910, doi:10.1029/2019ef001210 (accessed 13 Aug. 2021).
77 O'Mallon, F. and Tiernan, E. (2020), 'Australia's 2019-20 bushfire season', *Canberra Times*, 10 January 2020, https://www.canberratimes.com.au/story/6574563/australias-2019-20-bushfire-season (accessed 11 Jun. 2021). Read, P. and Denniss, R. (2020), 'With costs approaching $100 billion, the fires are Australia's costliest natural disaster', The Conversation, 17 January 2020, https://theconversation.com/with-costs-approaching-100-billion-the-fires-are-australias-costliest-natural-disaster-129433# (accessed 11 Jun. 2021).
78 A$100 billion, converted to US dollars based on AUD1:USD0.7 as of 27 December 2019.

warming.[79] In Siberia, a prolonged heatwave in the first half of 2020 caused wide-scale wildfires, loss of permafrost and an invasion of pests. It is estimated that climate change has already made such events more than 600 times more likely in this region.[80]

As with many extreme weather events, attribution of tropical cyclones to climate change is challenging,[81] with many studies demonstrating conflicting results.[82] The large fluctuations in frequency and intensity of tropical cyclones complicates the attribution of their changing nature to climate change. However, future projections based on climate models have indicated the most intense cyclones are likely to substantially increase in frequency due to climate change, with increases in precipitation rate within 100 km of the storm centre increasing by around 20 per cent.[83]

4.1 Vulnerabilities mediating cascading risks

The vulnerabilities that experts are concerned will likely mediate the risk cascades can be thought of in two separate groups – those pertaining to natural systems, and those associated with human or societal systems. Across all six categories, the vulnerabilities that the experts who participated in the elicitation exercise expressed greatest concern about include:

- Fragility of the food system and lack of adaption measures and plans
- Natural systems and ecosystems at the edge of their capacity
- Lack of measures to cope with new pests and diseases that emerge at the intersection of human societies and shifting ecosystems
- Dependence of vulnerable demographics within developing countries on food production (particularly smallholder farmers) for their primary income, and a lack of alternative livelihood options
- Lack of sufficient social safety nets and social cohesion
- Non-diversified economies, fragility of markets, and a lack of business continuity plans
- Ageing populations, and the concentration of populations in geographies
- Extreme poverty, and unequal distributions of wealth and resources

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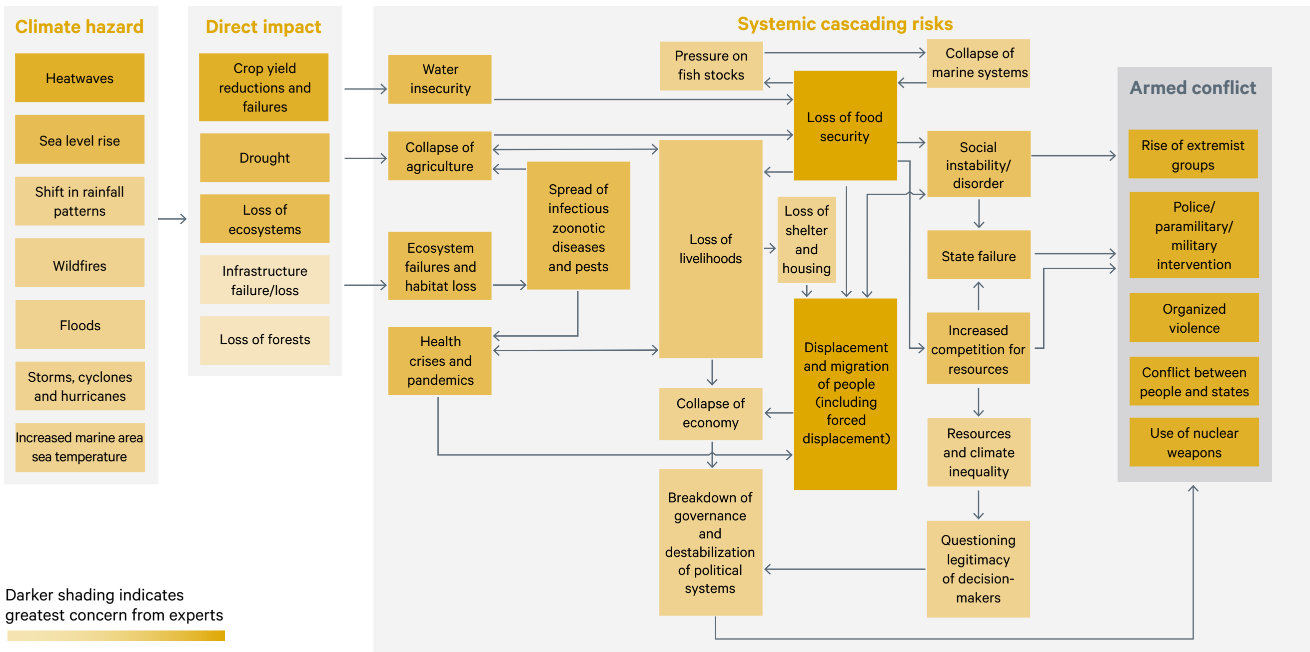
79 van Oldenborgh, G. J., Krikken, F., Lewis, S., Leach, N. J., Lehner, F., Saunders, K. R., van Weele, M., Haustein, K., Li, S., Wallom, D., Sparrow, S., Arrighi, J., Singh, R. P., van Aalst, M. K., Philip, S. Y., Vautard, R. and Otto, F. E. L. (2021), 'Attribution of the Australian bushfire risk to anthropogenic climate change', *Natural Hazards and Earth System Sciences*, 21(3): pp.941–960, doi:10.5194/nhess-2020-69 (accessed 13 Aug. 2021).
80 Ciavarella, A., Cotterill, D., Stott, P., Kew, S., Philip, S., van Oldenborgh, G. J., Skålevåg, A., Lorenz, P., Robin, Y., Otto, F., Hauser, M., Seneviratne, S. I., Lehner, F. and Zolina, O. (2020), *Prolonged Siberian heat of 2020*, World Weather Attribution, https://www.worldweatherattribution.org/wp-content/uploads/WWA-Prolonged-heat-Siberia-2020.pdf (accessed 13 Aug. 2021).
81 Moon, I.-J., Kim, S.-H. and Chan, J. C. L. (2019), 'Climate change and tropical cyclone trend', *Nature*, 570(7759): pp. E3–E5, doi:10.1038/s41586-019-1222-3 (accessed 13 Aug. 2021).
82 Knutson, T. R., McBride, J. L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J. P., Srivastava, A. K. and Sugi, M. (2010), 'Tropical cyclones and climate change', *Nature Geoscience*, 3: pp. 157–163, doi:10.1038/ngeo779 (accessed 13 Aug. 2021).
83 Ibid.

- Fragile infrastructure, centralized national energy and water supply systems, and weak healthcare systems
- Poor governance and weak institutions, particularly regarding measures that support the safe migration of vulnerable populations
- Pre-existing regional tensions
- Dependence on international trade and global supply chains, and the waning level of international cooperation

4.2 National and international security

Experts are principally concerned with climate hazards and direct impacts that will likely lead to reduced food and water security, and more health crises, culminating in loss of livelihoods, and displacement and migration of people. As set out in Figure 20, these cascades result in the potential breakdown of governance and political systems as societies become increasingly unstable due to lack of income as well as competition over limited food supplies. Experts are concerned that such situations could lead to impacts including the rise of extremist groups, paramilitary intervention, organized violence, and conflict between people and states. Some experts are concerned that conflict between states could lead to the use of nuclear weapons, as states themselves compete to secure resources for their citizens.

Figure 20. Experts' assessments of systemic cascading climate risks that are likely to lead to greater national and international insecurity



The US National Intelligence Council's *Global Trends 2040* report, published in March 2021, highlights that:

> Climate change will increasingly exacerbate risks to human and national security and force states to make hard choices and trade-offs. The burdens will be unevenly distributed, heightening competition, contributing to instability, straining military readiness, and encouraging political movements.[84]

4.3 Economic and trade disruption

As Figure 21 illustrates, experts are concerned by a diverse and complex set of cascading risks that could put economies at risk of significant disruption. Physical risk events from heatwaves, wildfires, floods and droughts are of particular concern because of their potential to impact food security, energy and water infrastructure, as well as lead to business defaults on a scale that the insurance industry would be unable to cope with. The failure of businesses would, experts fear, lead to significant falls in consumer spending. Equity markets would also see abrupt shifts as a result of destruction of infrastructure and crops, leading to a sell-off of assets, declining equity prices, and shortfalls in pension funds, and ultimately undermining the financial markets, all of which would then spill over into the real economy. Furthermore, experts highlighted during the elicitation exercise that a societal consensus could emerge that the free market economic model is unsustainable, and governments could move towards constraining people's consumption. Combined with the cascading impacts, this could lead to macro-economic discontinuities with far reaching consequences for inflation rates, asset prices, jobs and livelihoods.

Physical risk events from heatwaves, wildfires, floods and droughts are of particular concern because of their potential to impact food security, energy and water infrastructure, as well as lead to business defaults on a scale that the insurance industry would be unable to cope with.

International trade is also likely to be impacted by climate impacts. The Yangtze river flooding of 2020, caused by the highest rainfall in 60 years,[85] forced authorities to destroy a dam at risk of collapse,[86] and disrupted cargo ships

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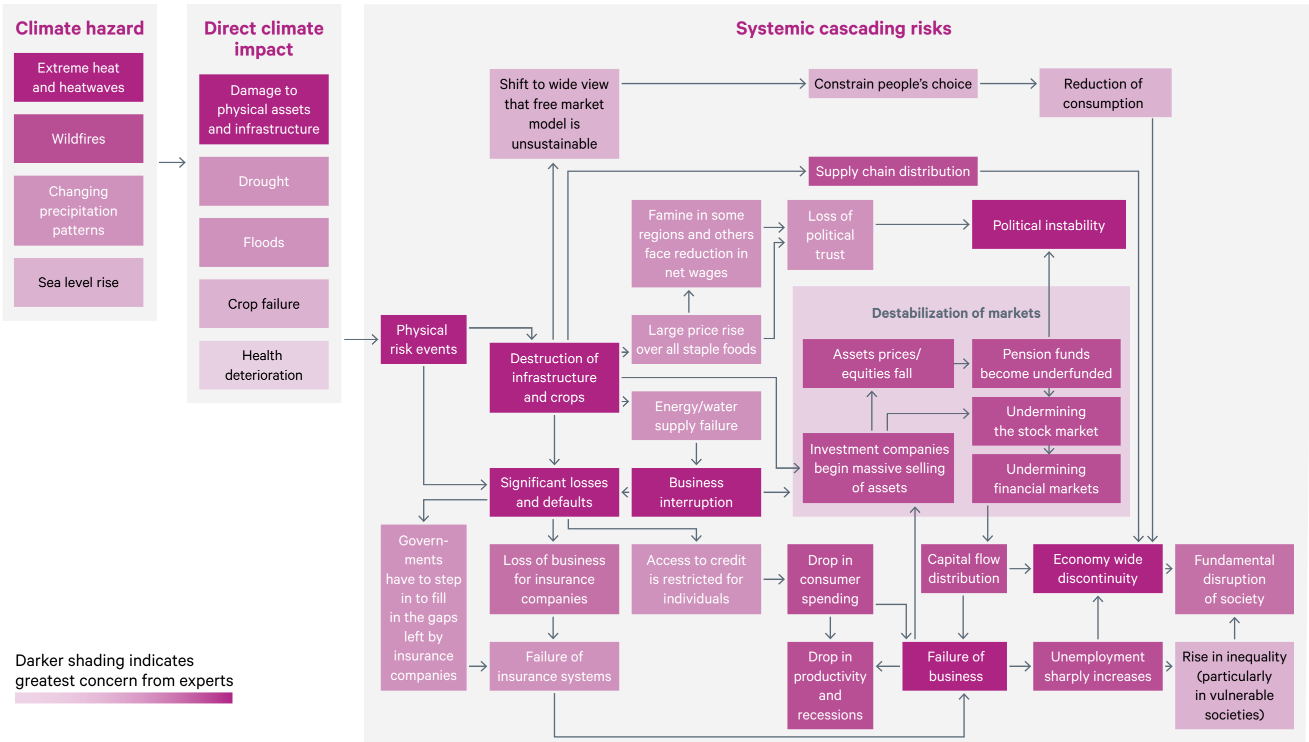
84 U.S. National Intelligence Council (2021), *Global Trends 2040. A More Contested World,* Washington, DC: U.S. National Intelligence Council, https://www.dni.gov/files/ODNI/documents/assessments/GlobalTrends_2040.pdf (accessed 13 Aug. 2021).
85 Guo, Y., Wu, Y., Wen, B., Huang, W., Ju, K., Gao, Y. and Li, S. (2020), 'Floods in China, COVID-19, and climate change', *The Lancet Planetary Health*, 4(10): pp. E443–E444, doi:10.1016/s2542-5196(20)30203-5 (accessed 14 Aug. 2021).
86 Piesse, M. (2020), 'Floods in China Threaten Supply Chains for Critical Goods', Future Directions International, 22 July 2020, https://www.futuredirections.org.au/publication/floods-in-china-threaten-supply-chains-for-critical-goods (accessed 3 May 2021).

down the river and within Shanghai port itself.[87] The floods caused hundreds of deaths and other casualties in affected areas, as well as heavy financial losses for China,[88] and global supply chains were disrupted, including exports of personal protective equipment for health workers battling COVID-19.[89]

Figure 21. Experts' assessments of systemic cascading climate risks that are likely to lead to economic and trade disruptions



4.4 Migration pressures

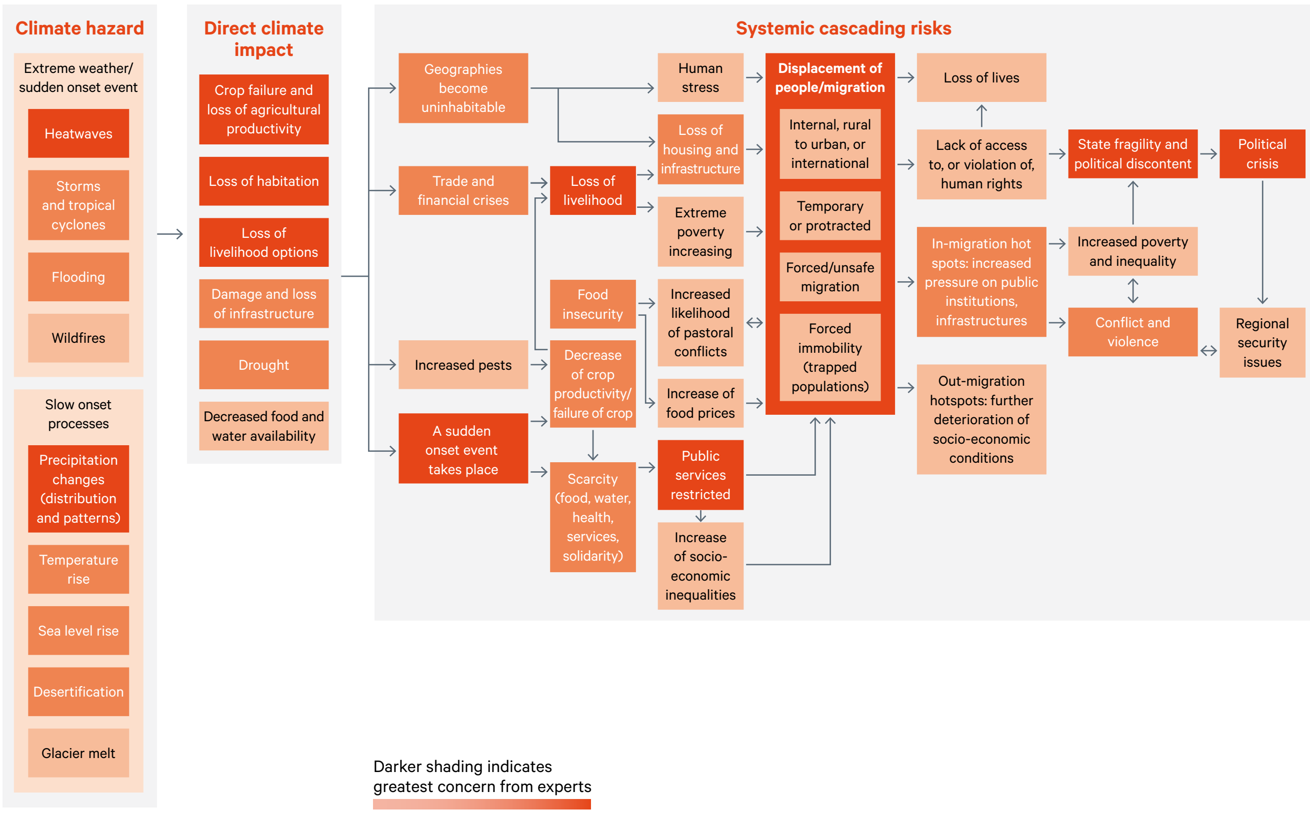
As with other systemic risks, experts are principally concerned that direct climate risks will likely drive food insecurity and loss of livelihoods, resulting in displacement of people, and migration pressures. As Figure 22 illustrates, they assess that these pressures will likely lead to loss of life, human rights violations, increased pressures on public institutions and infrastructure, and a deterioration of socio-economic conditions. Experts are concerned that heightened conflict, violence, political instability and regional security issues would then manifest.

Globally, each year in 2008–20, an average of 21.8 million people have been internally displaced by weather-related disasters in the form of extreme heat, drought, floods, storms and wildfires.[90] In the latter year, some 30 million

87 Far East Cargo Line (no date), 'Floods in China disrupt Yangtze River cargo flow', https://www.fecl.co.uk/news/79 (accessed 3 May 2021).
88 Guo et al. (2020), 'Floods in China, COVID-19, and climate change'.
89 Kelly, P. (2020), 'Floods disrupting PPE and critical supply chains', Norman Global Logistics, 29 July 2020, https://www.normanglobal.com/floods-disrupting-ppe-and-critical-supply-chains/?web=1&wdLOR=c0A13D337-4B90-4D6D-A8CC-5B24753E061B (accessed 3 May 2021).
90 Internal Displacement Monitoring Centre (2020), Global Internal Displacement Database, https://www.internal-displacement.org/database/displacement-data (accessed 9 Aug. 2021).

people in 143 countries worldwide were displaced by weather-related disasters, 4.3 million of whom in sub-Saharan Africa.[91] In 2015, as the number of refugees and migrants entering Europe, having fled conflict in the Middle East and Africa, reached its highest point, at more than 1 million,[92] an equivalent number of people – some 1.1 million – were displaced by extreme weather events in sub-Saharan Africa alone.[93]

Figure 22. Experts' assessments of systemic cascading climate risks that are likely to lead to migration pressures



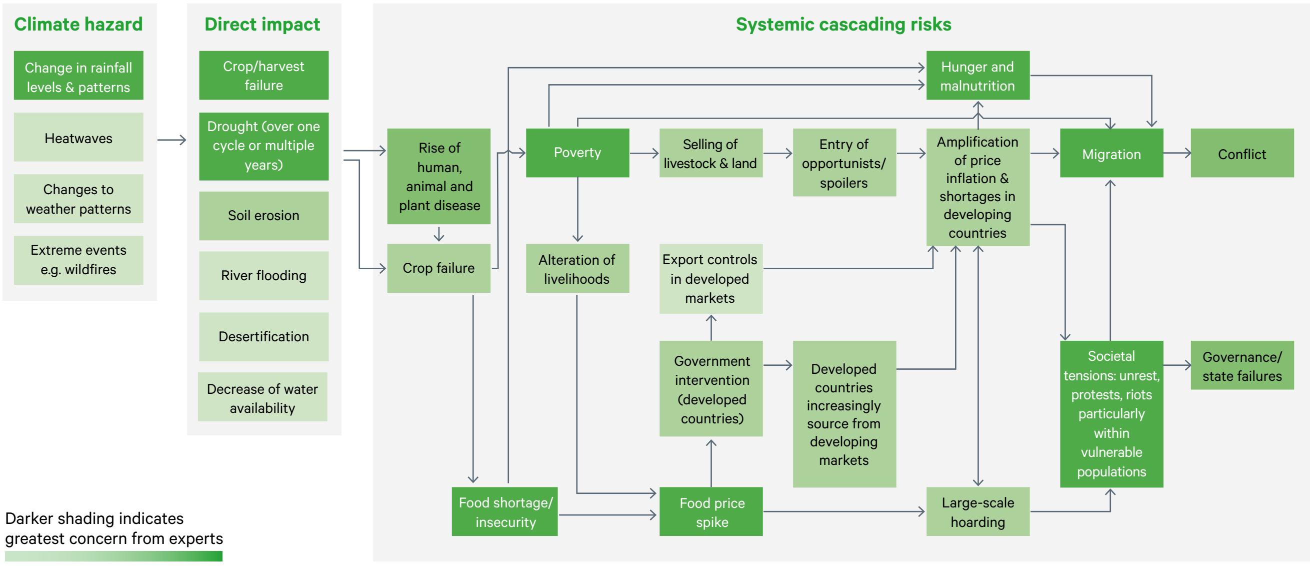
4.5 Food security

Food insecurity was cited by experts across all six systemic cascading risk assessments (except energy security) as being a major driver of cascading climate impacts. Figure 23 can therefore be interpreted as a detailed depiction of the drivers of food insecurity, applicable to the other risk cascade diagrams. Further to the previously highlighted dynamics of food insecurity – animal and plant diseases contributing to crop failures, hunger and malnutrition, alterations of livelihoods and resulting poverty that drive societal tensions, migration and conflict – a number of factors were identified that might be expected to amplify food shortages and price increases. As livelihoods of farmers changed, these farmers would likely sell their

91 Ibid.
92 UNHCR (2021), Operational Data Portal, https://data2.unhcr.org/en/situations/mediterranean (accessed 12 Aug. 2021).
93 Internal Displacement Monitoring Centre (2020), Global Internal Displacement Database.

livestock and land, opportunists would enter the market, and as developing countries increasingly turned to developed markets for food supplies, developed countries would likely introduce export bans and people would resort to large-scale hoarding. All this would likely result in a negative feedback loop, amplifying shortages and price increases.

Figure 23. Experts' assessments of systemic cascading climate risks that are likely to lead to food insecurity



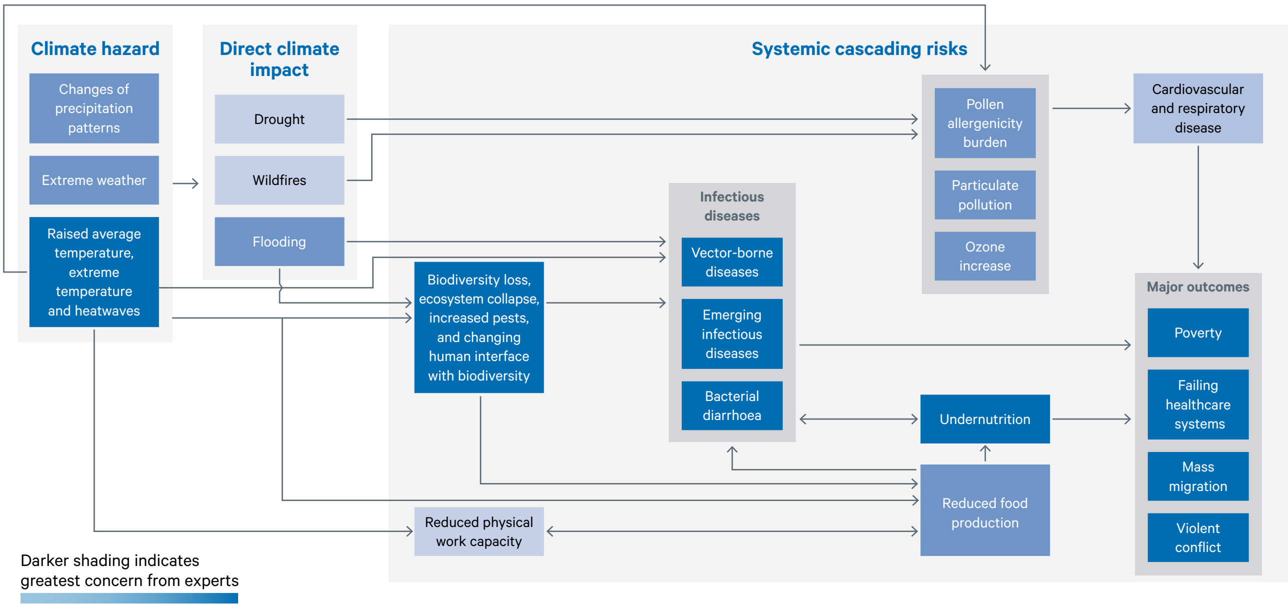
4.6 Health crises

As Figure 24 illustrates, experts are concerned that climate change is likely to increase the prevalence of emerging infectious diseases and vector-borne diseases. Climate change disrupts ecosystems and increases the risk of diseases jumping to new hosts.[94] Scientists have been warning for many years of the probability of pandemics increasing as a result of climate change.[95] Over the past decades, the number of emerging infectious diseases that either have the potential to be transmitted to humans, or have actually made that jump, has significantly increased. In 2008, a study published in the journal *Nature* found that over the previous decade nearly one-third of emerging infectious diseases were vector-borne, with the jumps to humans corresponding to changes in the climate. For instance, insects such as infection-bearing mosquitoes follow changing geographic temperature patterns.[96]

94 Brooks, D. R., Hoberg, E. P. and Boeger, W. A. (2019), *The Stockholm Paradigm: Climate Change and Emerging Disease*, Chicago: The University Of Chicago Press.
95 Curseu, D., Popa, M., Sirbu, D. and Stoian, I. (2009), 'Potential Impact of Climate Change on Pandemic Influenza Risk', *Global Warming*, pp. 643–657, doi:10.1007/978-1-4419-1017-2_45 (accessed 14 Aug. 2021).
96 Jones, K. E., Patel, N. G., Levy, M. A., Storeygard, A., Balk, D., Gittleman, J. L. and Daszak, P. (2008), 'Global Trends in Emerging Infectious Diseases', *Nature*, 451(7181): pp. 990–993, doi:10.1038/nature06536 (accessed 14 Aug. 2021).

The Lancet Countdown on health and climate change reported in 2019 that the climate suitability for transmission of pathogens was increasing.[97] For instance, nine of the 10 most suitable years for the transmission of dengue fever have occurred since 2000. Moreover, displaced populations often lack sufficient sanitary and medical facilities, which in turn can contribute to the spread of disease across borders.[98] Given the World Bank estimates that climate change is likely to displace around 140 million people by 2050,[99] from and within sub-Saharan Africa, South Asia and Latin America (together accounting for some 55 per cent of the developing world's population), disease prevalence is likely to increase. There is clear evidence, too, that extreme weather events expand the habitats of disease vectors.[100]

Figure 24. Experts' assessments of systemic cascading climate risks that are likely to lead to health crises



4.7 Energy security

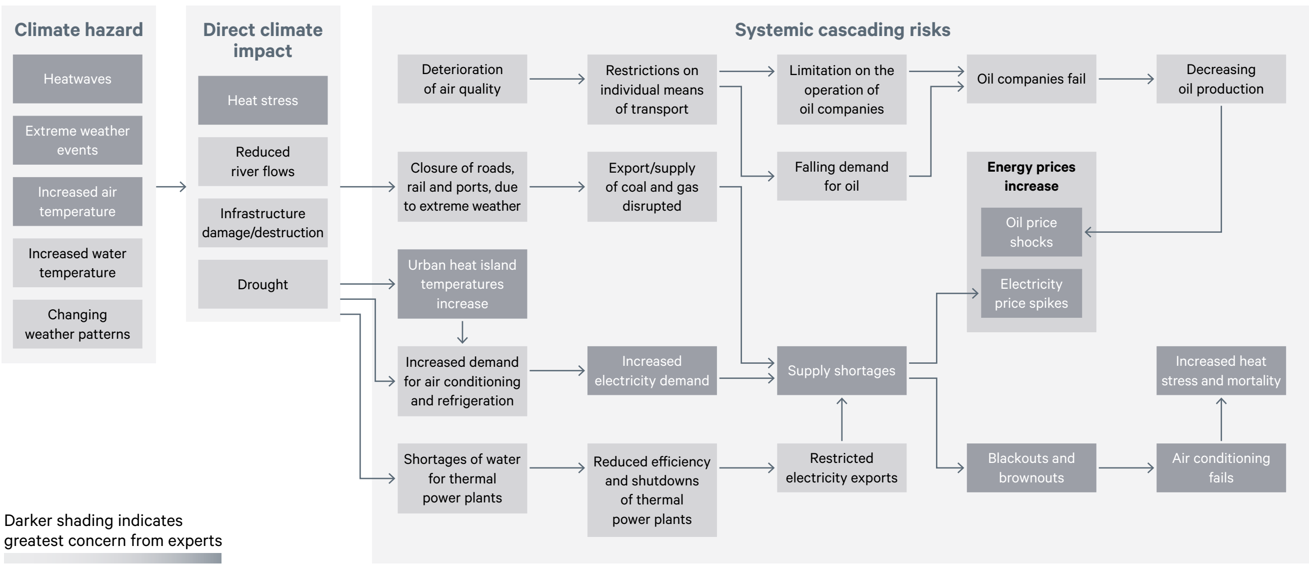
Experts are concerned by two discrete energy security risk cascades (Figure 25). Regarding electricity, increased urban heat islands, combined with reduced water for cooling within thermal power stations, will likely lead to heightened demand and supply shortages. Experts fear this scenario would be exacerbated by export controls, leading to black- and brownouts and ultimately a lack of cooling services, and thus heat stress and mortality. The second potential cascade focuses

97 Watts et al. (2019), 'The 2019 report of The Lancet Countdown on health and climate change: ensuring that the health of a child born today is not defined by a changing climate'.
98 King, D. et al. (2017), *Climate Change: A Risk Assessment*.
99 Rigaud, K. K., de Sherbinin, A., Jones, B., Bergmann, J., Clement, V., Ober, K., Schewe, J., Adamo, S., McCusker, B., Heuser, S. and Midgley, A. (2018), *Groundswell: Preparing for Internal Climate Migration*, Washington, DC: World Bank, https://elibrary.worldbank.org/doi/pdf/10.1596/29461 (accessed 14 Aug. 2021).
100 Committee on Climate Change and China Expert Panel on Climate Change (2018), *UK-China Cooperation on Climate Change Risk Assessment: Developing Indicators of Climate Risk*.

on deteriorating air quality leading to increased restrictions on transport and hence falling oil demand, bringing restrictions on the operations of oil companies. This, experts fear, would lead to oil companies failing and, ultimately, oil price shocks.

A recent global shortage of semiconductor chips was partly due to the shutdown of production plants because of the rolling power outages during the abnormally cold spell in Texas in February 2021.[101] The power outages also led to a lack of safe drinking water.[102] Evidence points to the warming of the Arctic, and the resultant weakening of the polar vortex, pushing cold air far further south than normal and bringing about the coldest period Texas has experienced in more than 30 years.[103]

Figure 25. Experts' assessments of systemic cascading climate risks that are likely to lead to energy insecurity



101 BBC News (2021), 'Texas freeze shuts chip factories amid shortages', 18 February 2021, https://www.bbc.co.uk/news/technology-56114503 (accessed 2 Aug. 2021). Chang, A. (2021), 'Why the cold weather caused huge Texas blackouts – a visual explainer', *Guardian*, 20 February 2021, https://www.theguardian.com/us-news/2021/feb/20/texas-power-grid-explainer-winter-weather (accessed 2 Aug. 2021).
102 Oxner, R. and Garnham, J. P. (2021), 'Over a million Texans are still without drinking water. Smaller communities and apartments are facing the biggest challenges', *Texas Tribune*, 24 February 2021, https://www.texastribune.org/2021/02/24/texas-water-winter-storm (accessed 2 Aug. 2021).
103 UN News (2021), 'Polar vortex responsible for Texas deep freeze, warm Arctic temperatures', 9 March 2021, https://news.un.org/en/story/2021/03/1086752 (accessed 3 May 2021).

05 Conclusions

The governments of highly emitting countries have a critical opportunity to accelerate emissions reductions through ambitious revisions of NDCs at COP26, significantly enhancing policy delivery mechanisms, and incentivizing rapid large-scale investment in low-carbon technologies.

Unless NDCs are dramatically increased, and policy and delivery mechanisms commensurately revised, many of the climate change impacts described in this paper are likely to be locked in by 2040, and become so severe they go beyond the limits of what nations can adapt to. If emissions follow the trajectory set by current NDCs, there is a less than 5 per cent chance of keeping temperatures well below 2°C above pre-industrial levels, and less than 1 per cent chance of reaching the 1.5°C Paris Agreement target. There is currently a focus on net zero pledges, and an implicit assumption that these targets will avert climate change. However, net zero pledges lack policy detail and delivery mechanisms, and the gap between targets and the global carbon budget is widening every year.

If emissions do not come down drastically before 2030, then by 2040 some 3.9 billion people are likely to experience major heatwaves, 12 times more than the historic average. Temperature increases are already resulting in the equivalent of over half of COVID-19-induced lost working hours. By the 2030s, 400 million people globally each year are likely to be exposed to temperatures exceeding the workability threshold, and the number of people exposed to heat stress exceeding the survivability threshold is likely to surpass 10 million each year.

To meet global demand, agriculture will need to produce almost 50 per cent more food by 2050. However, yields could decline by 30 per cent in the absence of dramatic emissions reductions. The probability of a synchronous, greater than 10 per cent crop failure across the top four maize producing countries, which together account for 87 per cent of exports, during the decade of the 2040s is just less than 50 per cent.

Cascading climate impacts will likely cause higher mortality rates, drive political instability and greater national insecurity, and fuel regional and international conflict. During an expert elicitation exercise, the cascading risk that experts had greatest concern over were the interconnections between shifting weather patterns, resulting in changes to ecosystems, and the rise of pests and diseases, which combined with heatwaves and drought will likely drive unprecedented crop failure, food insecurity and migration. Subsequently, these impacts will likely result in increased infectious diseases, and a negative feedback loop compounding each of these impacts.

The governments of highly emitting countries have a critical opportunity to accelerate emissions reductions through ambitious revisions of NDCs at COP26, significantly enhancing policy delivery mechanisms, and incentivizing rapid large-scale investment in low-carbon technologies. This will lead to cleaner and cheaper energy, and avert the worst climate impacts.

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104 Arnell et al. (2019), 'The global and regional impacts of climate change under representative concentration pathway forcings and shared socioeconomic pathway socioeconomic scenarios'.

Cover image: Rescue teams evacuate patients and medical workers from the flooded Fuwai Central China Cardiovascular Hospital after torrential rains in Zhengzhou, Henan Province, China, 22 July 2021.
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