Human system impacts of overshoot pathways

Global consequences of climate overshoot pathways: Annex 6

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Key messages from this report

1. Even warming of 1.5 °C will have negative impacts on human systems.

Sea levels will rise, increasing coastal flooding. Precipitation patterns will change and extreme weather will be more frequent and more intense, affecting water and sanitation through more intense droughts and floods, and reducing agricultural productivity in some areas. But some high-latitude regions will benefit economically from higher temperatures.

2. Temporarily overshooting 1.5 °C will worsen the impacts compared to not overshooting 1.5 °C.

Extreme weather events will become more frequent and intense as the temperature rises. Heat waves will occur more often. Damage to crops, water supplies and sanitation infrastructure will increase. The magnitudes of these impacts will depend on the vulnerability of populations to climatic variability and change. Adaptation could reduce these impacts, but the economic costs of adaptation measures are not well understood. If the resilience of populations were not increased, then increased poverty and migration would become more likely.

3. Impacts of climate change might be more difficult to adapt to in an overshoot.

Keeping the global temperature rise below 1.5 °C would require rapid cuts in greenhouse gas emissions that would slow climate change. Hence, the human impacts of climate change would also be slowed as the temperature stabilised in 2050, although time would be required for a new equilibrium to be reached. In contrast, overshooting would lead to the temperature not stabilising until 2100, meaning long-term temperature and precipitation patterns would be constantly changing for a much longer period. The risk of triggering climatic tipping points with deleterious global consequences would be higher.

This delay to reaching a new equilibrium climate would be expected to cause more severe human impacts in the absence of greater investments in adaptation to improve population resilience. But while greater adaptation investments might reasonably be needed for a more variable climate, there is not a good enough understanding of adaptation needs in the literature to make a well-evidenced judgement.

About this report

The "Global consequences of climate overshoot pathways" study has examined the natural and human system consequences of the world overshooting 1.5 °C, but then using carbon dioxide removal technologies to return the global temperature to 1.5 °C by 2100.

The final report summarises the findings from the study. Six annexes present the technical evidence that underpin the final report:

- Annex 1: Development of overshoot pathways.
- Annex 2: The feasibility of deploying CDR at the rate required for overshoot pathways.
- Annex 3: Economic implications of climate overshoot.
- Annex 4: Hysteresis and tipping points analysis using the UK Earth System Model.
- Annex 5: Natural system impacts of overshoot pathways.
- Annex 6: Human system impacts of overshoot pathways.

Around 40 scientists have contributed to these annexes and more than 900 literature sources are cited.

This annex, Annex 6, examines the potential impacts of overshoot on human systems in general and on the UN Sustainable Development Goals (SDGs) in particular.

About CS-N0W

Commissioned by the UK Department for Energy Security & Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5.5 million research programme, that uses the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation and resilience ambitions.

CS-N0W enhances the scientific understanding of climate impacts, decarbonisation and climate action, and improve accessibility to the UK's climate data. It contributes to evidence-based climate policy in the UK and internationally, and strengthens the climate resilience of UK infrastructure, housing and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by **Ricardo** and includes research **partners Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL)**.

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Acronyms

AMOC	Atlantic Meridional Overturning Circulation
AR5	IPCC’s Fifth Assessment Report (2013-2014)
AR6	IPCC’s Sixth Assessment Report (2021-2022)
BEIS	Business, Energy and Industrial Strategy
CCC	Committee on Climate Change
CDR	Carbon Dioxide Removal
CPM	Convection-Permitting Model
DACCS	Direct Air Carbon Dioxide Capture and Storage
DESNZ	Department for Energy Security and Net Zero
DIVA	Dynamic Interactive Vulnerability Assessment
ENSO	El Niño-Southern Oscillation
FIShMIP	Fisheries and Marine Ecosystem Model Intercomparison Project
GCM	General Circulation Model
GMST	Global Mean Surface Temperature
HMG	His Majesty’s Government
HO	“High Overshoot” pathway
IPCC	Intergovernmental Panel on Climate Change
IPO	Interdecadal Pacific Oscillation
ISIMIP	The Inter-Sectoral Impact Model Intercomparison Project
JMP	Joint Monitoring Programme
LO	“Low Overshoot” pathway
MDG	Millennium Development Goals
NAO	North Atlantic Oscillation
NbS	Nature-based Solutions
NO	“No Overshoot” pathway
OECD	Organisation for Economic Co-operation and Development
PDO	Pacific Decadal Oscillation

RCP	Representative Concentration Pathway
SDG	Sustainable Development Goals
SLR	Sea-level rise
SSP	Shared Socioeconomic Pathways
TIAM-UCL	TIMES Integrated Assessment Model at University College London
UKESM	UK Earth System Model
VHO	“Very High Overshoot” pathway

Executive Summary

This evidence annex examines the potential impacts of overshoot on human systems in general and on the UN Sustainable Development Goals (SDGs) in particular. We consider potential changes to flood risk and intensity, changes in water availability and quality for agriculture, household consumption and sanitation, and changes to food production, health and energy. We conclude by reflecting on how all these impacts might affect poverty and migration.

Background and overarching methodology

We have developed three temporary overshoot pathways, including a “Very High Overshoot” pathway in which the mean global surface air temperature rise peaks at 1.9 °C before reducing to 1.5 °C by 2100. This report compares the impacts of this overshoot pathway against a counterfactual “No Overshoot” pathway in which the global temperature rise does not exceed 1.5 °C. Annex 1 of this study describes these pathways in detail.

The IPCC published a special report in 2018 that compared the consequences of a global temperature rise to 1.5 °C and 2 °C. It concluded that climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C compared to the present, and to further increase with if the global temperature rises to 2 °C. These are projected to have the greatest impact on the most vulnerable populations, particularly in low-income countries.

Very little literature has analysed the impacts of a rising temperature and then a falling temperature following overshoot similar to the overshoot pathways examined in this study. This means our approach for some impacts has been to compare impacts at 1.5 °C and 2 °C to understand the potential impacts of overshoot beyond 1.5 °C, in which cases we speak of overshoot in general terms rather than in terms of the overshoot pathways we developed. But this is challenging because much of the evidence of climate impacts is for pathways with a temperature rise of 2 °C or more, while our counterfactual pathway reaches an equilibrium temperature rise of only 1.5 °C. For many impacts, only a qualitative analysis is possible. While the general direction of change (i.e. better or worse) can be assessed, the magnitude of impacts cannot be assessed with any confidence as there are so many uncertain factors and non-climatic influences in each of the examined areas.

Coastal and inland flooding

Many SDGs are affected by flooding (e.g. SDGs 1, 2, 8, 9, 11, 12, 13 and 14). For example, salinisation affects food production, while disasters due to flooding cause infrastructure and livelihood damage and loss of tourism.

Coastal flooding is likely to increase in many areas as sea levels rise due to climate change. A time lag exists between global temperature rise and subsequent sea-level rise, meaning that the impacts of today's emissions may not be seen for decades. Rates of rise are expected to accelerate this century for both overshoot and no overshoot pathways reaching an equilibrium global temperature rise of 1.5 °C. If overshooting were to cause enhanced rates of losses of the West Antarctic Ice Sheet and trigger marine ice cliff instability, leading to rapid ice loss, then sea level rise could further accelerate.

Particularly vulnerable regions include polar regions (due to sea-ice free summers and permafrost melting), Eastern Central American and North American coasts (due to more extreme El Niño events affecting storms and beach erosion), low-lying atoll islands in the Indian and Pacific Oceans, low-lying deltas world-wide and coastal zones that are sensitive to changes to landslides, sediment availability or compound flooding from rivers.

Rising global temperatures are expected to increase the intensity of river floods, even where moderate floods reduce, but there are no studies addressing the impact of an overshoot scenario on inland flooding from rivers so these conclusions are uncertain. In an overshoot, an adaptive approach in which planned actions are implemented in stages, when they are deemed necessary given the latest information available, could avoid over-engineering assets by providing flexibility, given the uncertainties of the impacts of climate change in the future.

Water resources

Terrestrial precipitation is projected to vary in complex ways with global warming. More intense storms, floods and droughts are expected that will affect agriculture, drinking water and sanitation. Overall precipitation is expected to rise in some regions and fall in others as the temperature rises, yet in some regions these changes could reverse if the temperature rises further.

Changes in water requirements for crops vary substantially between regions. Both wheat and barley could require 2–6 times more irrigation groundwater under a 2 °C scenario in key growing regions than for a 1.5 °C scenario, due to higher evapotranspiration from crops as the temperature rises and lower rainfall. It is likely that this would increase demand for groundwater where is available, leading to a greater risk of groundwater depletion during an overshoot within these regions.

SDG 6 sets ambitious targets for clean water and sanitation that are not currently on track to be met, with the disadvantaged less likely to have access to clean water and safely managed sanitation. Progress towards SDG 6 is dependent on a complex interplay of natural and human-based systems, many of which are already being impacted by climate change.

Wetter conditions in some areas, and more frequent and intense precipitation events more generally, will damage crops, harm infrastructure, disrupt water and sanitation services, and jeopardise water quality. Meeting ‘safely managed’ targets for drinking water and sanitation will become more difficult under overshoot scenarios in areas experiencing wetter conditions due to increased flooding, especially in fast-growing informal settlements where climate risk and poverty increasingly coincide. Aridity, drought and/or water scarcity will increase in other areas, particularly affecting vulnerable water supply and sanitation systems that are unable to draw on safe storage such as aquifers or large surface reservoirs.

Food system

A temperature rise to 2 °C, in an overshoot scenario, is projected to have little impact on mean yields of wheat, rice, soybean and barley, but the interannual variability of wheat and soybean yields could increase. As temperature increases beyond 2 °C is projected to reduce wheat, rice and soybean yields.

The potential impacts of overshoot on food production in the year 2050 due to an overshoot are small as the temperature difference between the two pathways is only 0.3 °C. There are regional variations with higher yields causing an increase in GDP of up to 0.6% in high-latitude regions but with higher food prices and GDP reductions of up to 6% in South and Southeast Asia.

Changes in ocean temperature will cause a redistribution of consumer fish towards the poles, with a loss of biomass at the equator and to a lesser extent at the poles. The overall loss of biomass is likely to be small for the overshoot pathways but will be greater than for the NO pathway due to higher oceanic temperatures for an extended period. The redistribution of fish would vary by species and could lead to fishing communities needing to adapt their approach to fishing, particularly in tropical areas where total fish biomass would likely reduce.

Health

Overshooting would increase the frequency and intensity of heatwaves, causing higher heat-related mortality and morbidity by 2050. The largest increases in heatwave duration and frequency are projected for sub-Saharan Africa, but the lack of epidemiological data means that projecting changes in heat-related mortality and morbidity is not possible. In all regions, however, declines in population susceptibility due to physiological acclimatisation and additional cooling measures such as air conditioning may result in a lower-than-expected health burden in an overshoot. Such adaptations are not always considered in current epidemiological models but consistently emerge in historical data.

Higher levels of food insecurity under a high overshoot pathway might increase malnutrition that exceeds health risks from population exposure to heat. An overshoot would expand the spread of many vector-borne diseases to more northerly latitudes, but could decrease incidence in areas where vectors are already endemic.

Mitigating greenhouse gas emissions could result in several co-benefits that substantially reduce mortality and morbidity. Improving diet has the largest potential benefit. Lower air pollution would be particularly valuable in Asia, where many cities have poor air quality. Physical activity, by contrast, has smaller potential benefits for morbidity and mortality.

Indoor and outdoor workers are exposed to high temperatures and humidity in workplaces, particularly in low and middle-income countries. The estimated loss of labour capacity, supply, and productivity in moderate outdoor work due to heat stress ranges from 2%–14%, varying depending on the location and indicator. Changes in the frequency and intensity of extreme temperatures due to an overshoot would increase heat stress and reduce productivity, and hence GDP, in those regions.

Energy

Substantial investments to decarbonise the energy system are required over the next 30 years to avoid overshoot. To avoid overshooting, fossil fuel use is reduced by 20%, and coal use by 60%, in the NO pathway from 2020 to 2030, and then there are further steady reductions over the following decades. Electrification of many processes in industry, buildings and transport would be necessary, powered by a massive expansion of renewable generation.

Overshooting could reduce production from thermal and nuclear power plants by 7% in 2050 as these plants require large quantities of water at a sufficiently low temperature. Many power plants use (and hence heat) river water and would need to shut if the water temperature exceeded a threshold to avoid damaging aquatic organisms. Changes in hydropower potential would vary across the world according to changes in precipitation in an overshoot, but the aggregated global hydropower potential would be similar. Changes in wind power speeds are expected to vary between regions and to change within regions as global temperature continues to increase. Solar PV generation would decrease as a result of slower reductions of fossil fuel consumption causing higher atmospheric aerosol levels, and also cloud cover and higher surface temperatures in some regions. Overshooting would also reduce transmission capacity in summer and could increase distribution infrastructure failure due to faster pole decay and more intense storms.

It is estimated that 675 million people lacked access to electricity in 2021 and a further 2.3 billion people were without access to clean cooking fuels and technologies. SDG 7.1 aims to ensure universal access to affordable, reliable, and modern energy services by 2030. Although climate change mitigation could have short-term costs that increase energy prices, efficiency improvements from global climate policy (SDG 7.2) could offset the additional electricity generation needed to achieve universal access, and climate policies could stimulate the expansion of renewable off-grid systems. In contrast, climate change, including overshoot, is projected to increase energy insecurity worldwide. It could also indirectly hinder efforts to achieve universal access to clean cooking.

Poverty, inequality and migration

The number of people living in extreme poverty is expected to decline substantially from around 700 million in 2020 to around 130–160 million in 2050, with the trend unlikely to be substantively affected by an overshoot.

Migration has a range of drivers, some of which are made worse by climate change. Exposure to flooding is a key driver but temperature rise and precipitation changes, for example increased drought, are also important. Most displacement to date has occurred within countries, often from rural to urban areas, rather than across borders. The likelihood of migration depends on the level of investment in adaptation measures, the characteristics of the population and the resilience of local communities and institutions. It is very difficult to assess with any confidence the extent to which climatic changes have caused migration to date. It is even more difficult to project future changes as these depend on both uncertain future weather patterns and social factors. Overshoot is expected to lead to greater flooding, more frequent and severe droughts and more powerful storms for a period of 50 years, compared with not overshooting. It is therefore likely that migration would be higher in an overshoot, but the magnitude of the increase is very difficult to project compared to other impacts.

1. Introduction

This report examines the potential impacts of overshooting a 1.5 °C mean global surface air temperature rise on human systems in general and on the UN Sustainable Development Goals (SDGs) in particular. Annex 5, on natural system impacts of overshoot, has already examined terrestrial ecosystems and biodiversity (SDG15). This annex focuses on human system impacts.

There has been increased interest in recent years in mapping interactions between the SDGs. Fuso Nerini *et al.* (2019) have mapped relationships between energy (SDG7) and other SDGs, while Priti Parikh (2021) has similarly examined relationships with clean water and sanitation (SDG6). Dagnachew *et al.* (2021) have mapped the many synergies and trade-offs with climate change measures and sustainable development goals. Transitioning from these types of qualitative studies to quantitatively projecting the impacts of climate change on SDG targets is difficult because there are many diverse targets and they are relatively short-term compared to climate change impacts, but initial modelling studies have been attempted (e.g. Dagnachew and Hof, 2022).

In this study, we do not focus on particular SDG targets. Instead, we examine the potential impacts of overshooting 1.5 °C in the areas covered by SDGs that are likely to be directly affected by climate change:

- SDG1 (poverty): in Section 8.1.
- SDG2 (hunger): crop yields and food production in Sections 5.1 and 5.2, respectively.
- SDG3 (good health and wellbeing): health impacts of overshoot, loss of health co-benefits through mitigation and the economic consequences of poor health, in Section 6.
- SDG6 (clean water and sanitation): including case studies of irrigation water needs, water supply and sanitation in Section 4.
- SDG7 (affordable and clean energy): in Section 7.
- SDG 10 (inequality): examining climate-driven migration in Section 8.2.

- SDG14 (marine resources): fisheries in Section 5.3.

Many human impacts are caused by extreme weather. The frequency and magnitude of extreme events is expected to increase as the global temperature rises (IPCC, 2023). Floods have some of the greatest impacts worldwide, affecting a range of SDGs, so coastal and inland floods are examined in Sections 2 and 3.

1.1 Pathways examined in this report

In Annex 1 of this study, we develop four future climate pathways that vary according to the peak global mean surface air temperature (GSAT) that is reached. We specify this as the increase in temperature above the pre-industrial period, in degrees Celsius (°C), in a similar way to the International Panel on Climate Change (IPCC) (IPCC, 2021a). We refer to it as the global temperature rise in this report. The pathways are:

- “No Overshoot” (NO), in which the global temperature does not exceed 1.5 °C.
- “Low Overshoot” (LO), in which the global temperature peaks at 1.6 °C in about 2060 before returning to 1.5 °C by the year 2100.
- “High Overshoot” (HO), in which the global temperature peaks at 1.8 °C in about 2065 before returning to 1.5 °C by the year 2100.
- “Very High Overshoot” (VHO), in which the global temperature peaks at 1.9 °C in about 2065 before returning to 1.5 °C by the year 2100.

Each of these pathways reaches 1.5 °C in the next 25 years and has climate impacts that are more severe than today.

1.2 Overall methods

In this annex, we primarily focus on the human system impacts caused by following the VHO pathway as this is likely to have the most substantial impacts of these four scenarios. We compare these impacts where possible to the NO pathway as a counterfactual.

The IPCC published a special report in 2018 that compared the consequences of a global temperature rise to 1.5 °C and 2 °C (IPCC, 2018). It concluded that climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C compared to the present, and to further increase with if the global temperature rises to 2 °C. The most vulnerable populations, particularly in low-income countries, are projected to be at greatest risk of climate impacts.

Most impact studies have focused on the impacts of climate change for a temperature rise of 2 °C or more. For example, the ISIMIP repository[1] contains many datasets for an RCP2.6 trajectory, which is consistent with a 2 °C rise, but no datasets for an RCP1.9 trajectory consistent with a 1.5 °C rise. Virtually no literature considers the potential impacts of an overshoot to almost 2 °C followed by a reduction to 1.5 °C. Hysteresis is expected in some natural systems so 2 °C impacts would not reduce as the global temperature were reduced.

Our strategy in this report was therefore to take evidence for 2 °C from the literature and augment it with our own analyses where possible. This can be characterised as a worst-case scenario for overshoot pathways that almost reach 2 °C at their peak. For some impacts, it was necessary to use different pathways that were close to our pathways as analogues. Where possible, we built our analysis on the natural system impacts examined in Annex 5 of the main report.

Many studies in the literature are based on scenarios developed to inform IPCC analyses:

- Shared Socioeconomic Pathways (SSPs) are scenarios of projected socioeconomic global changes up to 2100.
- Representative Concentration Pathways (RCPs) have been widely used by climate modellers to represent scenarios of GHG emissions in the future. They represent a range of climate forcing levels due to human actions (expressed in terms of W m^{-2}).

The IPCC has a set of representative SSP/RCP combinations that have received detailed analysis (Jung and Schindler, 2022, Lei *et al.*, 2023). These are discussed in Section 2 of Annex 1 of this study.

1.3 Structure of this annex

We examine coast flooding and inland fluvial flooding in Sections 2 and 3, respectively. Section 4 continues the analysis of potential freshwater impacts by examining case studies

[1] Inter-Sectoral Impact Model Intercomparison Project: https://data.isimip.org/

of changes in irrigation water requirements and of water supply and sanitation challenges. The focus switches to food in Section 5, covering crop yields, crop production and fishing. Human health is the focus of Section 6, including direct and indirect impacts of overshoot, lost co-benefits from not mitigating greenhouse gas emission and the economic consequences of heat stress. Section 7 examines energy systems, including changes due to slow mitigation and the impacts of overshoot on energy production. Poverty and climate-driven migration are the subject of Section 7.9. We draw conclusions in Section 9.

2. Impacts of coastal flooding

This section examines the implications of the overshoot on sea-level rise (SLR) and its wider impacts. Regardless of whether a 1.5 °C, 2 °C temperature is reached, or an overshoot, the coastal zone will be impacted by SLR in this century and beyond. SLR affects coasts through increased salinisation, rising water tables, flooding and erosion. This can impact livelihoods, such as salinisation impacting agriculture and water quality, flooding causing disruption in homes and erosion affecting land availability and tourism. Impacts of SLR will be worse in the second half of this century, even if significant adaptation is undertaken. Climate change on the coast, including SLR, affects some of the Sustainable Development Goals (SDGs) today and this could worsen in the future. These include the ability of societies to adapt to SLR and respond to hazards, and access to freshwater.

In this section, sea-level rise and the overshoot are considered in Section 2.1. Impacts, damage and adaptation at sub-global scales, including implications for the SDGs are explored in Section 2.2. In Section 2.3, the implications for adaptation and the SDGs are analysed.

The impacts of inland flooding are considered in Section 3. Impacts of inland flooding with climate change are influenced by changes to, for example, precipitations patterns (e.g. duration, intensity and spatial footprint), transpiration, land cover and permeability. Inland flooding can be caused by surface water flooding, fluvial (river) flooding and less commonly groundwater flooding. Human impacts include impacts to agricultural land, soil erosion, water supply, damage to infrastructure and livelihoods.

2.1 Sea-level rise and the overshoot

2.1.1 Background to sea-level rise

SLR is discussed in detail in Annex 5 of this study so only a brief overview is given here.

SLR is driven by the thermal (steric) expansion of the water column, terrestrial water storage (ground water pumping), and melting from land-based ice sheets and glaciers. The oceans are relatively insensitive to temperature rises over the short-term (few decades) as they take time to absorb emissions (O'Neill and Oppenheimer, 2004). This means an increase in emissions today will not appear in the sea-level record for decades (Parry *et al.*, 2009) or centuries (Schewe *et al.*, 2011, Schleussner *et al.*, 2016). An example is shown in Figure 1 (Jevrejeva *et al.*, 2018), where temperature is plotted against time (Figure 1a) and shows scenarios that stabilise at 1.5 °C (green lines), which is similar to the 1.5 °C NO pathway, and 2 °C (purple lines).[2] In Figure 1b, SLR is plotted against time, indicating that sea-levels will keep on rising regardless of temperature stabilisation. Thus, regardless of the magnitude of future warming (Mengel *et al.*, 2018), sea-levels will continue to rise for centuries to come and the rate of rise is projected to accelerate regardless of scenario. This includes under Representative Concentration Pathway (RCP) 2.6, for which SLR could exceed 3 m in 2300 (IPCC, 2021a).

If 1.5 °C is reached quickly (e.g. by 2050), it will initially appear that SLR will be less at 1.5 °C in 2050 than if 1.5 °C took longer to reach (e.g. by 2100). However, after 2100, as temperature rises continue, the former will have a greater magnitude of SLR. Hence, in communicating the implications of SLR at 1.5 °C, it is critical that timing is mentioned plus the implication that the rise, whether there is an overshoot or not, will not reach a new equilibrium until well into the 22nd century (Schleussner *et al.*, 2016). Hence, cumulative emissions and the rate, magnitude and duration of the overshoot is important for SLR (Li *et al.*, 2020, Kikstra *et al.*, 2022) over centennial scales.

[2] Throughout this section, “stabilisation scenario” refers to pathways similar to the NO pathway in which the global temperature rise does not exceed 1.5 °C.

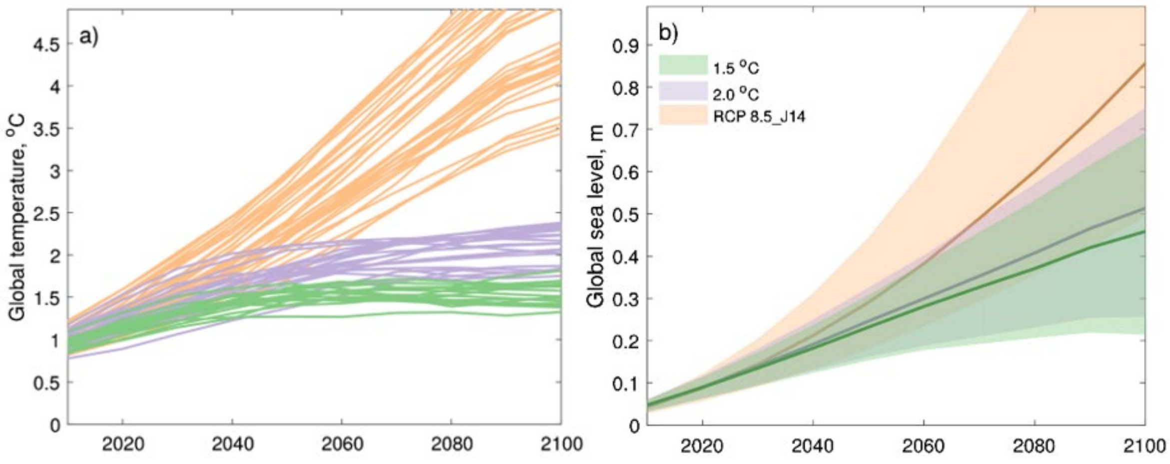


Figure 1. Global temperature pathways and sea level projections from RCP2.6, RCP4.5 (both relative to 1986–2005 plus 0.61°C to show relative to pre-industrial) and RCP8.5 from CMIP5 models.

(a) Global temperature pathways from RCP2.6 (where 1.5°C is reached by the end of the century – green lines and RCP4.5 (where 2.0°C is reached by the end of the century – purple lines) and RCP8.5 (orange lines). Each line represents a CMIP5 model). (b) Sea-level projections for the same scenarios. The line and shaded areas are median and 17th−84th percentile range respectively. Figure extracted from Jevrejeva *et al.* (2018), CC BY 3.0.

2.1.2 Overshoot and global mean sea-level rise

Wigley (2018) considered rises of 1.5 °C and 2 °C, including a small overshoot as a result of maintaining carbon dioxide concentrations at levels both higher and lower than today. As a result of warming and the overshoot, sea levels continue to rise for centuries, albeit as a slower rate for scenarios of lower CO_2 concentrations. Sanderson *et al.* (2017) reached similar conclusions, and that even with negative emissions, SLR will continue this century.

When considering how long sea levels could rise after the overshoot, Tsutsui *et al.* (2007) found that the rate of SLR could stabilise in the 23rd century, but overall sea levels would continue to rise. Schaeffer *et al.* (2012) found that in an ‘optimistic’ scenario with a low overshoot and temperatures slightly declining towards the end of the 21st century, there could be a small decline in the rate of SLR, with the overall magnitude of rise project to be between 0.75–0.8 m in 2100 with respect to 2000. However, sea levels would continue to rise, potentially resulting in 1.5 m of rise for a 1.5 °C scenario and 2.7 m rise for a 2 °C scenario in 2300 with respect to 2000.

Schwinger *et al.* (2022) found similar trends when considering just the steric component of SLR (i.e. expansion of the water column, not including additional components such as melting ice) through analysing of ocean heat uptake. However, when considering the steric component of SLR beyond 2500, Schewe *et al.* (2011) found a potential reversal of rise in the second half of the 23rd century – 200 years after the temperature peaked at 1.6 °C with respect to pre-industrial levels. Hence oceans take centuries to respond to an overshoot.

DeConto *et al.* (2021) analysed the overshoot through the assumption of CO_2 removal strategies reducing surface temperature and their effect on just the Antarctic contribution to SLR. They found that with each decade CO_2 removal was delayed after 2060, there was a substantial increase in the multi-centennial consequences for SLR from Antarctic contributions. An overshoot of less than 2 °C this century would restrict the Antarctic contribution to between approximately 0.05 m to 0.07 m by 2100 (and approximately 1.45 m to 1.6 m by 2300), compared with 0.05 m in 2100 (and approximately 1.3 m to 1.4 m by 2300) if CO_2 removal holds temperatures at 1.5 °C. This magnitude of rise is substantially lower than a 3 °C equivalent rise in temperature where rises of approximately 0.21 m in 2100 and 2.6 m in 2500 are projected. Whilst there is some debate about the levels of decline in the rate of SLR, there is high confidence that SLR will continue for at least a century even if temperatures and emissions stabilise, with differing sensitives given to the source of each component of SLR. As many scientific studies (particularly prior to the 2015 Paris Agreement) only report outputs to 2100, impacts associated with SLR beyond that date are often not considered (Clark *et al.*, 2016), including the implications of an overshoot scenario.

Over the past decade, there have been concerns over potential tipping points in the Earth system, where transient rates of temperature rise (O'Neill and Oppenheimer, 2004, Ritchie *et al.*, 2021), including that of an overshoot, could significantly influence the magnitude of SLR. Processes of concerns include enhanced rates of losses of ice sheets (Robinson *et al.*, 2012, DeConto and Pollard, 2016, Schleussner *et al.*, 2016, Rückamp *et al.*, 2018), particularly the West Antarctic Ice Sheet and the possibility of triggering marine ice cliff instability leading to rapid ice loss, noting that that these effects may not be fully felt until after the year 2100. Annex 5 on natural system impacts further examines these processes.

2.1.3 Overshoot and regional sea-level rise

Palter *et al.* (2018) found with a 2 °C overshoot pathway that returns to 1.5 °C by 2100, compared with a 1.5 °C stabilisation in 2100 scenario, the global steric component of SLR could be 18% higher (reaching approximately 0.25 m above the pre-industrial level) due to large-scale Earth system oceanic processes, such as the Atlantic Meridional Overturning Circulation (AMOC) and processes influencing the coverage of sea ice. The global steric component would be 0.04 m higher in 2100 due to overshoot but could be locally up to 0.1 m higher, for example, north of Cape Hatteras in North Carolina (including around the east coast of Canada and Greenland), but not to the south. Increases in the steric component are also seen in patches in the Southern Ocean. Due to the lack of proximity of land masses, these are unlikely to have a significant impact on coastal flooding *en masse*, except locally for small islands. A decrease in steric sea-level rise component (<0.1 m) with the overshoot scenario in 2100 is seen around the Caribbean, parts of the east coast of American, Northern Europe, Southeast Asia and parts of the Pacific and Southern Ocean. It must be stressed these changes are small relative to other uncertainties in the model and emission scenario, so cannot provide a clear picture of any global regions that may be riskier than others. Additionally, Tachiiri *et al.* (2019) considered impacts of an overshoot (of 2 °C, then declining to 1.5 °C) on regional sea levels compared with a stabilisation scenario. They found the difference in the steric component of SLR to be around 0.02–0.03 m in 2100, but could lead to 0.09 m of difference in 2300 in the Pacific Ocean where many small islands are located. Hence there are regional sensitivities of SLR, which are also apparent in the overshoot, which will play out over long time scales.

2.1.4 Global causes of extreme water level events

Mean sea level rise is just one cause of future flooding. Tides, surges and waves vary from daily to multi-decadal timescales, driven by large-scale Earth system processes and day-to-day weather. Combined, these driving factors form extreme water levels that contribute to flooding today, and will do in the future too, particularly if they increase in magnitude. These components of extreme water levels are complex to project, but are known to have differences between warming of 1.5 °C and 2 °C (Rasmessen *et al.*, 2018, Tebaldi *et al.*, 2021). Tebaldi *et al.* (2021) found that with 1.5 °C of warming that around 50% of their 7,283 data locations world-wide experienced today’s 1-in-100 year extreme sea-level at least annually. This was particularly notable in the tropics and least notable in the northern latitudes.

Tides are broadly predictable but vary day-to-day due to the meteorological conditions – including the surge where low pressure, such as during a storm, can raise the mean water level. Large-scale Earth system processes affect the weather. The subsequent surge and waves that interact on the coast, which could be sensitive to the overshoot, include: (i) the annual effect of melting sea-based ice (Hoegh-Guldberg *et al.*, 2018a) (see Section 2.2.8); (ii) the uptake of heat in the oceans as this takes a long time to dissipate when cooling occurs; (iii) interactions between these processes. This manifests itself through the El Niño-Southern Oscillation (ENSO) leading to greater oceanic warming (Wang *et al.*, 2017), interdecadal Pacific Oscillation (IPO) (Henley and King, 2017), North Atlantic Oscillation (NAO) with warmer cold events (Bader *et al.*, 2011, King and Karoly, 2017), ocean acidification (Palter *et al.*, 2018) and the AMOC (Palter *et al.*, 2018, An *et al.*, 2021).

Regional impacts of these processes are described in the sections below. More generally, interactions of short- and long-term processes include the potential for a delayed autumn/winter negative pattern in the NAO (Bader *et al.*, 2011). Observations indicate sea-ice variability influences the intensity of storms, and that less sea ice leads to more intense storms (Simmonds and Keay, 2009). Additionally, for the AMOC, the timing and duration of overshoot matters (Ritchie *et al.*, 2021). Palter *et al.* (2018) investigates a 2 °C overshoot and found the AMOC to slow down, inevitably causing the ocean surface to be cooler compared with a 1.5 °C stabilisation scenario, which could lead to expansion of sea ice in the polar areas of the North Atlantic Ocean and Southern Ocean. Furthermore, globally it is projected that there will be an increase in the number of intense tropical cyclones (high confidence) with an increase of 10% at 1.5 °C and 13% at 2 °C. (Wehner *et al.*, 2018, Arias *et al.*, 2021). The overall total global number of tropical cyclones are projected to decrease or remain unchanged (medium confidence) (Arias *et al.*, 2021). The implications of the overshoot on these processes have not been investigated. In all these papers and others, feedback mechanisms are complex, and there is limited research on this with respect to the overshoot or the implications this could have globally.

2.1.5 Sea-level rise scenarios

SLR has not been examined in overshoot scenarios in the literature that are the same as the overshoot pathways developed in this study. A range of scenarios (where temperature and sub-global or country impact metrics were also available) have been reviewed for scenarios of 1.5 °C, 2 °C and RCP 2.6. These included Hinkel *et al.* (2014), Brown *et al.* (2018a), Jevrejeva *et al.* (2018), Nicholls *et al.* (2018), Arnell *et al.* (2019), Tiggeloven *et al.* (2020), Brown *et al.* (2021), Lincke *et al.* (2022), and Kirezci *et al.* (2023). Data was selected from Brown *et al.* (2021) as this provided a clear time series of data needed with a small overshoot in temperature. This included two scenarios where temperature increases above 1.5 °C and then declines by 2100, which were called the <1.5 °C and <2 °C scenario (Brown *et al.*, 2021). In the <1.5 °C scenario, the temperature increased to 1.7 °C in 2040 then declined to 1.4 °C in 2100. For the <2 °C scenario, temperatures rose to 1.8 °C in 2050 then stayed at a similar level until 2100 (Table 1). Comparing in terms of temperature, the VHO pathway is somewhere between the two, with a steep rise in temperature until 2060 similar to the <2 °C scenario followed by a decline in 2100 similar to the <1.5 °C scenario. The principal difference is that the VHO pathway has a steeper decline in temperature after 2080 so it returns to 1.5 °C by 2100. However, this will have little immediate impact on SLR.

Table 1. Temperature and sea-level rise throughout the 21st century for the <1.5 °C and <2 °C scenarios. Data extracted from Brown *et al.* (2021). For sea-level, the 50th percentile is shown with the 5th and 95th percentiles in brackets.

Year	Temperature rise (°C) with respect to 1986-2005 for the < 1.5 °C scenario	Mean sea-level rise (m) with respect to 1986-2005 for the < 1.5 °C scenario	Temperature rise (°C) with respect to 1986-2005 for the < 2 °C scenario	Mean sea-level rise (m) with respect to 1986-2005 for the < 2 °C scenario
2000	-	0.02 (0.02–0.03)	-	0.02 (0.02–0.03)
2010	0.99	0.07 (0.05–0.09)	0.99	0.07 (0.05–0.09)
2020	1.25	0.13 (0.1–0.16)	1.25	0.13 (0.1–0.16)
2030	1.53	0.2 (0.16–0.25)	1.53	0.2 (0.16–0.25)
2040	1.67	0.29 (0.23–0.35)	1.69	0.29 (0.23–0.35)

2050	1.65	0.37 (0.29–0.46)	1.77	0.38 (0.3–0.46)
2060	1.63	0.46 (0.36–0.56)	1.80	0.47 (0.37–0.57)
2070	1.58	0.56 (0.44–0.68)	1.80	0.58 (0.46–0.7)
2080	1.52	0.65 (0.51–0.79)	1.79	0.68 (0.54–0.83)
2090	1.48	0.74 (0.57–0.9)	1.77	0.79 (0.62–0.96)
2100	1.44	0.82 (0.64–1.01)	1.76	0.89 (0.7–1.08)

In the IPCC Special Report on 1.5 °C (Hoegh-Guldberg *et al.*, 2018a), SLR at 1.5 °C in 2100 was reported as being between 0.20 m to 0.99 m depending on the confidence intervals used. This indicated no consensus in spread. However, in 2100, the difference between global mean SLR at 1.5 °C and 2 °C is around 0.1 m (0.04–0.16 m) for all outputs (Hoegh-Guldberg *et al.*, 2018a). The difference in SLR between the scenarios presented in Table 1 are similar to this range. There are no scenarios available for changes in tides, surges or waves, hence the main focus of this section is on changes due to SLR.

2.2 Regional impacts

SLR will lead to salinisation, increased risk of flooding and potentially heightened erosion (very high confidence), especially in the second half of this century (Oppenheimer *et al.*, 2019), regardless of the scenario. The effects will be felt in virtually all coastal zones world-wide (unless land is uplifting for geological reasons such as in Northern Scandinavian regions). SLR will be exacerbated by land subsidence, such as through fluid extraction and natural compaction of soft sediments (e.g. in certain deltas and cities) (high confidence). Impacts will particularly affect low-lying areas, such as deltas and atolls, and also countries that will struggle to adapt, such as developing nations (Nicholls and Cazenave, 2010). SLR will also affect habitats and associated biodiversity, particularly where hard barriers present migration inland (Oppenheimer *et al.*, 2019), or where sediment is trapped or removed up-stream in rivers restricting vertical growth of estuarine and coastal wetlands. SLR is also projected with high confidence to causes damage and impact economic growth through loss of land, natural capital, infrastructure loss, damage to transport systems, food insecurity, social capital and livelihoods (Oppenheimer *et al.*, 2019). These impacts are projected to continue even if temperatures are held at 1.5 °C or 2 °C (Hoegh-Guldberg *et al.*, 2019, Oppenheimer *et al.*, 2019, Glavovic *et al.*, 2022) or with an overshoot, including beyond 2100.

In this section, impacts at sub-global level based on IPCC regions (Gutiérrez *et al.*, 2021) are reviewed. Systems and regions where the 1.5 °C threshold are critical for impacts, and where an overshoot could cause substantially greater damage, are examined qualitatively. Quantitative damage and adaptation costs are reviewed for the <1.5 °C scenario (Table 1) as there is an overshoot in temperature, albeit closer to the HO pathway than the VHO pathway. This data was previously presented at a global level (see Brown *et al.*, 2021) and in the Searchable Inventory developed by the CS-N0W programme (Warren *et al.*, 2022). It is not possible to directly compare costs against a 1.5 °C stabilisation scenario as other scenarios (e.g. Jevrejeva *et al.*, 2018) have a different set of assumptions in the modelling process.

2.2.1 Methods

Qualitative results were undertaken by means of a literature review for sub-global impacts, building on Warren *et al.* (2022). Quantitative results were derived from Brown *et al.* (2021), using the Dynamic Interactive Vulnerability Assessment (DIVA) modelling framework (Hinkel, 2005, Vafeidis *et al.*, 2008, Hinkel *et al.*, 2014) and Shared Socio-economic Pathway 2 (SSP2). Further processing of raw data was taken to derive the IPCC regions (Gutiérrez *et al.*, 2021). As output was at country level, all countries were allocated to a region where most of their coastline fell. Russia's coastline spans Asia, Polar Terrestrial (known as Polar) and Europe; as most of the coastline is in the Polar region, it was allocated to that region.

2.2.2 Africa

Africa's coastal zone varies from low-lying shores (e.g. Nile, Niger and Volta deltas) to more hilly and mountainous areas. For example, nearly 90% of the land area in the Volta delta is situated less than 5 m above mean sea-level (Brown *et al.*, 2018b)). SLR is projected to be 0.43 m (0.34–0.53 m) in 2060 and 0.77 m (0.60–0.95 m) in 2100 (Table 2). This is less than the global mean. Cyclones (e.g. around the Southwest Indian Ocean) are projected to decline in number but become more intense (Malherbe *et al.*, 2013). However, Gutiérrez *et* *al.* (2021) indicates on the IPCC atlas a medium confidence of increase in tropical cyclones in Southeast Africa, including on the Southwest Indian Ocean coast. Cyclones making landfall in the Southwest Indian Ocean over Southern Africa are projected to decrease up to 2 °C of warming then stay stable at higher temperatures (Muthige *et al.*, 2018).

48% of Africa's population live in cities of a population greater than 300,000 people, with 8% living in cities of 10 million or more (Dodman *et al.*, 2022). Growing populations are a major driver of flood risk (Tellman *et al.*, 2021), particularly in West and North Africa (Neumann *et al.*, 2015, Merkens *et al.*, 2016, Reimann *et al.*, 2023). For example, in the low economic coastal zone, populations in 2060 (with 0.21 m of SLR) could increase to 245 million people, compared with 54 million today (Trisos *et al.*, 2022).

Key risks around the continent include flooding, erosion (Hinkel *et al.*, 2012, Evadzi *et al.*, 2017, Trisos *et al.*, 2022), and salinisation of groundwater (Musa *et al.*, 2014), plus compound risks. Examples of compound risks include declining precipitation affecting agriculture and food production, and heat-related labour productivity and sea flooding, especially in West Africa (Muthige *et al.*, 2018, Trisos *et al.*, 2022). These risks have the potential to disrupt education, healthcare, water treatment and access to electricity (Trisos *et al.*, 2022), affecting numerous SDGs, including decent work and economic growth (SDG 8) and sustainable cities and communities (SDG 11).

Damage and adaptation costs are shown in Table 2. Due to the significant and projected growth in infrastructure, cities are considered likely to experience significant damage costs (Abadie, 2018, Abadie *et al.*, 2020, Trisos *et al.*, 2022). Not all cities will be able to afford or have sufficient resource to adapt (Abadie, 2018), leaving significant vulnerabilities. Adaptation should take into account sustainable development, equity and vulnerability to avoid unintended consequences. For instance, sand extraction near Accra, Ghana, for construction increases erosion (Boateng, 2012, Appeaning Addo, 2015), which will only worsen with sea level rise. This creates challenges for responsible consumption and production (SDG 12) as there is little regulation. Adaptation will be especially important where there are growing populations (especially in low income urban areas – Dodman *et al.* (2022)) and where infrastructure to support people has yet to be built. Education and awareness in such places are essential to ensure SLR is considered ahead of urban expansion.

Table 2. Annual sea dike costs and annual flood costs with and without adaptation in Africa for the < 1.5 °C scenario under SSP2 (50th percentile, with 5th and 95th percentile in brackets). Data generated from Brown *et al.* (2021).

Year	Mean sea-level rise (m) with respect to 1986-2005 for the < 1.5 °C scenario	Without additional adaptation: Total annual sea flood costs ($bn/yr)	With additional adaptation: Total annual sea dike costs ($bn/yr)	With additional adaptation: Total annual sea flood costs ($bn/yr)
2000	0.02 (0.01–0.02)	0.2 (0.2–0.3)	0.7 (0.5–0.8)	0.1 (0.1–0.1)
2010	0.06 (0.05–0.08)	2 (1–3)	0.9 (0.9–1)	0.3 (0.2–0.3)
2020	0.12 (0.09–0.15)	19 (12–26)	2 (1–2)	0.6 (0.5–0.7)
2030	0.19 (0.15–0.23)	61 (50–70)	3 (2–2)	2 (1–2)
2040	0.27 (0.21–0.33)	131 (111–155)	2 (1–2)	3 (3–4)
2050	0.35 (0.28–0.43)	261 (211–295)	2 (1–3)	7 (5–8)
2060	0.43 (0.34–0.53)	438 (374–501)	2 (1–2)	12 (10–14)
2070	0.52 (0.41–0.64)	702 (600–811)	3 (2–2)	21 (17–25)
2080	0.61 (0.48–0.74)	1060 (895–1235)	2 (1–3)	34 (27–40)
2090	0.69 (0.54–0.85)	1524 (1273–1794)	2 (2–3)	51 (41–62)
2100	0.77 (0.60–0.95)	2139 (1774–2539)	2 (1–2)	75 (60–92)

2.2.3 Asia

Asia's coastline includes numerous low-lying delta regions, hilly areas and islands. Low-lying deltas are sensitive to SLR and extremes. For example, Feng *et al.* (2018) found with a 2 °C rather than a 1.5 °C rise there is an considerable increase in extreme sea levels along the Chinese coast. Gutiérrez *et al.* (2021) indicated on the IPCC atlas a medium confidence of increase in tropical cyclones in East and Southeast Asia. SLR is projected to be 0.39 m (0.31–0.48 m) in 2060 and 0.70m (0.55–0.86 m) in 2100 (Table 3). This is less than the global mean. Compounding this is subsidence, which can locally be in excess of 3 mm/yr, with 100 mm/yr not uncommon in delta regions (Ericson *et al.*, 2006, Nicholls *et al.*, 2021).

According to Dodman *et al.* (2022), 15% of Asia's population live in cities of more than 10 million people. Twelve of the top 20 countries exposed to SLR are in Asia (Neumann *et al.*, 2015) and Kulp and Strauss (2019) found that 70% of global population living on land exposed to SLR live in one of eight Asian countries (China, Bangladesh, India, Vietnam, Indonesia, Thailand, Philippines and Japan). Many coastal cities are exposed to higher than average rises in sea level (Hallegatte *et al.*, 2013, Jevrejeva *et al.*, 2016) and will be affected by other climate forcings (Becker *et al.*, 2023).

Brown *et al.* (2018b), Mohammed *et al.* (2018) indicated that in coastal Bangladesh, when flooding does occur in unprotected areas due to combined physical coastal and catchment processes in the delta the depth of flooding on the land is projected to increase 50% and the inundated area is projected to increase 2.5 times in a 3 °C scenario compared with a 1.5 °C scenario. They also noted, given uncertainties, a greater overlap between the findings at 1.5 °C and 2 °C, compared with 2 °C and 3 °C. Mohammed *et al.* (2018) indicated that river flood flows with a 100-year return period are projected to increase in the delta area by about 27% and 29% (Ganges), 8% and 25% (Brahmaputra) and 15% and 38% (Meghna) under 1.5 °C and 2 °C respectively. Sections 4.7 and 4.8 examine water resource challenges in Bangladesh and the Ganges basin in more detail. In East Asia, warming will mean more extreme precipitation and pluvial folding (Li *et al.*, 2019). This could result in greater flushing of sediments which could change the morphological environment or conditions that could lead to compound flooding (a coincidence of coastal, fluvial and pluvial flooding), especially in low-lying deltas.

Damage and adaptation costs are shown in Table 3. Damage is projected to be large in megacities (Abadie, 2018, Abadie *et al.*, 2020), requiring adaptation (Du *et al.*, 2020). Anthropogenic drivers such as mangrove deforestation, pollution, loss of coral reefs, tide marshes, seagrass meadows and agriculture could enhance damage, especially when the temperature rise exceeds 2 °C (Shaw *et al.*, 2022). These impact upon zero hunger (SDG 2) and life below water (SDG 14) targets. Migration driven by extreme events is already happening (Shaw *et al.*, 2022). Agricultural areas are already challenged by increases in soil salinity, with mitigation strategies including cultivation of alternative crops, suitable irrigation and land use strategies (Mukhopadhyay *et al.*, 2021), impacting SDGs (e.g. zero hunger (SDG 2) and decent work and economic growth (SDG 8)). Food security and enhanced poverty is happening now with significant implications for livelihoods (Eswar *et al.*, 2021, Lam *et al.*, 2022). Embankments have traditionally offered some protection against salinity increases, but a greater range of strategies will be needed, including a broader portfolio of political, land use and water infrastructure measures (Smajgl *et al.*, 2015).

Table 3. Annual sea dike costs and annual flood costs with and without adaptation in Asia for the < 1.5 °C scenario under SSP2 (50th percentile, with 5th and 95th percentile in brackets). Sea dike costs without adaptation are close to zero in all years. Data generated in Brown *et al.* (2021).

Year	Mean sea-level rise (m) with respect to 1986-2005 for the < 1.5 °C scenario	Without additional adaptation: Total annual sea flood costs ($bn/yr)	With additional adaptation: Total annual sea dike costs ($bn/yr)	With additional adaptation: Total annual sea flood costs ($bn/yr)
2000	0.02 (0.01–0.02)	11 (10–12)	3.2 (3–4)	7.8 (7.7–7.8)
2010	0.06 (0.04–0.07)	58 (44–74)	5 (3–6)	17 (17–18)
2020	0.11 (0.08–0.14)	278 (191–390)	7 (5–6)	33 (31–33)
2030	0.17 (0.14–0.21)	1043 (665–1662)	6 (5–7)	51 (49–53)
2040	0.25 (0.19–0.30)	3167 (1888–3813)	7 (5–9)	72 (67–76)
2050	0.32 (0.25–0.39)	4899 (3879–6370)	7 (5–7)	93 (85–101)
2060	0.39 (0.31–0.48)	7404 (5488–9002)	7 (7–8)	117 (105–128)
2070	0.48 (0.37–0.58)	10051 (7819–12376)	7 (5–9)	146 (129–162)
2080	0.55 (0.43–0.68)	12942 (10105–15676)	6 (6–12)	175 (153–198)
2090	0.63 (0.49–0.77)	15856 (12368–18120)	6 (4–9)	208 (178–238)
2100	0.70 (0.55–0.86)	18330 (14885–20589)	9 (5–7)	244 (209–283)

Adaptation is being undertaken through building on levees and sea walls, often with a focus on disaster risk reduction (Shaw *et al.*, 2022), in part to achieve related SDGs (e.g. no poverty (SDG 1), sustainable cities and communities (SDG 11) and climate action (SDG 13)). Future adaptation needs will be considerable (Glavovic *et al.*, 2022) with adaptation planning still in the early stages in Asian cities (Dulal, 2019), with a large adaptation gap for exposed urban populations on low income (Dodman *et al.*, 2022).

2.2.4 Australasia

Australia's coast includes long stretches of open coastline, with cities and corals. SLR is projected to be 0.66 m (0.52–0.80 m) in 2060 and 1.17 m (0.91–1.43 m) in 2100 (Table 4). This is greater than the global mean. Under RCP2.6, SLR and extremes are projected to be greatest in Eastern Australia compared with other coasts (McInnes *et al.*, 2015, Lawrence *et al.*, 2022). A greater proportion of severe cyclones are projected with warming greater than 2 °C (with no clear evidence at 1.5 °C and 2 °C) (Lawrence *et al.*, 2022), which could cause substantial flooding and erosion. Where wind speed increases, the increase in extreme storm surge heights is projected to be two times smaller than the contribution of sea-level rise (McInnes et al 2013). Gutiérrez *et al.* (2021) indicates on the IPCC atlas a low confidence of change in wind storms.

Key risks including SLR, high tides and storm surges. This heightens flood risk in low-lying areas and estuarine locations, including cities (60% of the population live in cities of 1–5 million people (Dodman *et al.*, 2022)), key transport networks, indigenous populations (medium confidence) and wetlands and coral environments (Lawrence *et al.*, 2022). As with atolls and reefs (see Small Islands in Section 2.2.9), there are concerns about the implications of warming of 1.5 °C for the Great Barrier Reef (McWhorter *et al.*, 2022), with temperature increases greater than this approaching a tipping point (see Annex 5 on natural system impacts). Sustained warming is projected even during La Niña conditions when the Pacific is cooler. Wang *et al.* (2017) found no intermodal consensus on the change in extreme La Niña events and their frequency, and as such there is no statistically-significant projected increase in extreme La Niña events as a direct consequence of 1.5 °C or 2 °C of warming. This has implications for local flooding and erosion, marine life (SDG 14 life below water) and sustainable tourism.

Damage and adaptation costs are shown in Table 4. Adaptation in Australia and New Zealand has increased (SDG 13 – climate action), but barriers, such as competing objectives, differing values, legal issues and engagement, remain (Lawrence *et al.*, 2022), with a greater shift to anticipatory planning needed, including land use planning and insurance. Managing adaptation is primarily focused on reducing anthropogenic pressures and facilitating natural adaptation (high confidence). Compared with other world regions (Dodman *et al.*, 2022), Australasia has greater planned adaptation for those on the highest income in urban areas, with greater planned adaptation needed for those on low income.

Table 4. Annual sea dike costs and annual flood costs with and without adaptation in Australasia for the < 1.5 °C scenario under SSP2 (50th percentile, with 5th and 9th percentile in brackets). Data generated in Brown *et al.* (2021).

Year	Mean sea-level rise (m) with respect to 1986-2005 for the < 1.5 °C scenario	Without additional adaptation: Total annual sea flood costs ($bn/yr)	With additional adaptation: Total annual sea dike costs ($bn/yr)	With additional adaptation: Total annual sea flood costs ($bn/yr)
2000	0.03 (0.02–0.04)	0.1 (0.1–0.1)	0.1 (0.1–0.1)	0.1 (0–0.1)
2010	0.1 (0.07–0.12)	0.2 (0.1–0.2)	0.1 (0.1–0.4)	0.1 (0.1–0.1)
2020	0.18 (0.14–0.23)	0.7 (0.4–1.4)	0.2 (0.5–0.2)	0.3 (0.2–0.4)
2030	0.29 (0.23–0.35)	5 (2–8)	0.5 (0.2–0.5)	0.6 (0.5–0.8)
2040	0.41 (0.32–0.50)	16 (8–23)	0.2 (0.4–0.3)	1 (0.9–2)
2050	0.53 (0.42–0.65)	31 (22–38)	0.4 (0.2–0.2)	2 (1–2)
2060	0.66 (0.52–0.80)	45 (36–53)	0.2 (0.3–0.6)	3 (2–4)
2070	0.79 (0.62–0.97)	62 (50–72)	0.6 (0.2–0.3)	4 (3–6)
2080	0.92 (0.72–1.13)	80 (67–94)	0.7 (0.2–0.7)	6 (5–8)
2090	1 (0.81–1.28)	99 (82–118)	0.2 (0.3–0.3)	8 (6–11)
2100	1 (0.91–1.43)	122 (99–145)	0.2 (0.2–0.3)	11 (8–14)

2.2.5 Central and South America

Central and South America contain contains low-lying areas, mountainous/hilly coasts and deltas. Caribbean islands are considered under the Small Island region, but some of the meteorological forces are the same as for Central America. There is limited research into the impacts of 1.5 °C for Central and South America.

SLR is projected to be 0.53 m (0.42–0.65 m) in 2060 and 0.95 m (0.74–1.16 m) in 2100 (Table 5). This is greater than the global mean. Local subsidence can enhance this risk (e.g. Restrepo-Ángel *et al.*, 2021). Gutiérrez *et al.* (2021) indicates on the IPCC atlas a medium confidence of increase in tropical cyclones in Central America and Northeastern South America, with low confidence in the direction of change in storms.

Local sea-levels will continue to be enhanced during ENSO events (Villamizar *et al.*, 2017) or from swell waves (Andrade *et al.*, 2013). For 1.5 °C of warming, Wang *et al.* (2017) found that extreme El Niño events increase linearly with temperature rise. Due to the oceanic thermocline sustaining faster warmer in the Eastern Equatorial Pacific, extreme ENSO events continue for up to a century after temperatures have stabilised, (Wang *et al.*, 2017). With warming, there is an eastward shift in intensification of ENSO-related atmospheric teleconnections (Cai *et al.*, 2021). More extreme El Niño events impacts Central (and Eastern North) American coasts through increase storm events, causing severe beach erosion (Barnard *et al.*, 2017). For these impacts, the magnitude of overshoot is important as it influences the duration of extreme events after the overshoot has passed.

17% of the population of Latin America and the Caribbean live in cities of more than 10 million people, with a further 25% living in cities of 1–5 million people (Dodman *et al.*, 2022). SLR has potential to increase salinisation, including in deltas (Rojas *et al.*, 2018), but this is also dependent on rates of sedimentation and river flow (the latter also being affected by climate change). Extreme events can cause disasters affecting development of entire countries (SDG 8 – decent work and economic growth, SDG 11 – sustainable cities and communities).

Table 5 notes damage and adaptation costs for Central and South America. Dodman *et al.* (2022) notes that adaptation in urban areas is relatively high for the exposed population with the highest income, compared with those on the lowest income. Planned adaptation significantly widens the gap between those on the highest and lowest income, with potential remaining to adapt for those in lower-income areas (Dodman *et al.*, 2022). In many South American countries, adaptation is constrained by poverty, resources and other social priorities (Villamizar *et al.*, 2017), hence these factors need to be addressed at the same time as promoting adaptation.

Table 5. Annual sea dike costs and annual flood costs with and without adaptation in Central and South America for the < 1.5 °C scenario under SSP2 (50th percentile, with 5th and 95th percentile in brackets). Total sea dike costs each year are close to zero without additional adaptation. Data generated in Brown *et al.* (2021).

Year	Mean sea-level rise (m) with respect to 1986-2005 for the < 1.5 °C scenario	Without additional adaptation: Total annual sea flood costs ($bn/yr)	With additional adaptation: Total annual sea dike costs ($bn/yr)	With additional adaptation: Total annual sea flood costs ($bn/yr)
2000	0.02 (0.02–0.03)	0.4 (0.4–0.5)	1 (1–2)	0.3 (0.3–0.4)
2010	0.08 (0.06–0.1)	3 (2–4)	1.2 (0.7–1.5)	0.9 (0.8–1)
2020	0.15 (0.11–0.18)	13 (9–19)	2 (3–2)	2 (2–3)
2030	0.23 (0.18–0.29)	37 (25.6–48)	2 (1–4)	5 (4–6)
2040	0.33 (0.26–0.41)	75 (55–84)	2 (2–3)	9 (7–10)
2050	0.43 (0.34–0.53)	109 (94–121)	4 (2–3)	14 (11–16)
2060	0.53 (0.42–0.65)	149 (130–168)	3 (2–6)	20 (17–24)
2070	0.64 (0.5–0.78)	199 (172–228)	4 (2–3)	29 (23–36)
2080	0.75 (0.58–0.91)	258 (220–300)	2 (3–4)	40 (32–51)
2090	0.85 (0.66–1.04)	326 (273–385)	2 (2–3)	55 (42–68)
2100	0.95 (0.74–1.16)	406 (336–486)	2 (1–4)	72 (53–86)

2.2.6 Europe

Europe's coast ranges from polar areas to low-lying deltas and rocky coasts. Land raising through geological processes occurs in northern latitudes, reducing the risks associated with

SLR, with subsidence occurring elsewhere due to glacial isostatic rebound[3] and locally in some deltas (Antonioli *et al.*, 2020). SLR is projected to be 0.35m (0.28–0.43 m) in 2060 and 0.63 m (0.49–0.77 m) in 2100 (Table 6). This is less than the global mean. Compared with open coasts, SLR is likely to be lower in the Mediterranean and Baltic Seas as these are semi-enclosed water bodies (Fox-Kemper *et al.*, 2021). Gutiérrez *et al.* (2021) indicates on the IPCC atlas a medium confidence of increase in severe wind storms across the whole continent. Wetter conditions in Northern Europe (during winter months, often associated with storm conditions that promote flooding and erosion) tend to be associated with the positive phase on the NAO (Bader *et al.*, 2011). Positive phases can last for consecutive winters, such as from the mid-1960s to the mid-1990s (Stephenson *et al.*, 2000). If a positive NAO phase were to coincide with an overshoot, this could potentially change the associated weather conditions. However, there is very little research in this area so the potential sensitivity to the overshoot is not well understood.

Dodman *et al.* (2022) indicate that 57% of Europe's population live in cities of a population less than 300,000. Europeans at risk from a 100-year flood event (coast and inland) will rapidly increase beyond 2040, assuming present protection and population levels (Bednar-Friedl *et al.*, 2022). Risks of inundation and flooding will increase at an accelerating pace (high confidence), with erosion affecting many sandy European coastlines (high confidence) as 27%–50% of Europe's coast are eroding today (high confidence) (Bednar-Friedl *et al.*, 2022).

Damage and adaptation costs are shown in Table 6. 75% of European nations are already planning for SLR (McEvoy *et al.*, 2021), which is integrated with shoreline management planning. This supports SDG 13 on climate action. Exposed populations with lower income and higher income are equally balanced in terms of current adaptation, with planned adaptation favouring population with higher income (Dodman *et al.*, 2022). Few nations are considering the period beyond 2100, meaning the significance of SLR may not be fully integrated with adaptation. Whilst sea walls or dikes are advocated as a means of defence and are economically viable (Lincke and Hinkel, 2018), alternative softer solutions (e.g.

[3] Glacial isostatic rebound is the rise of land masses following the disappearance of the huge weight of ice sheets that were present during the last ice age.

beach nourishment – Bednar-Friedl *et al.*, 2022) are commonplace and property level resilience and set-back zones are increasingly considered. For example, Wolff *et al.* (2023) found that implementation of set-back zones reduces exposure to SLR of new urban developments by at least 50% by 2100, indicating that urban design is as important as SLR. Managed realignment (i.e. the co-ordinated movement of the coastline to allow sea to flood the land) is considered for areas with low population density that is not economically viable to protect (Haasnoot *et al.*, 2021) or in wetland restoration (Schernewski *et al.*, 2018), reinforcing SDG life below water (SDG 14). Nature-based solutions are increasingly being used. These provide co-benefits of increasing biodiversity, enhancing mitigation and food provision (Parmesan *et al.*, 2022), but are themselves under threat from rising seas, such as where there are rapid rates of rise or reduced space (e.g. on the foreshore due to coastal squeeze) so their efficiency declines (Bednar-Friedl *et al.*, 2022).

Table 6. Annual sea dike costs and annual flood costs with and without adaptation in Europe for the <1.5 °C scenario under SSP2 (50th percentile, with 5th and 95th percentile in brackets). Data generated in Brown *et al.* (2021).

Year	Mean sea-level rise (m) with respect to 1986-2005 for the < 1.5 °C scenario	Without additional adaptation: Total annual sea flood costs ($bn/yr)	With additional adaptation: Total annual sea dike costs ($bn/yr)	With additional adaptation: Total annual sea flood costs ($bn/yr)
2000	0.02 (0.01–0.02)	2 (2–2)	0.9 (0.8–1.1)	2 (2–2)
2010	0.05 (0.04–0.07)	3 (3–3)	1.1 (0.8–1.3)	4 (4–5)
2020	0.1 (0.08–0.12)	4 (3–4)	1.3 (1–1.5)	8 (6–10)
2030	0.16 (0.12–0.19)	5 (4–5)	2 (1–2)	18 (12–28)
2040	0.22 (0.17–0.27)	7 (6–8)	2 (2–2)	53 (30–87)
2050	0.29 (0.23–0.35)	9 (8–11)	2 (1–2)	130 (76–200)
2060	0.35 (0.28–0.43)	13 (11–15)	2 (1.6–2.3)	267 (159–391)
2070	0.43 (0.33–0.52)	18 (14–21)	2 (2–3)	445 (288–648)
2080	0.5 (0.39–0.61)	23 (19–29)	2 (1.4–2.4)	676 (427–1039)

2090	0.56 (0.44–0.69)	30 (24–36)	2 (1–2)	999 (609–1538)
2100	0.63 (0.49–0.77)	38 (29–46)	1.7 (1.5–2.1)	1434 (8389–2116)

2.2.7 North America

North America has a range of coasts from hills to deltas to wetlands. SLR is projected to be 0.41 m (0.32–0.50 m) in 2060 and 0.73 m (0.57–0.90 m) in 2100 (Table 7). This is slightly less than the global mean. Subsidence exceeding 3 mm/yr affects most coastal areas including wetlands (in particular marshes), forests, agriculture areas and developed areas (Ohenhen *et al.*, 2023), with rates of relative SLR not fully appreciated in impact assessments, thus underestimating risk. Subsidence can enhance SLR, but in parts of Canada, land is uplifting in response to the retreat of glaciers and ice sheets (Peltier *et al.*, 2015). To some extent, this uplift will offset the rise today, but will become less noticeable in the future, especially for higher rates of sea-level rise (Kopp *et al.*, 2014, Peltier *et al.*, 2015, Fox-Kemper *et al.*, 2021).

Coastal flooding is already occurring locally where hurricanes combine with high tides (Heberger *et al.*, 2011, Fu *et al.*, 2016, Wdowinski *et al.*, 2016). Gutiérrez *et al.* (2021) indicate on the IPCC atlas a medium confidence of increase in tropical cyclones and severe wind storms across North America, apart from Northern North America and Canada, increasing flood risk. When a fuller range of extremes are considered (e.g. long-period tides), in an impact assessment on US cities, this can increase flood damage costs by 28% and cause extreme sea-levels to come earlier than expected. Hence these driving factors can be more important than the overshoot (Rashid *et al.*, 2021). Compounding this has been increased development on both fluvial and coastal flood plains in general, meaning an increase in assets and people are becoming exposed to risks (Trenberth *et al.*, 2018).

Impacts include increased salinisation and the flooding and erosion of wetlands (e.g. the Florida Everglades), low-lying areas, sandy beaches and barrier islands. This could displace millions of people and cause property and archaeological losses. Moreover, rising groundwater levels could impede drainage and saltwater intrusion could contaminate drinking water (Hicke *et al.*, 2022). Coral reefs in the Gulf of Mexico and Florida are facing risk of bleaching and mortality (high confidence) (Hicke *et al.*, 2022), which could affect ecosystems and tourism. With 24% of Northern American's population living in cities of under 300,000, 17% in cities with 5–10 million people and a further 10% in cities with greater than 10 million people, impact assessments tend to focus on urban areas. There is high confidence that SLR will affect public buildings, infrastructure, port and transportation facilities (Hicke *et al.*, 2022).

Table 7 lists damage and adaptation costs associated with SLR in North America. Adaptation to extremes and SLR has traditionally focused on hard responses, but is growing to include a fuller range of measures including protection of ecosystems, flood plain restoration (Hicke *et al.*, 2022) and relocation (Hauer *et al.*, 2016, Hauer, 2017), benefiting SDGs climate action (SDG 13) and life below water (SDG 14). Exposed populations with the highest income are well adapted to flood risks, with limited planned adaptation (potentially adversely affecting SDG11 on sustainable cities and communities). Exposed populations on lower incomes have a large adaptation gap, with limited adaptation planned, thus creating inequity in adaptation (Dodman *et al.*, 2022).

Table 7. Annual sea dike costs and annual flood costs with and without adaptation in North America for the < 1.5 °C scenario under SSP2 (50th percentile, with 5th and 95th percentile in brackets). Data generated in Brown *et al.* (2021).

Year	Mean sea-level rise (m) with respect to 1986-2005 for the < 1.5 °C scenario	Without additional adaptation: Total annual sea flood costs ($bn/yr)	With additional adaptation: Total annual sea dike costs ($bn/yr)	With additional adaptation: Total annual sea flood costs ($bn/yr)
2000	0.02 (0.01–0.02)	0.8 (0.7–0.8)	0.8 (0.9–0.9)	0.7 (0.7–0.7)
2010	0.06 (0.05–0.08)	2 (1.6–2.4)	0.8 (0.6–0.9)	2 (1–2)
2020	0.11 (0.09–0.14)	7 (5–12)	1.1 (0.8–1.2)	3 (3–4)
2030	0.18 (0.14–0.22)	45 (19–53)	2 (1–2)	5 (5–5)
2040	0.26 (0.2–0.31)	80 (59–110)	1.9 (1.3–1.4)	7 (6–9)
2050	0.33 (0.26–0.41)	151 (98–229)	1 (1.7–1.5)	11 (8–13)
2060	0.41 (0.32–0.5)	274 (169–367)	1 (1–2)	15 (12–18)

2070	0.5 (0.39–0.6)	419 (291–514)	1 (1–2)	20 (16–24)
2080	0.58 (0.45–0.7)	553 (419–637)	1 (2–2)	26 (21–31)
2090	0.65 (0.51–0.8)	672 (551–761)	1 (1–2)	32 (25–37)
2100	0.73 (0.57–0.9)	784 (669–908)	1 (1–2)	38 (31–43)

2.2.8 Polar

Polar regions can be low and rocky, including tundra and coasts protected by sea ice. Key risks include greater flooding through coastlines becoming ice-free either permanently or during summer months, or due to the melting of permafrost (Larsen *et al.*, 2014, Meredith *et al.*, 2019, Constable *et al.*, 2022). Land may be rising or falling in Polar regions (Jiang *et al.*, 2021). SLR is projected to be 0.38 m (0.30–0.46 m) in 2060 and 0.67 m (0.52–0.82 m) in 2100 (excludes data around Antarctic coastlines). This is very similar to the global mean in 2060 and less than the global mean in 2100. Extremes are not known.

Impacts will be driven by ice melting. Annex 4 noted substantially higher ice melt in the VHO pathway compared to the NO pathway. This is consistent with the literature, which has found the melting of sea-based ice to be sensitive to warming at 1.5 °C and 2 °C (Tachiiri *et al.*, 2019). Graff *et al.* (2019) projected that Arctic summers with no sea ice would to be rare with 1.5 °C warming, but would occur in 18% of years with 2 °C warming. Others have projected ice-free summers to occur more frequently in a 2 °C world compared with a 1.5 °C (Hoegh-Guldberg *et al.*, 2018a, Screen, 2018, Hoegh-Guldberg *et al.*, 2019) (medium confidence). Depending on the degree of sensitivity in observations, ice-free Arctic summers are very likely with 2 °C (Niederdrenk and Notz, 2018), or extremely unlikely at 1.5 °C of warming (Niederdrenk and Notz, 2018). Sanderson *et al.* (2017) also found a greater probably of an ice-free Arctic in September with a 1.5 °C overshoot scenario compared with a 1.5 °C stabilisation scenario. An 'intermediate' overshoot will have no long-term consequences in terms of Arctic sea-ice cover (high confidence) (Hoegh-Guldberg *et al.*, 2018a). Sea ice-free summers (and especially winters) are important to understand as coasts are subject to increased significant wave heights nearer to land (Ruest *et al.*, 2016) leading the greater potential for flooding and erosion including sediment movement (Hoegh-Guldberg *et al.*, 2019, Manson, 2022), and subsequent impacts on land use, associated infrastructure and shipping (very high confidence).

With higher temperatures, permafrost could thaw leading to flood damage to infrastructure (e.g. pipes, bridges, drilling platforms, residences, transport infrastructure) threatening industry, innovation and infrastructure (SDG 9) and responsible consumption and production (SDG 12). Hjort *et al.* (2018) reports that by 2050 under a RCP4.5 scenario (with mean annual ground temperatures 0.86 °C above the 2000–2014 baseline), 70% of Arctic infrastructure is located in areas of risk from permafrost thaw (which also releases carbon) and subsidence (medium confidence). Whilst much of this infrastructure is inland, a proportion will be coastal (Larsen *et al.*, 2014). Even with large reductions in greenhouse gas emissions comparable to a RCP2.6 scenario in 2050 (with mean annual ground temperatures 0.85 °C above the 2000–2014 baseline), a similar number of infrastructures would be affected compared with a non-mitigation scenario (Hjort *et al.*, 2018). Hence damages are very sensitive to the degree of warming and overshoot in Polar regions.

Table 8 lists the damages and adaptation costs. Due to model outputs being at country level, the Polar region data contains Russia which contains coasts in Europe and Asia (Far East Russia), so an overestimate is presented here. Sea flood costs grow particularly in the second half of the century. Adaptation in Polar regions will be different to others due to a mix of other environmental concerns and a low population density. Given the substantial risks to infrastructure (including oil and gas infrastructure that many countries use), the planning of adaptation to protect infrastructure will become increasingly important, especially beyond 1.5 °C. Present governance planning, preparation and response has been ‘limited in scope’ (Constable *et al.*, 2022) for a range of climate change impacts in Polar regions.

2.2.9 Small islands

Small islands in the Atlantic, Pacific and Indian Oceans and Caribbean Sea vary in their elevation, geology and coastal oceanography (Nunn *et al.*, 2016, Mycoo *et al.*, 2022). This means they have different risks associated with SLR: high islands may only be affected around their low-lying rim, but in atolls, whole nations could be impacted (Brown *et al.*, 2023). There is very high confidence that small islands are at risk from SLR and extreme events.

SLR is projected to be 0.64 m (0.50–0.78 m) in 2060 and 1.14 m (0.088–1.39 m) in 2100 (Table 9). This is greater than the global mean, mostly due to the number of islands in the Pacific Ocean where there is a higher than average projected rise (Oppenheimer *et al.*, 2019).

Table 8. Annual sea dike costs and annual flood costs with and without adaptation in Polar regions for the < 1.5 °C scenario under SSP2 (50th percentile, with 5th and 95th percentile in brackets). Data generated in Brown *et al.* (2021).

Year	Mean sea-level rise (m) with respect to 1986-2005 for the < 1.5 °C scenario	Without additional adaptation: Total annual sea flood costs ($bn/yr)	With additional adaptation: Total annual sea dike costs ($bn/yr)	With additional adaptation: Total annual sea flood costs ($bn/yr)
2000	0.02 (0.01–0.02)	0.2 (0.2–0.2)	0.1 (0.1–0.1)	0.2 (0.2–0.2)
2010	0.06 (0.04–0.07)	0.5 (0.5–0.6)	0.1 (0.1–0.1)	1 (0.4–0.4)
2020	0.11 (0.08–0.13)	1 (1–2)	0.1 (0.1–0.1)	3 (0.6–0.7)
2030	0.17 (0.13–0.2)	3 (2–3)	0.2 (0.1–0.2)	5 (1–1)
2040	0.24 (0.19–0.29)	6 (4–10)	0.2 (0.1–0.2)	7 (2–2)
2050	0.31 (0.24–0.37)	13 (7–17)	0.2 (0.1–0.2)	11 (2–3)
2060	0.38 (0.3–0.46)	20 (14–27)	0.2 (0.1–0.2)	15 (3–5)
2070	0.46 (0.36–0.56)	30 (21–44)	0.2 (0.1–0.3)	20 (4–7)
2080	0.53 (0.41–0.65)	45 (29–74)	0.2 (0.1–0.2)	26 (6–7)
2090	0.6 (0.47–0.74)	68 (38–92)	0.2 (0.1–0.2)	32 (7–8)
2100	0.67 (0.52–0.82)	93 (52–107)	0.1 (0.2–0.2)	38 (8–10)

Sea-level rise is a major risk factor of flooding in the Caribbean. Furthermore, for Caribbean Islands, Gutiérrez *et al.* (2021) indicates on the IPCC atlas a medium confidence of an increase in tropical cyclones in the Caribbean (other island regions are not shown). Kleptsova *et al.* (2021) found hurricane intensity is projected to remain at similar levels over the Caribbean. With 1.5 °C and particularly 2 °C of warming, extreme hurricane precipitation will increase (Vosper *et al.*, 2020). Collectively, this could cause greater landslides and erosion, which would temporarily increase sediment supply, including the volume of material transported down rivers.

In the Pacific, islands are often flooded with the compound effects of high tides, swell waves and La Niña conditions (Merrifield *et al.*, 2014, Ford *et al.*, 2018, Canavesio, 2019, Hoeke *et al.*, 2021). In El Niño years where total water levels are considered, average anomalies are largely statistically insignificant due to large tidal variabilities. When sea levels were analysed with an inundation model, ENSO had a significant but small impact on the number of people exposed to flooding on a global scale (not just in small islands) (Muis *et al.*, 2018). There is high confidence that tropical cyclones are already having an effect on flood and erosion, causing significant damage (Mycoo *et al.*, 2022). These extreme events have potential to instigate disasters, as seen in Vanuatu where the impact of repeated cyclones has affected development (United Nations, 2015)

Corals act as buffers against wave attenuation and when broken down provide sediment. Severe impacts to corals are projected unless warming is limited to well below 2 °C (Hoegh-Guldberg *et al.*, 2018b). Rises of greater than 1.5 °C, including any overshoot, will have limited impact on SLR in the 21st century, but will have significant impact beyond. However, rises in sea surface temperatures increase thermal stress (Lough *et al.*, 2018), that can be locally amplified during ENSO events (Claar *et al.*, 2018, Mycoo *et al.*, 2022) and surface temperatures if coinciding with the positive phase of the IPO (Henley and King, 2017). Tachiiri *et al.* (2019) and van Hooidonk *et al.* (2016) found that with an overshoot greater than 1.5 °C, almost all corals were at risk due to the warmer temperatures and potential coral bleaching. Additionally, with a 2 °C overshoot, this could lead to greater ocean acidification (Palter *et al.*, 2018) that has implications for coral health. The surface temperature of the VHO pathway is at a critical boundary, as between rise of 1.5 °C to 2 °C can significantly impact coral (Hoegh-Guldberg *et al.*, 2018a) – see Annex 5 of this study for a discussion of the potential impacts on corals.

Bleached corals impact coastal flooding in two ways. First, through reduced natural protection during extreme events, which could be further enhanced as sea-levels rise (particularly at a rate of RCP4.5 – Perry *et al.* (2018)). Second, as corals break down they could contribute to sediment locally (Tuck *et al.*, 2021), but could be affected by sediment stress from silt-ladened water associated with run-off or dredging (Rogers and Ramos-Scharrón, 2022). Some corals, such as those of sand-dominated islands, are threatened more than islands composed of rubble grade material. Decreasing rates of reef accretion, increasing rates of bioerosion and any increases in storm conditions could cause reefs and accompanying beaches to become increasingly less stable (Hoegh-Guldberg *et al.*, 2007). Whilst there is evidence that some islands can respond and evolve under sea-level rise and sediment movement laterally and vertically (Webb and Kench, 2010, Masselink *et al.*, 2020), the response of small atoll islands, including those that are inhabited, remains uncertain. Hence, the survival of coral reef systems and associated islands and people that rely on them for livelihoods remain at high risk (high confidence).

Higher temperatures, changes to corals and potential enhanced flooding and erosion can impact tourism, which is a key economic sector for many small islands. Where surge heights are predicted to be higher (e.g. Caribbean) or other conditions cause inundation further inland with 1.5 °C of warming (Biondi and Guannel, 2018), this can impact key infrastructures in tourist and other sectors. Sustainable tourism (apparent in SDGs decent work and economic growth (SDG 8), responsible consumptions and production (SDG 12) and climate action (SDG 13)) could also be affected through warmer temperatures and changes in consumer demand (Scott, 2021). Impacts of flooding or erosion may be reduced by nourishment, in keeping with tourist needs, but will need to be managed carefully as sand is not an infinite resource.

Table 9 notes damage and adaptation costs. Damage costs are likely to be higher than presented (as data was run from a global model) due the significant connectivity in infrastructure (due to scales) and the close connectivity with the sea (i.e. cascading impacts). Adaptation may have limits that are reached earlier or later than mainland coasts, including under a low emissions scenario (Mycoo *et al.*, 2022). Climate action (SDG 13) includes consideration of SLR and extreme events that cause disasters, utilising the Sendai Framework for Disaster Risk Reduction (United Nations 2015) to ensure disaster risk reduction policies, plans and programmes are in place, to ensure greater partnerships to implement risk reduction measures. Adaptation includes forced or planned migration (Barnett and Adger, 2007, Constable, 2017, Thomas and Benjamin, 2018, McMichael *et al.*, 2019), seawalls (Nunn *et al.*, 2021), raised floors (Magnan *et al.*, 2018), land claim and raising (Esteban *et al.*, 2019, Brown *et al.*, 2020, Magnan and Duvat, 2020, Holdaway *et al.*, 2021). Many of these integrate into SDGs related to industry, innovation and infrastructure (9) and sustainable cities and communities (11). Dodman *et al.* (2022) reports small islands with exposed populations that have high income have greater adaptation to coastal flooding, with much more planned for lower-income population islands. There remains a shortfall in low-income urban areas (Dodman *et al.*, 2022) and non-urban areas, and there an urgent need to build capacity and more comprehensive adaptation strategies.

Table 9. Annual sea dike costs and annual flood costs with and without adaptation in Small Islands for the < 1.5 °C scenario under SSP2 (50th percentile, with 5th and 95th percentile in brackets). Data generated in Brown *et al.* (2021).

Year	Mean sea-level rise (m) with respect to 1986-2005 for the < 1.5 °C scenario	Without additional adaptation: Total annual sea flood costs ($bn/yr)	With additional adaptation: Total annual sea dike costs ($bn/yr)	With additional adaptation: Total annual sea flood costs ($bn/yr)
2000	0.03 (0.02–0.04)	0 (0–0)	0.2 (0.2–0.2)	0 (0–0)
2010	0.1 (0.07–0.12)	0.6 (0.3–1)	0.2 (0.5–0.3)	0 (0–0)
2020	0.18 (0.14–0.22)	5 (3–6)	0.3 (0.2–0.8)	0.1 (0.1–0.1)
2030	0.28 (0.22–0.34)	8 (7–9)	0.4 (0.8–1)	0.1 (0.1–0.2)
2040	0.4 (0.31–0.49)	12 (11–13)	0.9 (0.5–1)	0.3 (0.2–0.4)
2050	0.52 (0.41–0.63)	16 (15–17)	1 (0.9–1)	0.5 (0.3–0.6)
2060	0.64 (0.5–0.78)	21 (19–23)	1 (1–1)	0.8 (0.6–2)
2070	0.77 (0.6–0.94)	28 (24–32)	0.9 (0.9–0.7)	2 (0.8–2)
2080	0.9 (0.7–1.09)	36 (31–42)	0.6 (0.5–0.8)	2 (2–3)
2090	1 (0.79–1)	46 (38–54)	0.7 (0.9–1)	3 (2–3)
2100	1 (0.88–1)	58 (48–69)	0.7 (0.4–0.8)	3 (3–4)

2.3 Adaptation

Adaption to SLR and extreme events is essential, regardless of the degree of overshoot, as sea-levels will continue rising for potentially centuries even if emissions are stabilised (Hoegh-Guldberg *et al.*, 2018a, Nicholls *et al.*, 2018, Haasnoot *et al.*, 2021). This is an undervalued and underacknowledged hazard, where there are presently significant adaptation gaps in the second half of the century and beyond.

Adaptation helps drives some of the SDGs – such as climate action (SDG 13), but can also conflict with them, such as the need for sand for protection or tourist needs (Bendixen *et al.*, 2019) (SDG 12 – responsible consumption and production). SLR can also threaten SDGs where livelihoods depend on them, such as in deltas where agriculture is at risk from salinisation, posing increased risk of poverty (SDG 1), hunger (SDG 2) and decent work and economic growth (SDG 8). SLR can affect cities through the need for decent work, which can affect other SDGs, as seen with sand removal, and can also damage infrastructure (SDG 9 – industry, innovation and infrastructure) and sustainable cities and communities (SDF 11). Many adverse impacts occur during extreme events that may result in disasters. Warming impacts ocean ecosystems (SDG15 – life below water) such as corals, which can in turn affect coastal flooding.

For sensitive and mature systems (e.g. agriculture in deltas – see the Asia region) or those assets at high risk (e.g. coastal nuclear power stations), adaptation is happening today (see Australasia, Europe, North America regions), is mainstreamed into design of new infrastructures and builds towards SDGs (e.g. zero hunger (SDG 2) and industry, innovation and infrastructure (SDG 9)). However, the types of adaptations that are needed in the future may need to be intensified or varied according to changing or more intense hazards or needs. Adaptation often happens on a reactive basis after an extreme event (high confidence) (Glavovic *et al.*, 2022), but is increasingly proactive. For example, a global survey of coastal practitioners indicated that only 72% use SLR projections in adaptation or planning, mostly from developed nations (Hirschfeld *et al.*, 2023), illustrating a gap in practice.

On the coast, adaptation has historically involved protecting (e.g. building a sea wall), retreating (e.g. move inland) and accommodating (e.g. build on stilts, early warnings) (J.

Dronkers *et al.*, 1990). Soft approaches and nature-based solutions are increasingly popular (Oppenheimer *et al.*, 2019, Bongarts Lebbe *et al.*, 2021), with advancing land where there is a lack of space such as in cities (Glavovic *et al.*, 2022). The awareness and range of solutions has increased with the recognition that adaptation is a continuous process rather than an end goal, crossing psychosocial, economic, physical, technical and natural dimensions (Glavovic *et al.*, 2022), so increasingly a systems approach is required (e.g. Smajgl *et al.*, 2015). Adapting to SLR is complex due to the deep uncertainty that surrounds SLR and socio-economic change. Lead-in time is needed to adapt (Hermans *et al.*, 2023), noting that those systems or communities that require adaptation may not yet be in place. Staged adaptation through an adaptation pathway approach helps this (Glavovic *et al.*, 2022), and reduces the possibility of adaptation lock-in where part of a system is trapped. Increasingly, systems are being stretched or adaptation measures combined to reduce impacts. For example, adaptation options are being combined in agriculture regions of deltas (Smajgl *et al.*, 2015), and there is land raising and internal migration in atolls (Magnan and Duvat, 2020, Brown *et al.*, 2023). At times, today's unacceptable adaptation (which may be perceived as a failure to adapt) may become more acceptable in the future, where options become more limited as necessity is the mother of invention.

There has been increased awareness and understanding of potential limitations or appropriateness of adaptation, including maladaptation, impacting climate action (SDG 13) and wider implications for disaster risk management. For instance, sea walls are seen as a major means to adapt to SLR, but in the long-term can reduce beach levels or not resolve erosion (Nunn *et al.*, 2021, Griggs, 2022) and have potential to fail (Glavovic *et al.*, 2022). In delta areas, side-effects of embankments can increase salinity risk due to raising groundwater remaining. Sand is seen as an infinite resource, but in the coming decades it will become a competing resource (Parkinson and Ogurcak, 2018) or expensive, limiting it means as a method of protection (e.g Bendixen *et al.*, 2021). Hence ensuring responsible consumption and production (SDG 12) will become increasingly important.

Long-term behaviours and successes of newer adaptation measures are also being questioned as their benefits and effectiveness are uncertain. For example, there is uncertainty about whether some nature-based solutions will withstand extreme events as well as hard adaptation measures, and whether this adheres to people's expectations or recognised protection standards (Smith *et al.*, 2017). Particular challenges (as identified in the Ganges-Brahmaputra) are space constraints, biophysical feedbacks, policy recognition, public use and acceptance (Gain *et al.*, 2022). Site-specific knowledge, monitoring and upscaling can underpin successful adaptation.

The point where adaptation limits (i.e. the point or conditions where adaptation becomes an ineffective response or where objectives cannot be secured from intolerable risks) are reached is sometimes not clearly defined in terms of a point in time or space, or for people and livelihoods. Is it when a major disaster occurs, meaning a step-change in lifestyle in the aftermath? Is it where salinised land can no longer be farmed and there are no alternative sources of income? Is it where a greater proportion of the population is exposed to an increased frequency of extreme events? Is it where planned retreat is the only option? Without defining these questions, it is unclear what is the limit of adaptation. Adaptation limits are already being stretched as adaptation is an ongoing process, combined with other political, social, financial and environmental change. In high-risk areas, such as deltas and small, low-lying islands, adaptation limits may already be pushed, in part because these are dynamically changing environments which have seen significant change in the past, resulting in more mobile populations that we know today. Key governance challenges remain (high confidence) (Glavovic *et al.*, 2022) and these are essential to strengthen to build a solid foundation for future adaptation.

2.4 Conclusions

Sea levels are projected to rise with climate change, and rates of rise are projected to accelerate this century regardless of scenario. A time lag exists between global temperature rise and subsequent sea-level rise, meaning that the impacts of today's emissions may not be seen for decades. In an overshoot scenario, sea levels could keep rising for centuries. Globally, the broad implications of sea-level rise, such as hotspots of flooding and erosion, are qualitatively well known. However, the precise details, which are dependent on rates and magnitudes of sea-level rise and other drivers of extreme events (tides, waves, surge), are less well understood. An overshoot above 1.5 °C will particularly matter where large-scale Earth systems processes affect sensitive extreme events including:

1. Polar regions due to sea-ice free summers and permafrost melting, especially where waves reach land that has been blocked by ice. Melting of sea ice can affect wider oceanic processes.
2. Along Eastern Central and North American coasts due to El Niño affecting storms and beach erosion. Warming due to El Niño is projected to have a century-long legacy.
3. Coral warm water reefs worldwide that are highly sensitive to local sea surface temperature increase, especially combined with a severe El Niño event, leading to bleaching and ultimately causing flooding and erosion of atolls.
4. Low-lying atoll islands, including those in the Indian and Pacific Oceans, and deltas where there is insufficient sediment supply or subsidence, so that small changes in SLR can have significant impacts on flooding, particularly over centennial scales. Compounding this, the Pacific Ocean and the Australasia region are also projected to receive greater than average sea-level rise where many atoll islands lie.
5. Coastal zones sensitive to inland processes. Where storms or cyclones are sensitive to warming that results in more extreme precipitation, changes to landslides, sediment availability or compound flooding from rivers may result. There is limited information on these interactions.

Several Sustainable Development Goals (e.g. SDGs 1, 2, 8, 9, 11, 12, 13 and 14) are affected by coastal flooding. Cross-cutting issues include: (i) salinisation and food security; (ii) disasters including resilience and adaptation; (iii) infrastructure; (iv) sand as a resource; (v) sustainable tourism; and, (vi) nature-based solutions. These issues are critical to address when adapting to the effects of sea-level rise.

In an overshoot, adaptation will be particularly important in polar regions due to newly exposed infrastructure, and in sensitive locations such as low-lying islands and deltas.

3. Inland flooding

Inland flooding arising from fluvial (river) sources is discussed in this section. Pluvial (surface water) and groundwater flooding are not examined.

Flood occurrence depends on the interaction between precipitation (usually rainfall) and the physical state and characteristics of the catchment, with mechanisms varying with rainfall intensity or duration. The main causes of flood occurrence are river discharge exceeding river channel capacity leading to inundation of adjacent land, with the dominant driver being high precipitation accumulations, over hours, days or months, in the upstream catchment. Catchment properties such as size, slope, degree of urbanisation, forest cover, channelisation, dams and antecedent conditions such as snow cover and soil moisture modulate the precipitation signal. The scale of a flood event and its impact can vary with its underlying causes (Merz *et al.*, 2021). Short duration (<6 hours), high precipitation events leading to “flash floods” are often more impactful in small or urban catchments. Floods in larger catchments may develop over several days or even weeks as ground becomes saturated. In high latitudes and mountainous regions, snow and glacial melt, rain on snow, and ice jamming can trigger flooding (Merz *et al.*, 2021, Zhang *et al.*, 2022).

The link between increasing global temperature and changes in flood occurrence or flood magnitudes is highly variable (Wasko *et al.*, 2019). The thermodynamic response indicates that for a 1 °C increase in temperature there is 6.6% increase in water vapour (thermodynamic effect), however in the earth system this is limited by the energy budget and further constrained by water availably over land. While older studies projected a pattern of wet regions becoming wetter and dry regions drier as the global temperature rises (Allen and Ingram, 2002, Trenberth, 2011), more recent studies have projected much more complex patterns over land (Byrne and O’Gorman, 2015, Xiong *et al.*, 2022). Relationships between annual maximum precipitation and increasing surface temperature have been found in 1-day annual maximum precipitation (Westra *et al.*, 2013). This does not occur uniformly, however, as atmospheric dynamics (Fowler *et al.*, 2021, Wasko, 2022) and oceanic circulations (Kundzewicz *et al.*, 2019) affect the movement of heat and moisture that can lead to flooding. Furthermore, extremes in precipitation do not necessarily translate into extremes of flooding.

The trends in flooding globally to some extent follow the large-scale trends in other aspects of water cycle changes, with regions receiving higher rainfall having increased soil moisture and an increased frequency of flooding, whereas drier regions have a reduced soil moisture

(Tabari, 2020, Slater *et al.*, 2021). This appears to be confirmed in global modelling studies (Blöschl *et al.*, 2019, Hirabayashi *et al.*, 2021b). The exception is in cold regions where the impacts are determined by how much a region warms above the threshold for rain or snowfall as well as changes in seasonal snow and ice melt (Blöschl *et al.*, 2019, Do *et al.*, 2020, Slater *et al.*, 2021). A global detection attribution study (Hirabayashi *et al.*, 2021b) determined that 14 of 22 flood events occurring between 2010 and 2013 were affected by anthropogenic climate change, with snow-induced floods accounting for eight of the cases. Of these, three exhibited enhanced flooding due to higher precipitation alone, whilst two of the catchments in North America that had suppressed flooding experienced earlier snow melt peaks reducing the impact of higher precipitation (Hirabayashi *et al.*, 2021a). A more recent detection attribution study (Alifu *et al.*, 2022) found that 20 of 52 flood events analysed had altered probabilities due to anthropogenic warming, with 14 of these in South America and Asia, indicating global warming impacts on floods is still largely uncertain in many parts of the world.

Global modelling studies (Hirabayashi *et al.*, 2013, Hirabayashi *et al.*, 2021b) suggest an increase in flood frequency across South Asia, Southeast Asia, Northeast Eurasia, Eastern and low-latitude Africa, and South America. They project decreases in Northern and Eastern Europe, Anatolia, Central Asia, Central North America, and Southern South America by 2100 under the SSP5-8.5 scenario relative to a 1971–2000 “historic” period. They further summarise the flood hazards for 3 specific warming levels across the 8 GCMS (Figure 2).

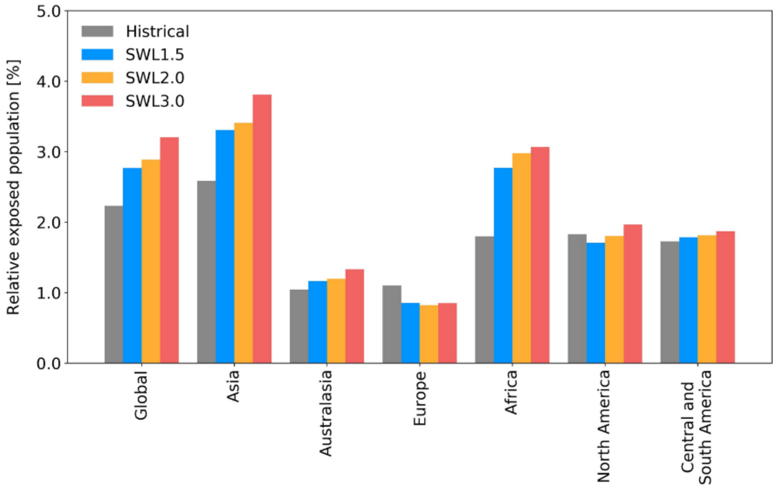


Figure 2. Potential flood exposure during the baseline period and projected future warming levels. The SSP5-8.5 scenario (SSP5 and RCP8.5) was applied to different regions. The percentage of the regional total population (fixed at the 2015 level) is shown for each region. Source: Hirabayashi *et al.*, (2021b), CC BY 4.0.

3.1 Overshoot and drivers of flooding

To date, there are no studies addressing the impact of an "overshoot" scenario on flooding.

The thermodynamically-driven increase in atmospheric moisture is a key driver of increasing precipitation intensities with global and regional warming (Westra *et al.*, 2013, Guerreiro *et al.*, 2018, Fowler *et al.*, 2021) particularly for short-duration rainfall events. This effect however is relatively short lived (1–2 weeks) (Trenberth, 2011) and the thermodynamic driven changes will adjust with global temperature and regional temperatures relatively quickly, having a direct impact on high intensity short duration rainfall events and on the wider intensification of the hydrologic cycle. The relationships between global temperature, oceanic circulations and atmospheric dynamics are not discussed in detail but it is noted that the impact of the overshoot is expected to have a longer lasting impact on the parts of the earth system with the largest lags (e.g. land ice and ocean systems). Studies linking ocean circulations to specific flood regimes globally are often highly uncertain, not least because the length of river flow records are often too short to capture multi-decadal oscillations, and the response is in any case mediated by the land surface. Nonetheless, a substantial number of studies have explored links between flooding and the El Nino-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Atlantic Multi-decadal Oscillation, and Pacific Decadal Oscillation (PDO) (Kundzewicz *et al.*, 2019). The longer lags associated with oceanic circulations, polar ice cover, and the position of the jet stream that influence the position and persistence of storm tracks might have longer-lived effects.

Land-based changes brought about by the VHO pathway will very likely enhance changes already being observed in water storage in land ice in response to increased regional temperatures, with a reduction in ice pack leading to a reduction in spring and summer flows compared with a NO pathway.

A temperature-mediated loss of forest cover associated with a VHO pathway and expansion of arid zones would lead to a reduction in the ability of the land to both intercept and infiltrate water. Assuming tipping points (e.g. Amazonian forest die back, Lenton *et al.* (2008)) are not crossed, the timescale of recovery of vegetation may be on the scale of decades. Any resulting change in land cover and loss of water holding capacity will most likely reduce the response time to rainfall and increase peak river flows.

3.2 Regional Impacts

Where possible, we have reviewed regional studies that analyse river flow records to extract information on flood trends and included regional modelling studies where they also consider drivers of flooding as well as projections.

3.2.1 Africa

Floods and causes of flooding across Africa are less well studied than other regions. The rain gauge density is smaller (Fowler *et al.*, 2021) and there are few publicly-available river flow datasets (Slater *et al.*, 2021). Catchment soil moisture is an important precondition for flooding, particularly in areas of higher aridity such as Western and Southern Africa (Tramblay *et al.*, 2022). No clear trend has been found in African flood events (Merz *et al.*, 2021, Alifu *et al.*, 2022), although trends are emerging of increasing storm intensities in West Africa (Taylor *et al.*, 2017) and higher rainfall accumulations during the East African short rains with a link to a positive Indian Ocean dipole (Palmer *et al.*, 2023).

3.2.2 Asia

India, South East Asia, maritime regions of China, Japan, and North Eastern Russia are projected to have increased flooding as the global temperature rises, whilst decreases are seen in the more arid regions in central Asia and Eastern Turkey (Hirabayashi *et al.*, 2013, Hirabayashi *et al.*, 2021a). There is no strong trend across the Tibetan plateau. The patterns are consistent with regional studies over India (Lutz *et al.*, 2019, Uhe *et al.*, 2019).

Glacial and snow melt of the high mountain areas around the Tibetan plateau feed many large river systems, with large losses (between 2000 and 2018) reported in glacial area and volume (Molden *et al.*, 2022). Glacial losses will continue as global and regional temperatures increase until they reach a "peak water", after which runoff will decrease (Molden *et al.*, 2022). The likelihood of reaching these thresholds increases with higher regional temperatures but the impact is likely to be relatively localised. The role of glacier loss on end-of-century flooding under an overshoot scenario is likely to be limited to upper catchments, where there is an increased chance of glacial lake burst events. The dominant driver of flooding across the wider Indus, Ganges and Brahmaputra plains will continue to be rainfall (Lutz *et al.*, 2019) associated with the Indian monsoon (see Section 4.8).

Our UK Earth System Model comparison of the VHO and NO pathways suggests a higher mean rainfall at the end of the 21st century (>20% annually) across Pakistan and Afghanistan, suggesting that extreme flood-inducing rainfall may persist up to 2100 and beyond. However, a greater number of simulations would be needed to identify statistically-significant trends.

3.2.3 Australasia

Australia encompasses strong hydro-climatic extremes from tropical to semi-arid and temperate maritime climates. An increase in the most extreme hourly rainfall has been observed in a comparison of hourly rain rates for 1966–1989 with 1990–2013 (Guerreiro *et al.*, 2018). However, analysis of floods (using a peak over threshold method) between 1975 and 2012 found a strong decreasing trend (magnitudes and frequency) across Southern Australia, in line with a declining trend in antecedent soil moisture, and this is expected to continue with increasing mean global temperatures (Gu *et al.*, 2020). While Guerreiro *et al.* (2018) found that ENSO had no significant impact on trends in hourly precipitation, Gu *et al.* (2020) did find significant lagged correlations between flood frequency in Eastern and Northern Australia with ENSO in a positive phase and is also consistent with other studies

(Ward *et al.*, 2014). Multi-model analyses (Gu *et al.*, 2020) show some model agreement in a reduction in flood magnitudes in Southern Australia by 2100 under RCP8.5.

As with other regions, flood risk trends overall are likely to begin to reverse by 2100. Any lagged impacts (e.g. via ENSO or a change in behaviour of ENSO to a positive phase in response to a VHO pathway) may influence flood occurrence and magnitudes.

3.2.4 Central and South America

Analysis of observed river flows is limited and coverage across the region is patchy. Slater *et al.* (2021) find a greater than 50% increase in flood magnitudes for 20-, 50- and 100-year return periods, though some catchments in the northern tropical zone exhibit a decrease. Analysis of flooding in CMIP6 models suggests an increase in flood frequency increase across Columbia and Southern Brazil with a decrease in Southern South America in CMIP6 models (Hirabayashi *et al.*, 2021a). Brêda *et al.* (2023) also conclude that for a small subset (7%) of catchments across South America, flood magnitudes for return periods <44 years will decrease in response to decreasing soil moisture, but rarer events will worsen, driven by higher rainfall accumulations.

3.2.5 North America

The global modelling study of CMIP6 models shows broad agreement across the RCPs of the direction of the trend in annual maximum discharge, which for central North America is predominantly an increase in the flood return period relative to the 100-year flood in 1971–2000 (Hirabayashi *et al.*, 2021a). There is an increase in flood magnitude across the Southeastern United States, and the Western coast. Cold regions show a less consistent signal.

In a VHO pathway, the region would likely experience a significant reduction in relatively frequent floods, which would likely follow deficits in soil moisture and might reduce the role of groundwater-induced floods for some time. As for other cold regions, snow and glacier melt may temporarily change the seasonality of flooding.

3.2.6 Europe

An analysis of flood trends across Europe for the period 1960–2010 (Blöschl *et al.*, 2019) found decreasing trends in medium-to-large catchments in Southern Europe due to decreasing winter precipitation and increasing evaporation, leading to drier soil moisture conditions. In Eastern Europe, warmer temperatures directly reducing winter snowfall resulted in reduced snowmelt. On the other hand, they found increasing autumn and winter floods in Northwestern Europe driven by higher precipitation and higher catchment soil moisture. A multimodal study (using multiple GCM and hydrologic models) examining specific warming levels found relatively small changes in flood magnitudes; decreases of -4.8% at 1.5 °C and -4.7% at 2 °C across the Mediterranean and increases of 2.4% at 1.5 °C and 2.9% at 2 °C for Atlantic regions relative to a 1971–2000 baseline (Thober *et al.*, 2018). Increases were also found across the alpine region, and decreases in northern and continental areas.

3.2.7 UK

Longer observational flow records in Northwestern UK follow a strongly cyclical pattern with flood-rich periods in winter months associated with positive phases of the North Atlantic Oscillation (Hannaford, 2015).

Studies using the UKCP18 regional projections (Murphy *et al.*, 2018) to drive a grid-based hydrological model suggest potential future increases in high flows by 2050–2080, although with large spatial variations and a large range of uncertainty between members of the RCM perturbed parameter ensemble, which are all based on the Hadley Centre GCM and the RCP 8.5 emissions scenario (Kay *et al.*, 2021, Lane and Kay, 2021). Arnell *et al.* (2021) used time-scaling with the UKCP18 global projections (Murphy *et al.*, 2018) to investigate changes in a variety of indicators of risk for a range of changes in global temperature. The results for flood magnitude and likelihood show a general increase in risk with temperature rise, although the changes vary between regions of the country, are often non-linear, and changes from the CMIP5-based GCM ensemble are generally greater than from the Hadley-Centre GCM ensemble (Arnell *et al.*, 2021, Fig. 6). Similarly, Rudd *et al.* (2023) combined the UKCP18 probabilistic projections with time-scaling and flood response surfaces to investigate changes in 50-year return period flood peaks across Great Britain for a range of changes in global temperature. The results generally showed an increase in flood peaks with the rise in global temperature, but with significant spatial variation; some southern regions showed flood peak changes accelerating with global temperature change. A recent analysis comparing hydrological impacts from the UKCP18 RCM and its nested convection-permitting model (CPM) suggests more consistent and larger increases in peak flows from the CPM than from the RCM (Kay, 2022).

3.3 Adaptation

In regions where flood hazard is expected to increase with an increase in global temperature, if an overshoot is likely then adaptation will still be required to control flood hazard and risk during the period of the overshoot, and for any possible time lag afterwards before the flood hazard can be expected to return to its previous level. However, if the increase in flood hazard is only expected to be temporary then the optimal adaptation options may differ substantially from those preferred under a sustained increase in hazard. For example, a flood defence scheme may be designed quite differently if it is only expected to be needed for a relatively short period of time rather than having to last many decades into the future. Encouraging and enabling increased household and business flood resilience may also be considered a good option to deal with relatively short-term expected increases in flood occurrence. Adaptation planning may be more difficult under an overshoot scenario though, as reliable information may be lacking on the length of time that the increase in flood hazard can be expected to last, thus adding extra uncertainty to the process.

In England, there is detailed guidance on how flood management authorities and flood risk assessments should allow for the future impacts of climate change (Environment Agency, 2020). While adapting such guidance to allow for overshoot scenarios may not be straightforward, the current guidance does suggest that, in some cases, an adaptive approach to managing flood risk may be a good option. An adaptive approach involves implementing planned actions in stages, when they are deemed necessary given the latest information available, and can avoid over-engineering assets by providing flexibility under the uncertainties of future climate change. Such flexibility will be more important under overshoot scenarios.

3.4 Conclusions

Modelling studies and analyses of observed trends and drivers of flooding, where available, suggest a divergent trend in floods even within countries. Overall flood magnitudes are likely to increase with global temperature increase across Northern South America, Central Africa, South and Southeast Asia, China, Japan, Eastern Australia and New Zealand, Northwestern Europe and Southeastern United States, primarily driven by an increase in precipitation. Areas experiencing a decreasing trend in flood magnitudes include Eastern Europe into Central Asia, Turkey, Southern South America and much of continental North America. There is some evidence that while moderate floods may reduce in magnitude, very rare events will increase in magnitude (e.g. in Brazil). The signal in cold regions is rather more mixed depending on how and when increased temperatures impact on snow fall, snow melt and glacial melt.

In an overshoot, the thermal-driven increase in atmospheric moisture availability will follow global temperature, though the magnitude will vary where regional temperature changes are different to the global temperature rise. But an increase in atmospheric moisture does not translate directly to increased flood risk as terrestrial precipitation changes are projected to be complex.

Any temporary increases in glacial melt due to overshoot could increase glacial lake outburst events, affecting smaller mountain catchments, but as temperatures fall back and/or glacier losses exceed a critical point, the flood risk will again reduce. There is a high degree of uncertainty as to how changes mediated via atmospheric and oceanic circulations will influence patterns of storm tracks and flooding regionally, but the impacts are potentially longer lasting. Similarly, there is high uncertainty as to where and for how long any resulting land cover changes may alter flood risk.

4. Impacts on water resources

There is high confidence that human influence has increased the chance of compound extreme events since the 1950s with more frequent and intense heatwaves, droughts and heavy precipitation (IPCC, 2023). However, attributing cause to historic trends in streamflow and groundwater storage is highly uncertain due to significant regional variations and multiple drivers of change. Total water storage trends (Figure 3) show significant regional variations over the last century, with rising, stable and falling trends seen in different parts of the world. There have been rising trends in parts of sub-Saharan Africa (SSA) and Northern USA, and falling trends in the Middle East, North Africa and SW USA (Bonsor *et al.*, 2018, Scanlon *et al.*, 2022, Scanlon *et al.*, 2023). Climate variability can account for some of the observed changes, but human intervention – particularly abstraction for irrigation – is also a major driver of change.

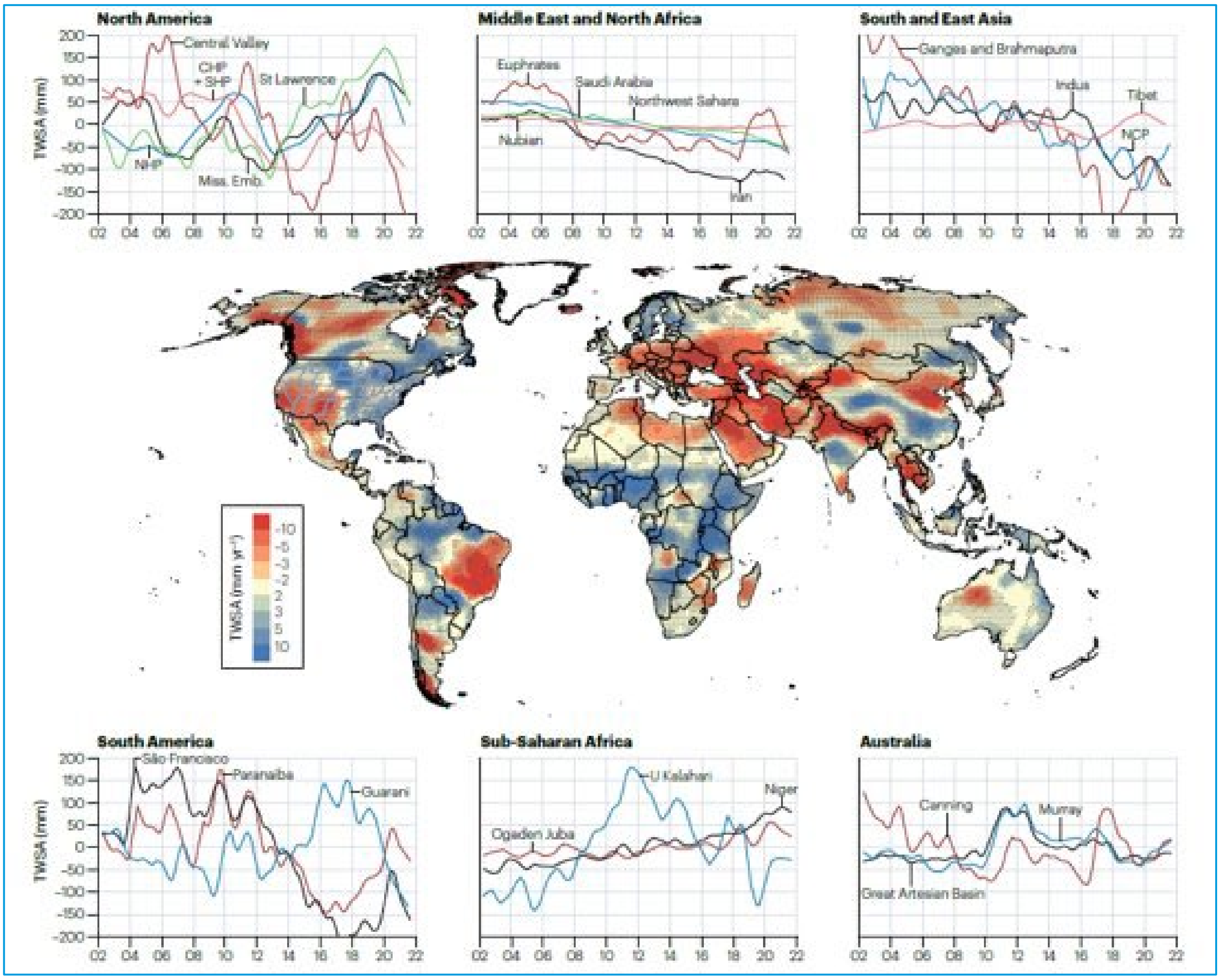


Figure 3. Terrestrial water storage changes from GRACE satellites during 2002–2022. Source: Scanlon *et al.* (2023). Note: Total water storage shows declining, stable and rising trends in total water storage over the past two decades in various regions globally. Climate variability causes some changes in water storage, but human intervention, particularly irrigation, is a major driver. Reproduced with permission from Springer Nature.

In this section, we examine the potential impacts of overshoot on water consumption. The impacts are largely driven by precipitation changes, so we start by reviewing potential global changes in precipitation. As much water is used for agriculture, we examine the implications for water and irrigation needs for two staple crops. We then qualitatively examine the potential implications of overshoot on clean water and sanitation, using case studies from Africa and Southern Asia. Water consumption for energy generation is examined in Section 7.5.

4.1 Overshoot and projections for 2 °C

With every increment of global warming, changes in extremes and the associated risks and impacts will escalate, becoming increasingly complex and difficult to manage (very high confidence – IPCC (2023)). They are higher for global warming of 1.5 °C than at present, and even higher at 2 °C (high confidence). Overshoot trajectories will therefore result in greater impacts during the period of overshoot compared to pathways that limit warming to 1.5 °C with no or limited overshoot. Changes to precipitation patterns during an overshoot are expected to diminish as the temperature is returned to 1.5 °C, as demonstrated in the UK Earth System modelling analysis in Annex 4 of this study. But increased long-term glacier mass loss caused by overshoot is expected to be irreversible on timescales of thousands to millions of years, with significant long-term implications for discharge in glacier-fed streams and watersheds that are fed by them (Ehlert and Zickfeld, 2018, IPCC, 2021a).

Changes in terrestrial precipitation resulting from a temperature rise to 1.5 °C and 2 °C are projected to vary between regions and to change within regions as temperature rises (Xiong *et al.*, 2022). Changes in global mean temperature and precipitation are expected to reverse following a reduction in CO_2 in an overshoot, but with a time-lag of years to decades, dependent on the degree and duration of overshoot (IPCC, 2021a). Our UK Earth System Model simulations of overshoot pathways, presented in Annex 4 of this study, did not examine enough scenarios to be able to identify statistically significant reversal of precipitation trends. There is evidence that, at a regional level, the lagged response of the hydrological cycle may be longer due to accumulated heat in the ocean, which may continue to intensify the hydrological cycle for decades to centuries after the atmospheric CO_2 concentration is reduced (Wu *et al.*, 2010).

Global warming of 1.5 °C with an initial overshoot to 2 °C is therefore likely to cause intensification of the global water cycle in line with a 2 °C scenario for at least several decades in the middle of the century. At the global scale, projected impacts on precipitation include increased variability and seasonality, increased monsoon precipitation, more frequent and intense heavy precipitation events, and more frequent compound heatwaves and droughts (IPCC, 2023). The portion of global land experiencing detectable changes in seasonal mean precipitation is projected to increase (medium confidence – IPCC (2023)). At the regional scale, both increases and decreases in mean precipitation are projected as outlined in Table 10.

Significant uncertainties remain over projections of evapotranspiration at the regional and seasonal scale, but there is medium confidence that evapotranspiration will increase over most land areas, except those that are moisture-limited (IPCC, 2021a).

Table 10. Regional projections for precipitation (IPCC, 2023).

Climate trend	Regional impacts
Increased mean annual precipitation	High latitudes, Equatorial Pacific Ocean, Mid-latitude wet regions, Monsoon regions, Tropical Oceans: North East Africa, Central Africa, Ethiopian Highlands Southern Arabian Peninsula, India, East, South and North Asia SE South America, N and E North America N Europe Polar regions
Wetter and longer wet seasons	S and E Asia, Central Sahel, East Africa
Decreased mean annual precipitation	Mid-latitude dry regions, Subtropical regions: Coastal West Africa, Northern Africa, Southern Africa Northern Arabian Peninsula

	SW South America, Amazonia, Central America, Caribbean SW Australia Mediterranean
Increased number of dry days	Subtropics Amazonia, Central America

Runoff and soil moisture are broadly expected to follow projected changes in regional precipitation. In snow-dominated regions, peak spring streamflow is expected to decrease and occur earlier in the year. Flows in glacier-fed streams are expected to increase in the near-term before declining due to glacier mass loss. The timing of the peak is dependent on the size of glacier and rate of loss (IPCC, 2021a).

Flooding is heavily dependent on non-climate-related factors, such as land-use and land-cover change, but is expected to increase at the global scale, with significant regional variations. Even under low-emissions scenarios, the duration and/or severity of droughts is expected to increase in those regions experiencing reduced precipitation. Future rates of aridification are expected to exceed those seen over the last millennium (IPCC, 2021a).

Land-use change, water management and abstraction will continue to impact the amount and variability of river discharge and groundwater storage at the global scale. There is medium confidence that increased precipitation intensity enhances groundwater recharge, most notably in the tropics, which is expected to continue under future warming (Cuthbert *et al.*, 2019). However, the potentially positive impacts of climate change on groundwater recharge will occur within the context of increasing demand and abstraction of water for irrigation and other consumptive uses, and growing threats to water quality. Without careful management, these pressures have the potential to deplete and degrade groundwater storage – as is already being observed in intensively irrigated dryland areas (Scanlon *et al.*, 2023).

4.2 Regional water stress impacts on agriculture

Climate change will affect both water resource availability and agricultural demand for water due to disruptions in the hydrological cycle and changes in weather conditions in agricultural areas. This section examines how changes in the supply and demand of water resources affect water-risk for future food production. It focuses on case studies of two staple crops, barley and wheat.

4.2.1 Methods

We calculate the water footprint (WF) of crops, representing the water demand by each agricultural crop in a given location over its growing season. The WF is influenced by location and timing of planting, crop type, and climatic conditions. However, the model does not account for the effects of extreme weather events or CO_2 fertilisation, which can also influence crop yield (see Section 5.1 on crop yield projection methods).

Our methods for calculating crop Water Footprint (WF) follow Tuninetti *et al.* (2015) and Bonetti *et al.* (2022). For each grid cell, daily crop evapotranspiration is estimated from the reference evapotranspiration using the crop-specific crop coefficient and the water stress coefficient with the approach from Allen *et al.* (1998). The reference evapotranspiration (i.e. potential evapotranspiration) is obtained from the ISIMIP database using the ORCHIDEE land surface model and HadGEM2-ES climate model under RCP6 (Gosling *et al.*, 2023). This potential evapotranspiration is based on climatic variables including temperature, air humidity and wind speed.

We compare two projections, corresponding to 1.5 °C and 2 °C of global warming, which are expected to occur in years 2032 and 2050, respectively, under this choice of RCP, land surface model and climate model (see the RCP 6.0 Table at (ISIMIP)). These correspond approximately to the peak difference between the VHO and NO pathways.

To calculate crop yield projections, the methodology follows that described under Section 5.1 under coherent choices of climate change scenarios. The modelling presented here does not include the additional effects of changes in population or diet that may affect water availability and the overall agricultural water demand.

4.2.2 Insights

Figure 4 and Figure 5 show the projected differences in water footprint between 2 °C and 1.5 °C pathways for wheat and barley, respectively. Only potential growing regions for each crop are shown. There is high spatial variability in how global climate change is expected to affect agricultural water requirements. Some regions are projected to experience decreases in wheat WF, but most are projected to see important increases in wheat WF, for example in Nepal, Mexico, and sub-Saharan Africa (e.g. Nigeria and Kenya). Similarly, for barley, numerous regions are projected to experience decreases in crop water needs but others have important increases, doubling or more in the USA, Iran and Yemen.

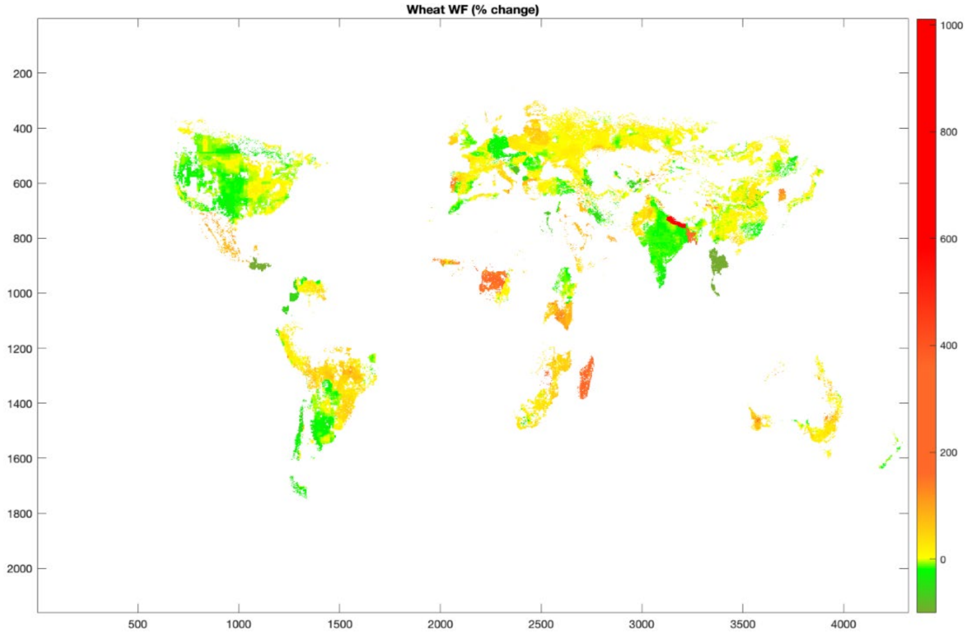


Figure 4. Relative difference in wheat water requirements (water footprint, WF) in a 2ºC scenario relative to a 1.5ºC scenario. Units are percentage difference (so 50 corresponds to a 50% increase).

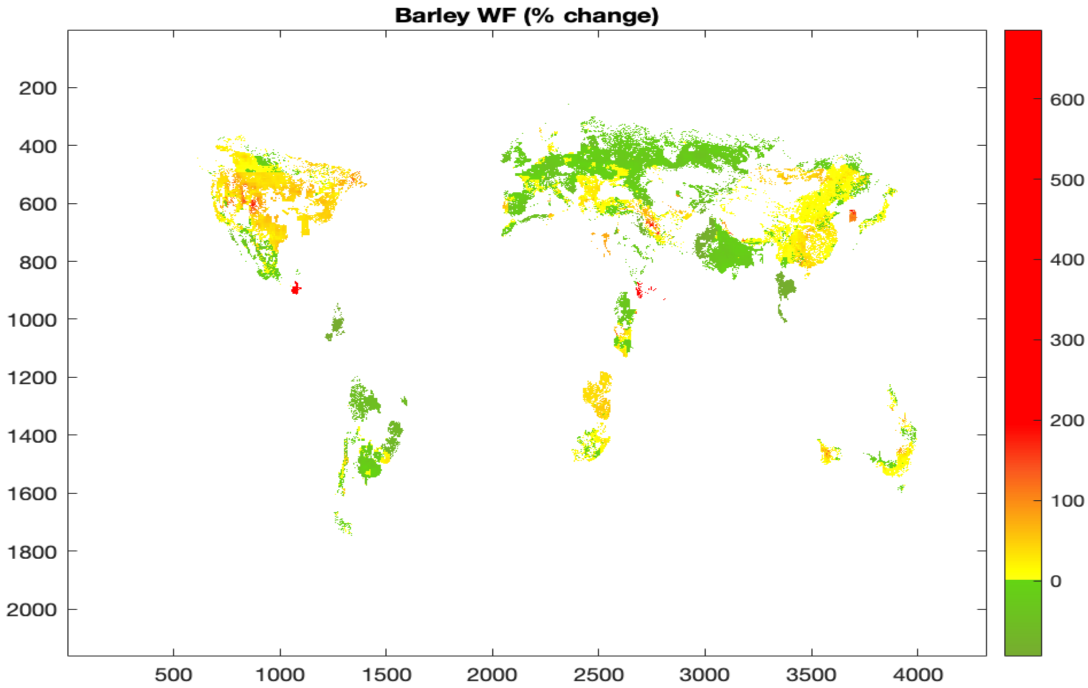


Figure 5. Relative difference in barley water requirements (water footprint, WF) in a 2 °C scenario relative to a 1.5 °C scenario. Units are percentage difference.

To understand how projected changes in precipitation at 2 °C might affect the demand for irrigation water in particular, relative to 1.5 °C, Figure 6 and Figure 7 show what is termed the "blue" part of the crop water footprint. This is the portion of the water footprint that exceeds the amount of water available to the crop from local precipitation. This blue WF thus represents the irrigation water need to cultivate the crop optimally (without water stress). For wheat, Figure 6 shows that some regions are projected to experience decreases in crop water needs (blue) due to climate change, while others see important increases (yellow to red), particularly in parts of central Asia and the USA, where groundwater would be depleted more quickly. Figure 7 similarly shows that crop water needs relative to precipitation would increase in more locations than they would decrease during an overshoot, particularly in East Asia and the USA.

Overall, changes in water requirements and agricultural water deficit vary substantially between regions. Both staple crops analysed here could require between two and six times more water under a 2 °C scenario in key growing regions such as Mexico and Kenya, for wheat, and the USA and China, for barley. Groundwater would deplete more quickly during an overshoot within these regions.

These projections focus on the expected changes in precipitation, temperature, and other meteorological variables affecting crop water demand. Other variables such as crop planting and harvesting calendars and the location of cultivation are assumed constant (with a baseline circa year 2000).

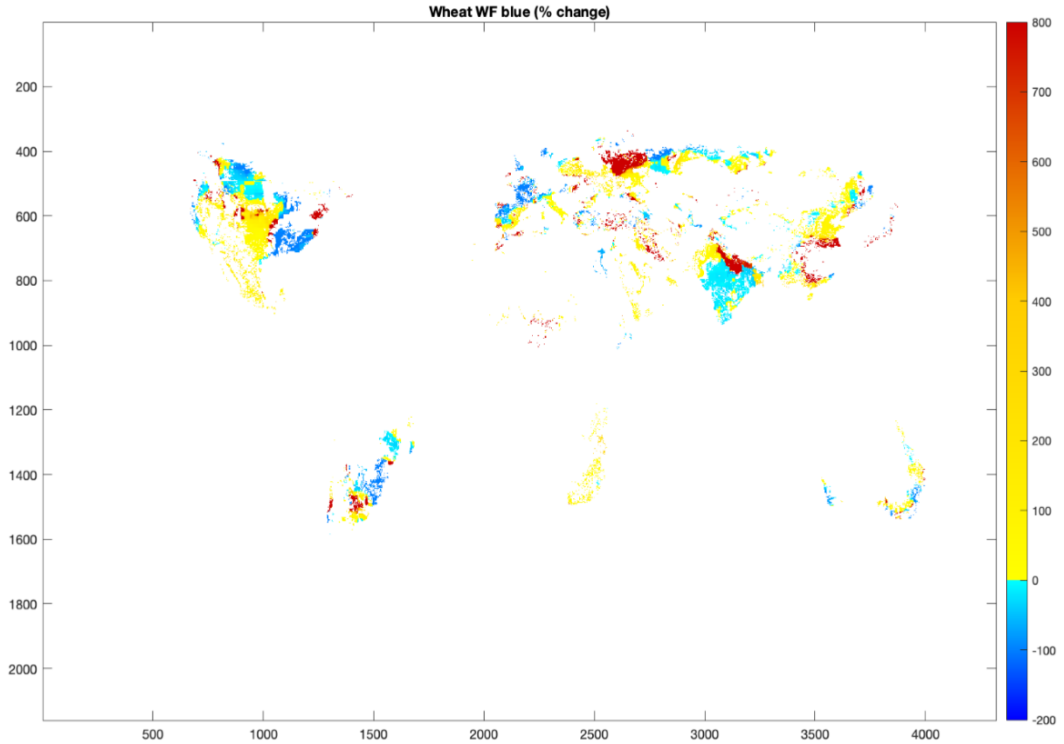


Figure 6. Relative difference in wheat irrigation water requirements (blue water footprint, WFb) in a 2 °C scenario relative to a 1.5 °C scenario. Units are percentage difference.

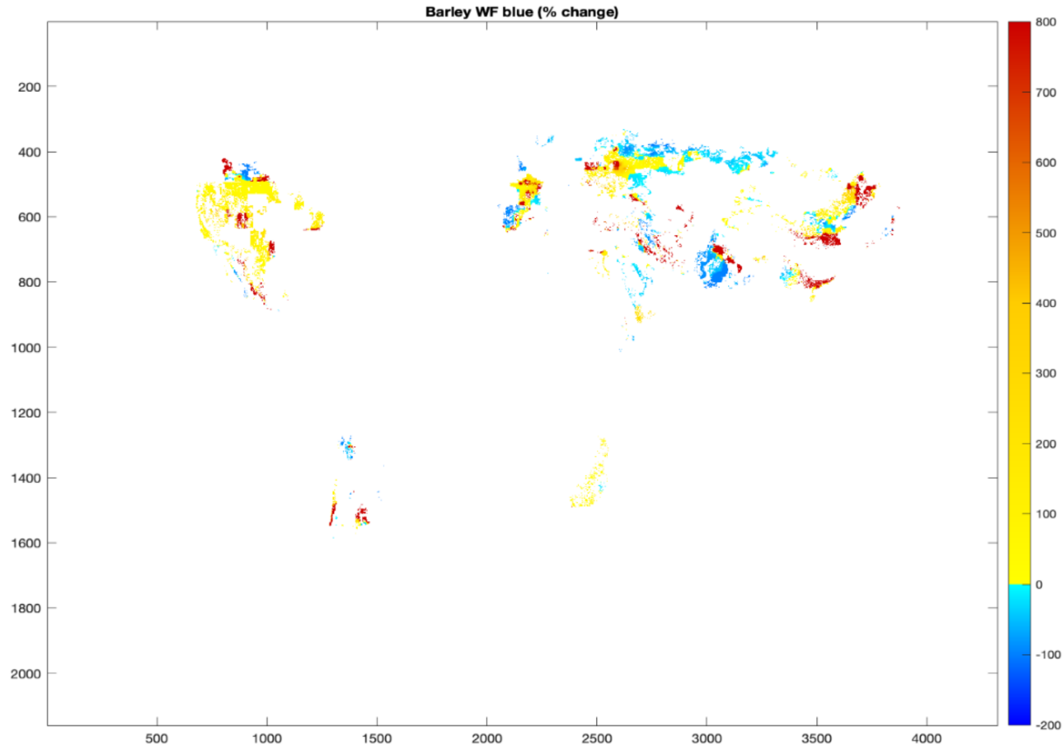


Figure 7. Relative difference in barley irrigation water requirements (blue water footprint, WFb) in a 2 °C scenario relative to a 1.5 °C scenario. Units are percentage difference.

4.3 Clean water and sanitation

SDG 6 on clean water and sanitation[4] sets ambitious targets for access to drinking water and sanitation (Targets 6.1 and 6.2, respectively) by 2030. In contrast to the preceding Millennium Development Goals (MDGs), these applied to all countries with a commitment to leave no one behind, with a strong focus on service levels: the quality, quantity and reliability of services that households, schools and health care facilities receive. SDG 6 also includes specific targets on the management of water resources, making explicit the link between service delivery and environmental stewardship.

[4] Specifically, 'Ensure access to water and sanitation for all'

For drinking water, a new 'safely managed' indicator (UN Water, 2021) emphasises the importance of continuous access to safe water on premises to support hygiene and handwashing, requiring higher volumes of water. For sanitation, the safely managed indicator goes beyond the hygienic separation of excreta from human contact to include the safe management of human waste along the sanitation chain, from containment and emptying to transport, treatment and reuse/disposal.

The WHO/UNICEF Joint Monitoring Programme (JMP) for Water Supply, Sanitation and Hygiene (WASH) is tasked with monitoring global progress against agreed targets. Latest data indicate that despite significant progress, the world is not on track to meet Targets 6.1 and 6.2, with major disparities in access to water and sanitation services linked to state fragility, wealth, gender and other markers of disadvantage (World Bank, 2018c, WHO and UNICEF, 2021). In 2020, eight out of ten people that lack even basic services lived in rural areas, with around half in low-income countries. People living in fragile contexts were twice as likely to lack safely managed services as those living in non-fragile contexts.

Achieving universal coverage by 2030 will require a quadrupling of current rates of progress in safely managed drinking water services, safely managed sanitation services and basic hygiene services. The challenge ahead lies in both extending access and improving service levels, particularly for poorer and more vulnerable populations that are most at risk of being left behind. Many inhabit areas where climate risk and poverty increasingly coincide (Howard *et al.*, 2016, Calow *et al.*, 2018, UNESCO, 2020).

The provision of water and sanitation, and associated behavioural change around hygiene practices, delivers wide-ranging benefits (Bartram and Cairncross, 2010). Most evidence focusses on public health, highlighting the consequences of unsafe water and poorly managed sanitation systems on disease, especially among young children (Howard *et al.*, 2016, UNESCO, 2020). The burden of disease from inadequate WASH has been estimated at various times over many years, and while most studies have focused on diarrhoeal disease, others have also assessed the WASH-attributable disease burden of other health outcomes, such as soil-transmitted helminth infections, malaria, trachoma, schistosomiasis, lymphatic filariasis, lower respiratory infections and protein energy malnutrition (see Prüss-Ustün *et al.* (2019) for a recent re-analysis).

4.3.1 Links between SDG 6 and other SDGs beyond health

Relationships between water and sanitation targets and other SDGs beyond health have also been highlighted (Figure 8), with access to clean water and safely managed sanitation supporting, for example, Zero Hunger (Goal 2), Quality Education (Goal 4), Gender Equality (Goal 5), Sustainable Cities and Communities (Goal 11) and Climate Action (Goal 13) (Calow *et al.*, 2018, UNESCO, 2020). Focussing on sanitation, Parikh *et al.* (2021) demonstrate the far-reaching benefits of sanitation investments across all 17 SDGs and 130 (77%) of the targets.

It follows that climate-related risks to water and sanitation systems and services can jeopardise not just public health outcomes, but a much broader set of development aspirations. Importantly, climate change also threatens to undermine progress to date; hard-won gains in extending services achieved in both MDG and SDG eras.

4.3.2 Water Resources – Direct and Indirect Impacts

Progress towards SDG 6 is dependent on a complex interplay of natural and human-based systems, many of which are already being impacted by climate change (Scanlon *et al.*, 2023). Global warming is causing changes across all dimensions of the water cycle with direct impacts on the availability and quality of water and consequently on water supply and sanitation systems. These impacts are projected to increase under all future emissions scenarios, with the direction and magnitude of change dependent on the degree of warming and the pathway taken to reach it (IPCC, 2021a). The impacts of climate change on water availability and quality occur within a context of land use change, urbanisation, population growth and increasing global demand for water (Boretti and Rosa, 2019), which in many regions are the major contributors to physical water scarcity.

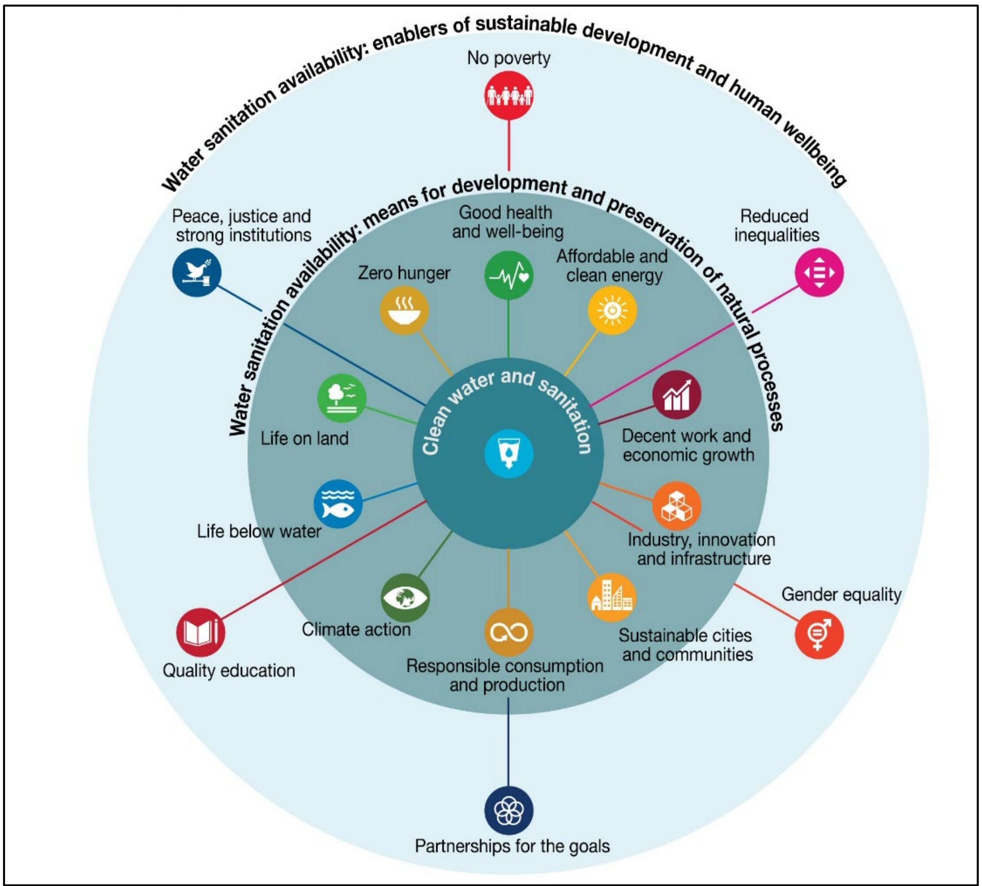


Figure 8. The relationship between SDG 6 and other SDGs. Source: UN-ESCAP (2017). Image by GRID-Arendal/Studio Atlantis.

4.4 Risks to WASH from climate change overshoot

The evidence linking climate variability and longer-term change with WASH outcomes is growing, although robust attribution remains tricky. This is because WASH programmes in many countries measure progress in terms of systems built: assumed access rather than outcomes over time (Calow *et al.*, 2018). It is also because the level, quality and reliability of services people receive depends on many different factors besides environmental conditions (UNESCO, 2020, Caretta *et al.*, 2022).

Nonetheless, we know that ‘Every increment of global warming will intensify multiple and concurrent hazards’ (high confidence – IPCC, 2023), and that climate change is already affecting the quality and reliability of services (Caretta *et al.*, 2022). The higher the magnitude and the longer the duration of any overshoot beyond 1.5 °C, the more societies are exposed to greater and more widespread impacts (IPCC, 2023).

Table 11 provides a summary of climate-related risks to WASH based on a simplified climate trend – impact framework. The approach is simplified because it isolates individual drivers of change and their impacts. In reality, risks can intersect and compound. For example, rising temperatures and intense precipitation events will exacerbate risks to health from waterborne disease, and more frequent and/or intense floods and droughts may be experienced at the same location at different times (Howard *et al.*, 2016, Calow *et al.*, 2018, Caretta *et al.*, 2022).

In the subsections below, we focus on two main impact pathways: (i) less water - aridity, drought and water scarcity; and, (ii) more water – wetter conditions, floods and sea level rise. The impacts of rising temperatures are considered in both pathways.

4.4.1 Aridity, drought and water scarcity

Aridity, drought and/or water scarcity will increase in some areas (Gutiérrez *et al.*, 2021), challenging those water supply and sanitation technologies unable to draw on safe storage (MacDonald *et al.*, 2019). Meeting 'safely managed' targets for drinking water will become more difficult under overshoot scenarios, especially where overall water demands are increasing and supplies become more variable, and of lower quality.

Longer-term (average) precipitation projections remain uncertain for many areas, although large areas of the Mediterranean, the Middle East and North Africa and Australia will likely become drier over the coming decades (Gutiérrez *et al.*, 2021). Drought risks are projected to increase over much larger areas, however, with a warmer climate intensifying both wet and dry weather (IPCC, 2021a, Caretta *et al.*, 2022).

Where long-term precipitation declines or, where drought risk increases, the safe and continuous supply of drinking water may be threatened. A number of studies highlight the importance of supply continuity in determining risks of diseases, with even short interruptions and reversion to unprotected sources increasing risks to health (Hunter *et al.*, 2009). Detailed water audits in rural Ethiopia demonstrate how poorer households, in particular, can struggle to meet minimum drinking water needs in a 'normal' dry season, even after cutting back on handwashing, livestock watering and cooking needs (Tucker *et al.*, 2014, MacAllister *et al.*, 2020) – see Case study 1 in Section 4.5.

Table 11. Climate hazards and vulnerabilities for WASH. Framework based on Calow *et al.* (2017), Calow *et al.* (2018). Sources for (1) and (2): IPCC (2021a, 2023); Caretta *et al.* (2022). Sources for (3): Howard *et al.* (2016); Calow *et al.* (2017), Calow *et al.* (2018); Caretta *et al.* (2022).

Climate trend	Hydrological impacts (amplified by overshoot)	Impacts on water supply, sanitation, and health (amplified by overshoot)
(1) Declining precipitation and/or increased drought. Long-term drying trend over parts of the subtropics and limited areas of the tropics, but average precipitation projections still uncertain for large areas. Intensification of wet & dry weather events; more frequent & intense droughts for many regions.	Average and/or periodic reductions in renewable surface and groundwater resources, though locally specific.	Threats to water supply, especially rainwater storage, ephemeral streams, shallow wells with less storage. Potentially less water for drinking, cooking, hygiene, and water-dependent sanitation. Reduced raw water quality because of less dilution – increasing exposure to waterborne contamination and/or higher treatment costs. Increased demand for surface water storage & groundwater to bridge surface water deficits; more vector breeding sites from surface storage. Growing competition between domestic and others uses, especially at the urban-rural interface.
(2) Increasing precipitation and/or more extreme precipitation events. Long-term wetting trend over high altitudes, equatorial Pacific, parts of monsoon regions, but average precipitation projections still uncertain for large areas. Intensification of wet & dry weather events; more frequent and intense precipitation events for most regions,	Average and/or periodic Increases in surface & groundwater resources. Flood and drought hazards – greater annual and multiannual variability in surface water flows.	Potentially more water available for domestic use, though short-term shortages due to more variability still likely. Rising groundwater levels and/or surface runoff may flood onsite sanitation and drainage - health risks from spread of faecal matter, contamination of soils, water resources and water sources. Floods cause damage to infrastructure, disruption of supply and treatment, reduction in raw water quality (sediment, nutrient, overflow contamination, pollution

even where average precipitation decreases.		loads). Floods may also overwhelm conventional sewerage and treatment. More frequent damage/destruction of household managed (onsite) sanitation may undermine demand for rebuilding & commitment to open defecation-free status.
(3) Higher temperatures Global increase, though rate of change and temp extremes vary by region. Increase in hot extremes, especially in urban areas (urban heat island effect).	Higher rates of evapotranspiration and soil moisture deficits affect water balance. Rise in temperature of rivers and lakes – reduced raw water quality. Higher overall demand for water. Rising sea levels (melting ice, expansion of sea water) now unavoidable for centuries to millennia for all future climates.	Threats to water availability – see drought above. Dry soil may increase risk of runoff and flooding after intense precipitation. Accelerated growth, persistence & transmission of waterborne pathogens. More algal blooms & increased risks from cyanotoxins and natural organic matter in water sources – threat to water quality & health even with conventional treatment. Higher ambient temperature increases demand for water. Intrusion of brackish or salty water into coastal aquifers – threats to groundwater quality with potential health impacts (high salt). Destruction/damage to WASH infrastructure in coastal areas from surges and inundation of sea water. Exacerbated by intensification of tropical cyclones and/or extratropical storms.

Reductions in precipitation and water availability, periodic or longer-term, pose a particular risk to more basic water supply systems unable to draw on significant storage (e.g. rooftop rainwater harvesting, springs, shallow dug wells) to bridge deficits. However, problems are not confined to low-income rural areas, as the experience of Cape Town, South Africa, demonstrates. Here, surface water sources almost dried up during the 2015–18 drought, forcing city planners to curb demand, invest in nature-based solutions (NbS) to augment catchment supply, and re-consider the role of groundwater storage as a buffer against drought and longer-term aridity - see Case Study 2 in Section 4.6.

Above 1.5 °C of global warming, limited freshwater resources pose potential hard adaptation limits for some small islands and regions dependent on glacier and snow melt (medium confidence – IPCC, 2023). Currently, around four billion people experience severe water scarcity for at least one month per year (Caretta *et al.*, 2022), although the scarcity experienced is typically economic (linked to access) rather than physical (constrained by availability). For example, a number of major river basin studies have concluded that while physical scarcity is likely to increase in some hot spot locations, aggravated by climate change, high levels of water extraction, and inefficient and inequitable use, remain the primary concern (e.g. Cook *et al.*, 2011, Grafton *et al.*, 2013, MacDonald *et al.*, 2016). In Southern Europe and the Middle East and North Africa (MENA), areas projected to face declining precipitation and greater aridity, there is more than enough water to meet basic needs. The key question in these areas is around the future of irrigated agriculture, by far the largest water-consumer, and the ability of institutions to manage scarce water for a range of competing interests (Zeitoun *et al.*, 2016, Calow *et al.*, 2018, Richardson, 2021).

Groundwater resources can provide resilient supplies even during severe drought. A series of groundwater-focused studies in SSA over the last decade (e.g. MacDonald *et al.*, 2019, MacAllister *et al.*, 2020) have demonstrated how even under drying conditions and severe drought, groundwater storage can support resilient drinking water supplies, with storage replenished from intense precipitation events (for example, in Case Study 1 in Section 4.5). A key conclusion is that most existing groundwater-based services are resilient, provided systems are built and maintained to reasonable standards.

Drying environments and periodic droughts pose less of a risk to sanitation, though much depends on whether water is part of the sanitation process. As a group of technologies, decentralised solutions such as septic tanks are generally considered resilient and, in drying environments, impacts may be positive for the attenuation of pathogens (notwithstanding caveats around greater flood risk, even where average precipitation declines). In contrast, declining water availability (and flooding) pose major risks to sewerage and septic systems relying on water to flush and dilute excreta (Howard *et al.*, 2016, Calow *et al.*, 2018). For example, sewerage systems may become more difficult to operate and maintain, particularly conventional sewerage with its higher water requirements. Treatment may also become more challenging if standards have to be raised to account for the lower absorptive and dilution capacity of receiving water bodies (Howard *et al.*, 2016, UNESCO, 2020).

4.4.2 Wetter conditions, heavy precipitation events

Wetter conditions in some areas, and more frequent and intense precipitation events more generally, will damage infrastructure, disrupt water and sanitation services and jeopardise water quality. Meeting 'safely managed' targets for drinking water and sanitation will become more difficult under overshoot scenarios, especially in fast-growing informal settlements where climate risk and poverty increasingly coincide.

On a global scale, average precipitation over land has increased since the 1950s, as has the frequency and intensity of heavy precipitation events (IPCC, 2021a, 2023). These trends are expected to continue, albeit with wide regional variation and uncertainties. However, while long-term (average) precipitation projections remain uncertain for many areas, climate models are consistent in projecting increases in the frequency and intensity of heavy precipitation (high confidence – IPCC (2021a, 2023)), increasing rain-generated local flooding (medium confidence – IPCC (2021a, 2023)). At a global scale, extreme daily precipitation events are projected to intensify by about 7% for each 1 °C of global warming (high confidence - IPCC, 2021), with a potential doubling of flood risk between 1.5 °C and 3 °C of warming.

Heavy precipitation events and local flooding pose direct physical threats to water and sanitation infrastructure and amplify the risk of water and ground water contamination and disease. Risks can be expected to increase further under overshoot scenarios, linked to the higher frequency and/or intensity of fluvial and pluvial events and rising sea levels. Populations with limited or no sanitation and safe water – still predominantly rural, low income – are most exposed to health risks because heavy rains can flood, damage or destroy latrines and spread faecal matter, including into unprotected/poorly protected water sources. In addition, where floods damage or destroy latrines, household demand for re-building may be compromised, undermining the commitment to open defecation-free status explicitly targeted in SDG Target 6.2 (Calow *et al.*, 2017, UNICEF and GWP, 2022).

Systematic reviews of the health evidence highlight strong links between flood events and outbreaks of water-related disease linked to poor/disrupted water and sanitation services, including cholera, hepatitis A and E, typhoid, polio and pathogenic E.coli (e.g. Alderman *et al.*, 2012). Increases in global ambient temperature have also been linked to increasing rates of diarrheal disease (Carlton *et al.*, 2016, Philipsborn *et al.*, 2016). Higher water temperatures can also encourage algal blooms and increase risks from cyanotoxins and natural organic matter in water sources, while higher runoff can increase contamination from fertilisers, animal wastes and particulates (Calow *et al.*, 2018).

Climate risk and poverty will increasingly coincide in urban areas, particularly in fast-growing informal settlements where poorer households occupy more exposed, flood-prone areas with limited and/or fragmented services (Hallegatte *et al.*, 2016, Hallegatte *et al.*, 2017, Dodman *et al.*, 2022). Urban flooding can then damage or overwhelm infrastructure, mix flood water and sewage over wide areas, and contaminate the environment and water supplies. Problems are exacerbated when floodwaters limit vehicular access to empty onsite systems (Howard *et al.*, 2016).

In Central and Southern Africa, over 60% of urban residents live in informal settlements exposed to multiple hazards; most rely on onsite sanitation with no access to systems of faecal sludge management (FSM) that include treatment of waste before final disposal (Doherty *et al.*, 2022, Richardson *et al.*, 2022). In Asia, over 500 million people live in climate-vulnerable informal settlements, with the number increasing rapidly (Shaw et al., 2022). In the city of Dhaka in Bangladesh, where monsoon floods are an annual occurrence, almost all faecal sludge ends up in drains or the wider environment, and outbreaks of cholera, typhoid and other diseases are common (Dasgupta *et al.*, 2015, Ross *et al.*, 2016) – see Case Study 3 in Section 4.7.

Most climate impact studies focus on centralised water supply and sanitation systems in high income countries (Hyde-Smith *et al.*, 2022). These also have multiple vulnerabilities linked to higher levels of global warming. For example, where precipitation increases or heavy precipitation events become more frequent, the separation of stormwater from sewage will become more difficult, with the potential to overwhelm collection and treatment systems. Increases in suspended solid loads in rivers may also mean that treatment systems require significant upgrading (Howard *et al.*, 2016). Wastewater treatment works are also vulnerable, since many are located in low-lying areas next to rivers. Risks can also cascade across and between networks, for example in interconnected (piped) systems where damage in one area affects water availability/quality in another, or where power outages affect water pumping and treatment (Dodman *et al.*, 2022).

Economic losses will be elevated where populations and physical assets are most concentrated and exposed. Disaggregated figures for water and sanitation infrastructure are not available, but overall flood damages are projected to increase by 4–5 times at 4 °C compared with 1.5 °C (medium confidence – Caretta *et al.* (2022)). Coastal areas exposed to a combination of sea level rise, river floods and storm surges may suffer the heaviest economic losses. Even if global temperatures recede by the end of the century, sea level rise is now unavoidable for centuries to millennia due to continuing deep ocean warming and ice sheet melt (high confidence – IPCC (2021a)). Sea level rise also threatens freshwater resources and drinking water sources because of the intrusion of brackish or salty water into groundwater resources – see Case Study 3 in Section 4.7.

A key challenge for many areas is to design WASH services for an uncertain future environment. For example, it is not clear whether rising temperatures will increase or reduce precipitation feeding two key rivers in South Asia (the Indus and the Ganges – see Case Study 4 in Section 4.8). This means new infrastructure would ideally be resilient to both scenarios, increasing the adaptation cost.

4.5 Case Study 1: Learning lessons from the 2015-16 El Niño drought in Ethiopia

Planning for climate change in Ethiopia, and the Horn of Africa more widely, is challenging. Although observational records highlight a drying trend over the last three decades, climate modelling points to wetter conditions, at least in the Ethiopian Highlands (IPCC, 2021a). What is clear, however, is that (i) average temperatures are increasing, and are already 1.0–1.5 °C above pre-industrial levels; (ii) annual and multiannual rainfall variability (naturally very high) is increasing; and, (iii) the frequency and intensity of extreme events (including droughts and floods) is also increasing, linked to the greater number of ENSO events in a warming climate (Cai *et al.*, 2021, IPCC, 2021a, Richardson *et al.*, 2022). These known trends will likely be amplified with every additional degree of global warming.

Predicting impacts on water-dependent services is complicated, particularly where high natural variability makes it difficult to isolate a climate change signal, and where many other factors influence service outcomes (Conway, 2013, Calow *et al.*, 2018) – see Figure 9). This has not stopped Ethiopia investing heavily in water and sanitation with some headline success. In 2015 the country met its MDG target for water supply – one of the few countries to do so in SSA – driven by a very rapid increase in rural areas (World Bank, 2018b). However, concerns about the sustainability of services came to the fore during the 2015–16 El Niño drought, with some development partners questioning the viability of conventional water supply programmes. The drought caused one of the worst humanitarian crises in East Africa for decades but impacts on rural water supply were mixed.

An analysis of performance data from over 5000 water points collected during the drought (MacAllister *et al.*, 2020) revealed that problems were mainly confined to those areas classified as 'unserved' (i.e. dependent on unprotected rivers, streams and ponds), those areas relying on hand-dug wells and springs, and those relying on deep motorised boreholes that broke down or ran out of fuel as demand increased. In these locations, daily water collection times could reach 12 hours, with volumes collected falling to 3–5 litres/capita/day (MacDonald *et al.*, 2019). In contrast, boreholes equipped with simple handpumps proved much more resilient – if they could be maintained.

A number of lessons can be drawn from Ethiopia's experience, with wider relevance for SSA. First, groundwater resources can provide resilient supplies even during severe drought because they store water between wet and dry cycles. Second, this 'buffering' function will grow in importance, particularly under 'overshoot' scenarios where rainfall variability and droughts intensify (MacAllister *et al.*, 2020, MacDonald *et al.*, 2021). Third, most existing groundwater technologies, with the exception of shallow hand dug wells and protected springs, can provide climate-resilient supply, provided systems are built and maintained to reasonable standards (Calow *et al.*, 2018, MacAllister *et al.*, 2020).

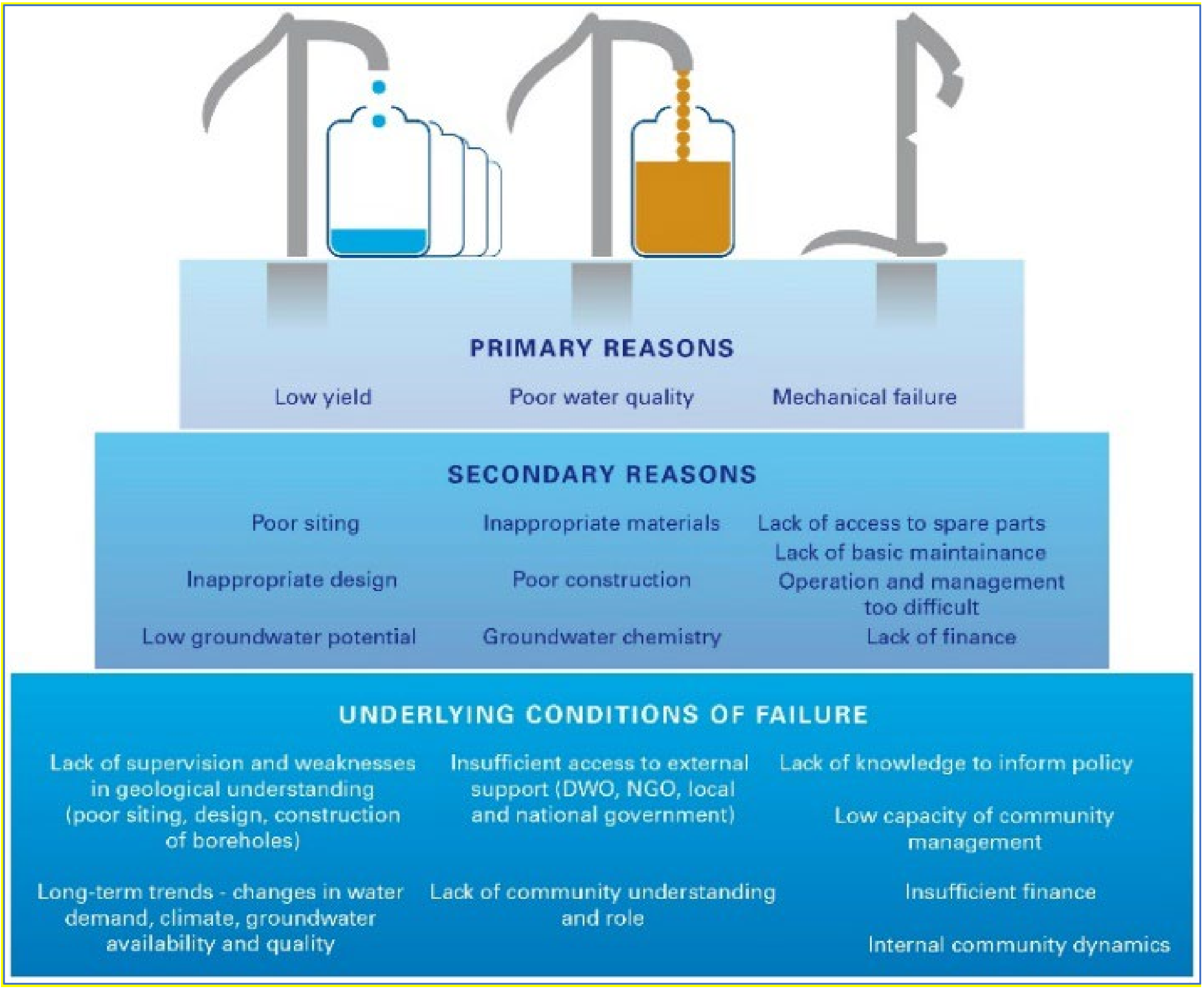


Figure 9. Unravelling the causes of water point failure. Figure from UKRI © BGS Bonsor et al. (2015).

4.6 Case Study 2: Cape Town's Day Zero: climate change, drought and nature-based solutions in South Africa

The city of Cape Town in South Africa is located in one of the few areas of SSA where there is reasonable confidence in average rainfall projections. By the 2050s, it is expected that the Southwestern part of Southern Africa will become drier, with more agreement across model projections for higher levels of global warming (Gutiérrez *et al.*, 2021). At a basin scale, reductions in river flow are projected in the Orange and Okavango (Hamududu and Killingtveit, 2012, Trisos *et al.*, 2022). In addition, average annual surface temperatures for Southern Africa as a whole have already risen by more than the global average – between 1 °C and 1.5 °C (1961 to 2015) – and this trend that is expected to continue (IPCC, 2021a).

Over the period 2015–18, Cape Town and its surrounding area experienced its worst drought since 1904. Climate change made drought five to six times more likely (Pascale *et al.*, 2020). The city's water supply (and peripheral irrigation demand) is dependent on streamflow from a relatively small area made up of several mountainous catchments, with water then stored in six downstream reservoirs. During the drought, dam levels dropped to less than 20% of their capacity, forcing the city authorities to plan for Day Zero – the day the taps would run dry. Stringent demand management was enforced to curb non-essential use. One consequence was a sharp fall in municipal revenue from water sales, compounded by a surge in off-grid (private) groundwater drilling by wealthier residents, straining the city's finances further (Simpson *et al.*, 2019).

Plans for increasing supply security have focused not just on hard infrastructure but also NbS to clear invasive trees in the upper catchments and restore native scrub vegetation that consumes less water (Opperman *et al.*, 2021, Holden *et al.*, 2022). In contrast to most NbS, detailed economic and scientific studies have been conducted to estimate how much water could be saved, and at what cost. Results indicate that an investment of roughly USD 25.5M can generate annual water gains of over 55 Mm^3/year within six years (equivalent to one-sixth of the city's current supply needs), increasing to 100 Mm^3/year within 30 years. Moreover, water gains are at least one-tenth the weighted unit cost of alternative supply options – Figure 10 (The Nature Conservatory, 2019).

A number of wider lessons can be drawn from Cape Town's experience. First, over-reliance on one source of water, and excluding groundwater storage from the mix, elevates supply risk. Second, fast-growing urban areas will increasingly compete for water with surrounding uses and users (often with prior rights), raising difficult questions about who gets what as cities grow. Third, water accounting studies offer a reminder that replacing native shrubland, savanna or grassland with forest will typically reduce streamflow. Tree-planting in 'new' areas for carbon capture, or under the assumption that water outcomes will be neutral or positive, may have unintended consequences.

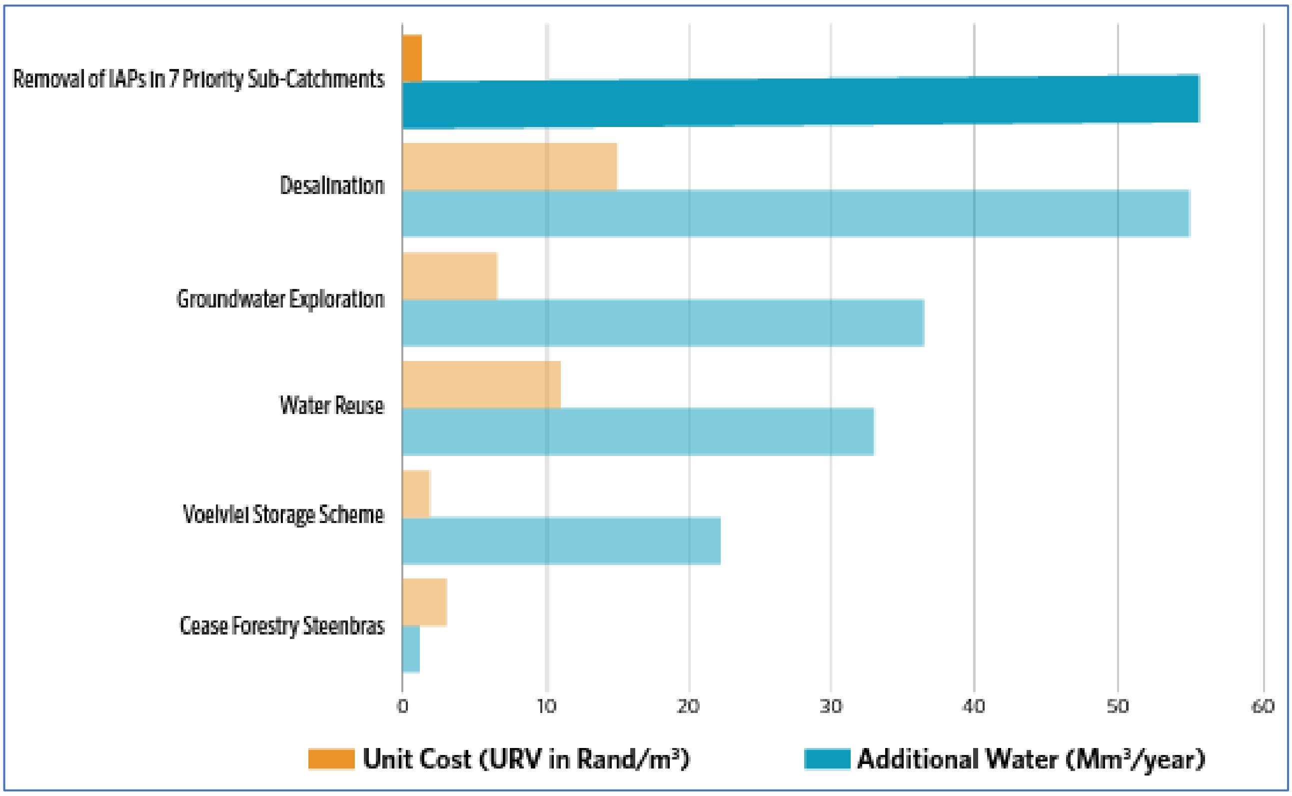


Figure 10. Comparison of water supply options for Cape Town, South Africa. Source: Conservatory (2019). Note: water supply gain and unit cost (URV) comparison between different catchment restoration and other supply options (costs include raw water treatment cost where applicable).

4.7 Case Study 3: Multiple risks to water and sanitation services in Bangladesh

Bangladesh is one of the most vulnerable countries in the world to climate-related hazards, including cyclones, droughts, floods and sea level rise. Although long-term rainfall projections remain uncertain, climate modelling is consistent in projecting more frequent and intense rainfall events and droughts, more intense tropical cyclones, rising sea levels and higher average temperatures (Lee *et al.*, 2018, Gutiérrez *et al.*, 2021, Shaw, 2022). Risks are amplified by high levels of poverty and the country's flat, flood-prone topography.

Bangladesh has made rapid progress in extending access to water and sanitation. Some 98% and 54% of the population have at least basic drinking water and sanitation services, respectively (WHO and UNICEF, 2021). However, the numbers benefiting from safely managed services are only 59% for drinking water and 39% for sanitation. A key issue is ground water contamination and disease in rural environments where basic pit latrines are poorly constructed with leakage of human waste into water sources. Emerging research in Bangladesh indicates that higher temperatures and rainfall are associated with higher prevalence of diarrhoea. Under likely climate change scenarios, waterborne diseases responsible for clinical illness are expected to increase (Grembi *et al.*, 2022, Nguyen *et al.*, 2022).

In low-lying coastal areas where poverty is most prevalent, the impacts of climate overshoot on WASH may extend well beyond a mid-century temperature peak. This is because sea level rise is now unavoidable for centuries to millennia (high confidence – IPCC (2021a)), increasing the risk of destructive storm surges and the ingress of saline water into freshwater sources. Impacts may be amplified in coastal Bangladesh by a decline in dry season river flows from the Himalayas (World Bank, 2018c).

In common with many other developing economies, large numbers of people are moving into urban areas, straining services. Dhaka, the capital, now has a population of around 22 million, up from just 336,000 in 1950 (World Bank, 2022). Roughly one-third of the population are classified as 'informal' residents, living in flood-prone areas where monsoon floods mix flood water, industrial waste and sewage over wide areas. Although most slum residents have access to improved drinking water (97%) and sanitation (86%) (Haque *et al.*, 2020), the reliability and quality of services are poor. Almost all (98%) faecal sludge ends up in drains, canals and the wider environment with no safe conveyance, treatment or disposal ((Dasgupta *et al.*, 2015, Ross *et al.*, 2016).

There are a number of wider lessons for overshoot pathways. First, more frequent and/or more intense rainfall events will create major risks to public health where drinking water and sanitation services remain rudimentary. Second, some of these risks are 'baked in' within exposed coasts because sea level rise will continue, whether or not temperatures decrease towards the end of the century, but higher sea levels from overshooting will have worse long-term impacts. Third, fast-growing cities struggling to meet demand for safely managed services face growing risks to public health, disproportionately affecting poorer households. With networked (piped) utility connections unavailable to most residents, a key priority is to strengthen, and regulate, business models for the safe collection, treatment and disposal (or reuse) of human waste.

4.8 Case Study 4: Risks to water resources of the Indus and Ganges

The Indus and Ganges river catchments are two of the most significant water resources in the world but are also amongst the most vulnerable to climate and human change (Immerzeel *et al.*, 2020). The two rivers depend on precipitation from the Indian Monsoon and Westerlies as well as glacier and snow melt (Yao *et al.*, 2022). Glacier melt forms a much more significant proportion of river flow for the Indus (estimated 40% of upper Indus flow) than for the Ganges (estimated 10% of upper Ganges flow) (Lutz *et al.*, 2014). Water demand in the two basins is extraordinarily high with irrigation dominating, and demand is expected to rise sharply in the coming decades (Immerzeel *et al.*, 2020).

Water is abstracted from the river basins through a combination of irrigation canals and groundwater abstraction. The Indus Basin Irrigation System is the largest contiguous irrigation system in the world (Yu *et al.*, 2013) and, combined with the Ganges, forms more than 100,000 km of canals. Groundwater abstraction from more than 10 million tube wells in the alluvial aquifers in the basins is estimated to be more than 200 km^3 per year, making it the most heavily exploited aquifer in the world (MacDonald *et al.*, 2016).

The Indus and Ganges river catchments are highly sensitive to climate change, given the dependence of flow on glacier and snow melt (Yao *et al.*, 2022), and the strong links between aquifer recharge and river / canal flow (MacAllister *et al.*, 2022). From 1980 to 2018, warming of the Asian Water Tower was twice the global average at 0.42 °C and total glacier mass reduced by an estimated 340 Gt (Yao *et al.*, 2022). Over the same period, annual precipitation decreased slightly for the Indus and Ganges but differences between the Westerlies and Indian monsoon give a complex spatial distribution. River flow has therefore increased significantly from 1980–2018 and is forecast to increase through the middle and possibly end of the 21st century as glaciers continue to melt possibly increasing by 20–50% by the end of the century (Yao *et al.*, 2022). Changes in seasonality of flow due to ice mass loss may be buffered by groundwater storage and baseflow to rivers (Andermann *et al.*, 2012). Groundwater storage is strongly linked to leakage from rivers and canals and abstraction (MacAllister *et al.*, 2022), and future changes in storage will depend on a complex interplay between recharge from the monsoon, canals and rivers, and increased abstraction.

Overshoot scenarios are forecast to accelerate the warming in the region, increasing the rate of glacier loss in most of Asia and intensifying the monsoon. However, the complex behaviour of the Westerlies on the western part of the Himalayas makes it difficult to confidently forecast precipitation in an overshoot scenario and therefore river flow in the upper Indus. The increased abstraction of groundwater storage from aquifers in the basins is likely to continue into the future, with resulting complex patterns of depletion and water quality degradation (Scanlon *et al.*, 2023).

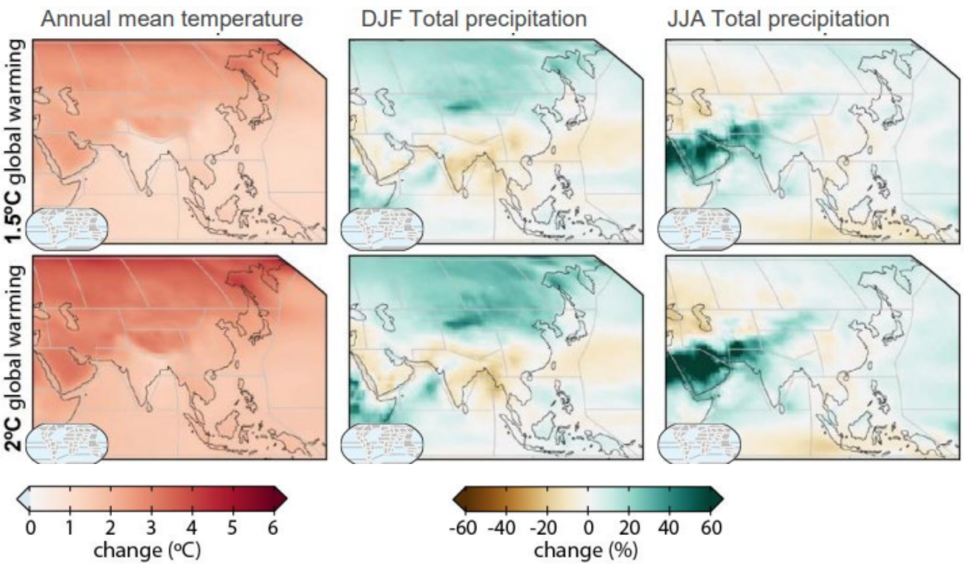


Figure 11. Forecast warming and precipitation for 1.5 and 2 degrees. From IPCC (2022d).

5. Food system impacts

Food systems will be affected by changes in temperature and precipitation on land and by changes in ocean temperature for fisheries. Changes in extreme weather could also have a substantial impact. This section considers the potential impacts of overshoot on crop yields and production in Sections 5.1 and 5.2. Fisheries are then examined in Section 5.3.

5.1 Impacts on crop yields

Two main approaches have been used to understand the potential impacts of climate change on crop yields.

A range of process models have been developed to estimate yields as a function of growing conditions, including weather and soil conditions, and some of these have been applied globally for a range of cereals to explore the potential impacts of weather changes caused by climate change (Carr *et al.*, 2020). While such models can theoretically examine non-linear impacts of severe climate change due to represented growth processes, in practice they do not represent the impacts of increasing severe weather or increasing pests and disease on crops.

Econometric analyses have been used to examine how changes in weather have affected crop yields in the past, and then used to project crop yields in the future as the climate warms. While such models might resolve changes in severe weather and examine yields over large areas and any adaptation to climate change, they cannot represent emergent behaviour as they do not consider individual growth processes.

A further challenge is that global warming of up to 2 °C has historically been considered to have a relatively small impact on crop yields, so most studies, and hence available datasets, have focused on higher levels of climate change. This means that datasets of global warming even for the VHO pathway are not available, and this limits analyses of overshoots on crops unless new initiatives produce such datasets.

5.1.1 Methodology

We use an econometric approach with two steps:

1. Estimating the coefficients related to the selected model for each crop using historical data (1986–2012). All the estimated coefficients are stated in Agnolucci *et al.* (2020).
2. Forecasting the crop yields based on the estimated coefficients from step 1 and weather scenarios (temperature and precipitation based on RCP2.6 and RCP6.0) for years between 2013 and 2100. Both have temperature trends closer to the VHO pathway than the NO pathway.

To account for country-based unobserved effects, following Agnolucci *et al.* (2020), we employ models that are estimated using either fixed effects, random effects or between effects, based on model selection methods. The general model includes a country-specific quadratic trend, an individual-specific time-invariant component, a common time-variant component, and a set of observed variables potentially affecting crop yield, denoted as X_{it}. The logarithm of crop yield, indicated as y_{it}, is modelled as a function of these components and random disturbances, ε_{it}, and is specified as follows:

$$y_{it} = \alpha_i + \lambda_t + \rho_{1i}t + \rho_{2i}t^2 + \beta X_{it} + \varepsilon_{it}$$

where:

$$\begin{aligned}\beta X_{it} = {} & \beta_1 Temp_{it} + \beta_2 Temp_{it}^2 + \beta_3 Temp_{it} \times Irr_i + \beta_4 Prec_{it} + \beta_5 Prec_{it}^2 + \beta_6 Prec_{it} \times Irr_i \\ & + \beta_7 Irr_i + \beta_8 Pest_{it} + \beta_9 Fert_{it}\end{aligned}$$

The explanatory variables used in the estimation (X_{it}) include temperature ($Temp_{it}$), precipitation ($Prec_{it}$), pesticides ($Pest_{it}$), fertilisers ($Fert_{it}$), and an indication of the level of irrigation which is utilised in the agricultural sector (Irr_i).

The methodology follows a general-to-specific approach in which models are estimated starting from the most general to the most specific one, in terms of the selection of explanatory variables and the statistical models being estimated for each crop. Table 12 presents the models and explanatory variables that are used for the selected crops.

Table 12. Variables used to model cereal yields based on a general-to-specific approach.

Crop	Model	Vars
Barley	Fixed effects (within effects) and controlling for country specific trend (ρ_1i t)	$Temp_{it}$, $Temp_{it}^2$, $Prec_{it}$
Rice	Between effects and controlling for time effects (λ_t)	$Temp_{it}$, $Temp_{it}^2$, $Prec_{it}$, $Prec_{it}^2$, $Pest_{it}$
Soybean	First difference fixed effects and controlling for time effects (λ_t)	$Temp_{it}$, $Temp_{it}^2$, $Prec_{it}$, $Fert_{it}$
Wheat	Between effects and controlling for time effects (λ_t)	X_{it}

In the second step, by using the estimated coefficients and weather scenarios (RCP2.6 and RCP6.0) inputs, we forecast the crops' yield for the years between 2013 and 2100. For instance, the forecasted yield of barley is calculated as follows:

$$\log \widetilde{Barley}_{it} = \hat{\alpha}_i + \hat{\rho}_{1i}t + \hat{\beta}_1 Temp_{it} + \hat{\beta}_2 Temp_{it}^2 + \hat{\beta}_4 Prec_{it}$$

where $\log \widetilde{Barley}_{it}$ is the forecasted barley yield (in logarithm term) for country i at time t and $\hat{\alpha}_i$, $\hat{\rho}_{1i}$, $\hat{\beta}_1$, $\hat{\beta}_2$, and $\hat{\beta}_4$are coefficients estimated in step 1. Values for the weather scenario ($Temp_{it}$ and $Prec_{it}$) are determined based on RCP2.6 and RCP6.0 scenarios.

Figure 13 shows that the temperature in the RCP2.6 scenario rises by up to 2 °C above at around 2050, after which it begins to decrease from 2060. In contrast, the RCP6.0 scenario initially starts with a temperature level below that of the RCP2.6 scenario, but it steadily increases and is projected to reach up to 3.9 degrees Celsius above pre-industrial times by 2100. For our pathways, RCP6.0 best represents the VHO pathway to 2040 and then RCP2.6 to 2060. Although we present the change in crop yield as a function of global mean temperature change for each scenario, we estimate the crop yield in each region using the changes in regional temperature and precipitation then sum the changes in yield globally.

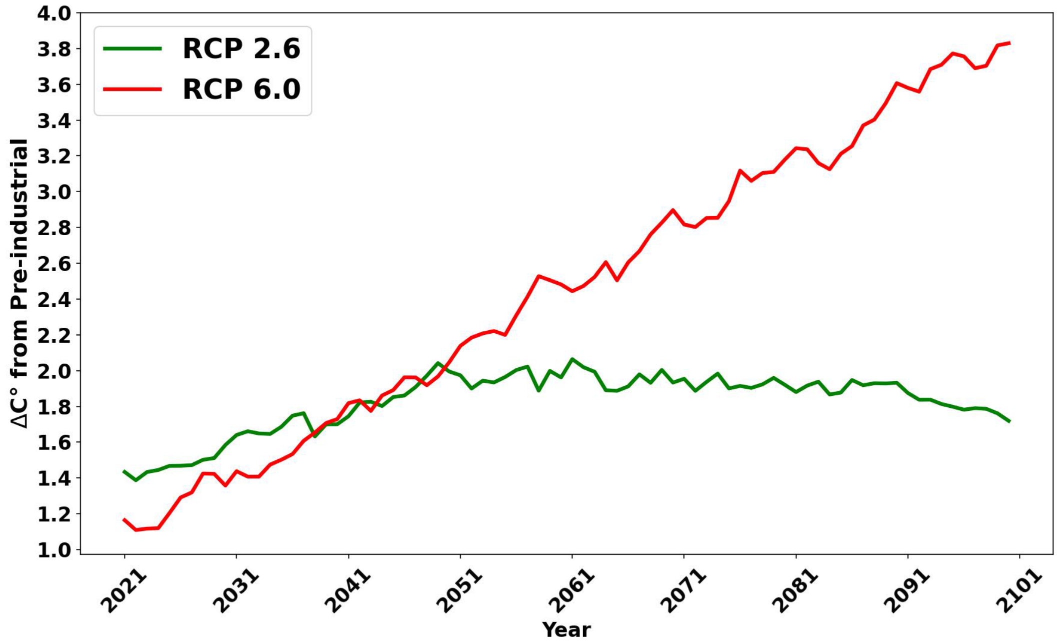


Figure 12. Global temperature rise in the RCP2.6 and RCP6.0 scenarios.

To calibrate the projections, we first calculate the difference between the fitted and observed values for the years between 2007 and 2012. Then, we compute the average value of these differences for each crop at the country level and add this average difference to the forecasted values. Furthermore, to consider the potential yield of the crops in each country, we set a plateau to reflect more realistic and feasible projections using the potential yield as a cap that is increased by 5% per decade.

5.1.2 Impact of local temperature changes on crop yields

We find that a local temperature rise of 1 °C above 22 °C causes a 2.8% decrease in rice yield. This finding aligns with numerous studies that have utilised panel regressions and county-level data to examine the relationship between temperature, precipitation and crop yields. These studies reveal an inverted U-shaped association between temperature and rice yield (Chen *et al.*, 2016, Zhang *et al.*, 2017a). Our findings also indicate that the rice yield tends to increase with rising temperatures up to 22 °C but thereafter decline, reflecting the inverted U-shaped relationship.

We find a nonlinear relationship between temperature and soybean yield with a threshold of 26 °C. This implies that soybean yield increases with temperature up to 26 °C, but thereafter, it decreases by 0.5% for every 1 °C increase in temperature. For comparison, Schlenker and Roberts (2009) identified a temperature threshold of 30 °C.

Wheat is primarily a temperate crop and a temperature increase of 1 °C above 15 °C (or 20 °C for countries with high irrigation rates) leads to a 1% yield reduction in our analysis. This finding is supported by existing literature, although the magnitude may vary since our analysis has used global data, whereas most studies have focused on individual countries. For example, Tack *et al.* (2015) conducted a study on wheat yields in the United States, analysing Kansas Performance Tests data from 1985 to 2013. They found that a one-degree day increase above 34 °C resulted in a 7.6% decline in wheat yields.

Moore and Lobell (2015) showed that long-term temperature and precipitation trends since 1989 led to a 3.8% decrease in barley yield in Europe. Along similar lines, we find that for every 1 °C increase above 18 °C causes a 0.5% decrease in the barley yield. We observed an inverted U-shaped relationship between temperature and barley yield, whereby the yield increases with temperature up to 18 °C but declines thereafter.

5.1.3 Projected impact of climate change on cereal yields

The right panel of Figure 14, which illustrates the yield-temperature relationship, indicates that higher global temperatures have a detrimental impact on wheat, soybean, and rice, leading to lower yields (comparing RCP6.0 to RCP2.6). Conversely, the crop yield of barley remains relatively unaffected by temperature variations. This discrepancy underscores the importance of understanding the unique responses of different crops to climate change, as it enables us to develop targeted adaptation strategies to mitigate potential losses.

Furthermore, the left panel of Figure 14 shows that the yield reduction observed in wheat, soybean, and rice is consistent throughout the RCP6.0 scenario. This indicates that the adverse effects of higher temperatures persist over the long term, jeopardising the future productivity of these crops. On the other hand, barley maintains a relatively stable yield.

To gain further insights into crop yield variation, we calculated the coefficient of variation (CV) for the first and last 15-year periods: 2021–2035 and 2086–2100. The CV values for each crop under both RCP2.6 and RCP6.0 scenarios are presented in Table 13. Soybean and wheat yields increase in interannual variability over the century, regardless of the climate scenario. Rice yield variability is almost the same for both periods and barley yield variability reduces. Hence agricultural productivity and production could become more variable for wheat and soybean. Increasing variability could lead to shortages in some years and require additional risk management to secure farmer livelihoods (Dodds, 2010).

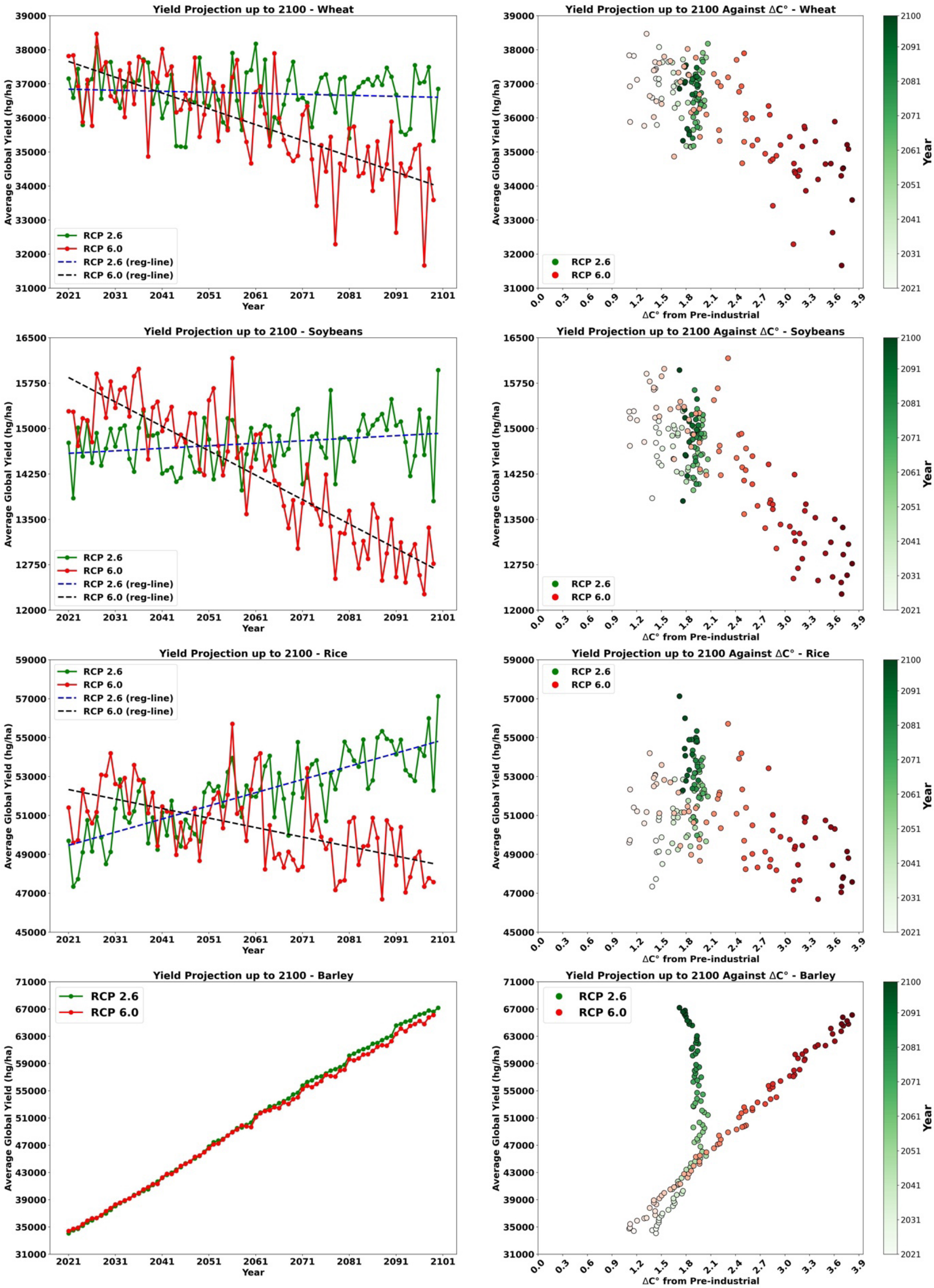

Yield Projection up to 2100 - Wheat
Average Global Yield (hg/ha)
Year
RCP 2.6
RCP 6.0
RCP 2.6 (reg-line)
RCP 6.0 (reg-line)
Yield Projection up to 2100 Against ΔC° - Wheat
ΔC° from Pre-industrial
Yield Projection up to 2100 - Soybeans
Yield Projection up to 2100 Against ΔC° - Soybeans
Yield Projection up to 2100 - Rice
Yield Projection up to 2100 Against ΔC° - Rice
Yield Projection up to 2100 - Barley
Yield Projection up to 2100 Against ΔC° - Barley

Figure 13. Crop yield projections for wheat, soybean, rice, and barley to 2100 (previous page). In all graphs, the RCP2.6 is green and RCP6.0 is red. In the four panels on the right, lighter markers represent years closer to 2021, while darker ones correspond to the years closer to 2100. The graphs in the left panel depict the weighted average projected crop yield for the globe up to 2100 under two weather scenarios. On the other hand, the right panel demonstrates the projected values against the difference in temperature compared to the pre-industrial period based on the same weather scenarios (RCP2.6 and RCP6.0).

Table 13. Coefficient of variation for crop yields in three distinct periods

	Rice	Soybean	Wheat	Barley
CV (2021-2035) – RCP2.6	3.45%	2.41%	1.35%	5.56%
CV (2086-2100) – RCP2.6	3.12%	4.19%	2.05%	2.90%
CV (2021-2035) – RCP6.0	3.26%	2.64%	1.75%	5.37%
CV (2086-2100) – RCP6.0	3.36%	4.03%	2.72%	2.82%

5.1.4 Summary

By examining the relationship between temperature and precipitation patterns and their effects on crop productivity, we can assess the vulnerability of wheat, soybean, rice, and barley to climate change.

Our crop yield projections indicate that under the RCP2.6 scenario, which represents a moderate increase in temperature, there is no significant reduction in crop yield across all four crops. This suggests that the projected temperature changes associated with this scenario do not pose an immediate threat to agricultural productivity. However, when comparing this scenario to the RCP6.0 scenario, characterised by higher temperature increases, we observe a clear negative relationship between temperature and crop yield for rice, soybean and wheat.

The overall findings of this study are consistent with the current state of the literature. Fisher *et al.* (2012) have demonstrated that climate change significantly decreases agricultural outputs, specifically affecting corn and soybean yields in the United States. Chen and Gong (2021) have shown that high temperatures induce a reduction in crop yields in China. Comparable studies conducted in other developing countries consistently reveal the adverse impacts of climate change on agriculture (Levine and Yang, 2006, Guiteras, 2009, Schlenker and Roberts, 2009, Feng *et al.*, 2010a, Colmer, 2021).

5.2 Impacts of overshoot on land food systems

Over the last 50 years, climate change has slowed growth of agricultural productivity in mid and low latitudes. In the future, climate change will make some current food production areas unsuitable for farming (IPCC, 2022a). Despite climate change increasing yields in temperate regions and the boreal north, the overall global impact has been estimated as a 1% reduction in global crop yields per decade (Porter, 2014). Differences in projected impacts vary by crop, region, timeframe and RCP, depending on the current temperature level and degree of warming.

In this section, we assess the economy-wide impacts of climate change on food production, consumption and trade behind the VHO and NO pathways using the ENGAGE computable general equilibrium (CGE) model.

5.2.1 Overview of the ENGAGE model

The UCL Environmental Global Applied General Equilibrium (ENGAGE) model is a multi-sector, multi-region, recursive dynamic CGE model for the analysis of energy, environmental, resource and economic policies (Winning *et al.*, 2017, Calzadilla and Carr, 2020, Nechifor *et al.*, 2020). ENGAGE estimates the macro-economic impacts across sectors and across countries, accounting for the economic characteristics of each country and adjustment processes[5] in domestic and international markets.

ENGAGE is based upon standard general equilibrium assumptions such a market clearance, zero profits, and utility maximisation/cost minimisation of representative agents. All industries are modelled through a representative firm, which maximizes its profits in perfectly competitive markets. The production functions of each economic sector to create a level of sectoral output are specified using a series of nested constant elasticity of substitution (CES) functions. Domestic and foreign inputs are not perfect substitutes and therefore are modelled using the “Armington assumption”, which accounts for product

[5] Adjustments processes refer to adjustments in the equilibrium conditions of internal and external markets (for goods/services and factors of production) to satisfy utility and profit maximisation.

heterogeneity between different world regions. A representative consumer in each region receives household income, defined as the service value of national primary factors. The national income is allocated between aggregate household consumption, public consumption and savings.

The version of the ENGAGE model used here is based on the GTAP9-Power database (Peters, 2016) and represents the global economy in 2011. ENGAGE represents the agriculture, energy, industry and service sectors of the economy in detail. ENGAGE models 27 economic activities, including explicit cultivation of several crops, in 16 regions with 4 factors of production (Table 14).

Table 14. Regions, sectors and factors of production in ENGAGE.

16 Regions		**27 Sectors**	
AFR	Africa	**PDR**	Paddy rice
AUS	Australia	**WHT**	Wheat
CAN	Canada	**GRO**	Cereal grains
CSA	Central and South America	**OCR**	Other crops
CHI	China	**A_F**	Agriculture and food
EEU	Eastern Europe	**MIN**	Minerals
FSU	Former Soviet Union	**PPP**	Paper
IND	India	**CRP**	Chemical
JAP	Japan	**NMM**	Non-metallic minerals
MEA	Middle East	**I_S**	Iron and steel
MEX	Mexico	**MPR**	Metal products
ODA	Other Developing Asia	**IND**	Other industry
SKO	South Korea	**COA**	Coal
UK	United Kingdom	**OIL**	Crude oil
USA	USA	**GAS**	Gas
WEU	Western Europe	**P_C**	Petroleum & Coke
		NUP	Nuclear power
		CFP	Coal-fired power
		GFP	Gas-fired power

		WIP	Wind power
		HYP	Hydroelectric power
		OFP	Oil-fired power
4 Factors of production		**OTP**	Other power
LND	Land	**SOP**	Solar power
LAB	Labour	**TnD**	Transmission and distribution
CAP	Capital	**SER**	Services
RES	Natural resources	**TRN**	Transport

5.2.2 Modelling approach

Estimates of crop yield changes behind the temperature increase under the VHO and NO pathways are based on the World Bank Policy Research Working Paper "Estimation of climate change damage functions for 140 regions in the GTAP9 database" (Roson and Sartori, 2016). Crop yield changes for maize, wheat and rice are estimated based on a meta-analysis provided in the Fifth IPCC Assessment Report (IPCC, 2014a), considering central values of the percentage simulated yield change (without adaptation) as a function of local temperature change and associating the type of region (temperate or tropical) to its latitude (Roson and Sartori, 2010). The productivity change for the whole agricultural sector is estimated based on reduced forms of agricultural response functions where the variation in output per hectare is expressed as a function of temperature, precipitation P and CO_2 concentration (Mendelsohn and Schlesinger, 1999).

Wheat and rice yield changes are used directly in ENGAGE, whereas maize yield changes are used as a proxy for the aggregated sector cereals. The aggregated cereals sector includes maize, sorghum, barley, rye, oats, millets and other cereals, but maize production in tonnes represents more than 80% of the total so this assumption is appropriate. Productivity changes for the whole agricultural sector are used as a proxy for the aggregated 'other crops' sector, as this sector includes vegetables, fruits, oil seeds, sugar crops, fibre crops and other crops not classified elsewhere.

The modelling of the VHO and NO pathways in ENGAGE are described in detail in Section 4 of Annex 3 of this study. Here, we assess the impacts of crop yield changes behind the expected temperature increase in both pathways as a shock in the crop's land productivity. All other assumptions remain unchanged.

5.2.3 Limitations of the modelling approach

Crop yield changes used in this analysis are based on econometric estimations of damage functions that used a similar approach to Section 5.1. This database was selected as it gives regional impacts at specific warming levels. ENGAGE uses only one source of crop yield changes to estimate the economic impacts so results are influenced by this choice. The uncertainty in crop yield changes could be investigated by examining results with alternative crop yield databases.

ENGAGE damage functions use local temperature changes to estimate crop yield changes. This implies that all regions experience the same warming level, which is not the case. Since land warms faster than oceans, the global temperature change is expected to be lower than local land temperature changes.

As most global economic models, the ENGAGE model includes very aggregated sectors and regions. This is a limitation of the model that averages out local effects.

5.2.4 Insights

Climate change is expected to not only reduce yields of staple crops such as rice, wheat, and maize, but also to disproportionately affect crop yields in different regions, with Canada being the only exception where an increase in maize yields is anticipated (Figure 15). The decline in wheat yields is more pronounced compared to other staple crops. The impact of a 1.5 °C or 1.77 °C warming on crop yields is almost negligible for rice. However, a higher temperature in the VHO pathway reduces cereal yields to a greater extent than in the NO pathway. The situation is similar for wheat in most regions. However, wheat yields are expected to improve with higher temperature in regions with a temperate climate and the boreal north, such as Canada, Eastern Europe, the former Soviet Union, and the UK.

The impacts of climate change on "other crops" shows even larger regional variations compared to staple crops (Figure 15). Moreover, global warming is expected to have positive effects in temperate regions and the boreal north. In fact, regions previously limited by cooler temperatures such as Canada, Eastern Europe, the former Soviet Union, the UK, and the USA, may benefit from warmer conditions, leading to longer growing seasons and potentially higher yields. However, it's important to note that these effects can vary widely depending on the specific crop and local conditions. Furthermore, the impact of climate change on individual crop types inside 'other crops' is under researched and uncertain (IPCC, 2022a).

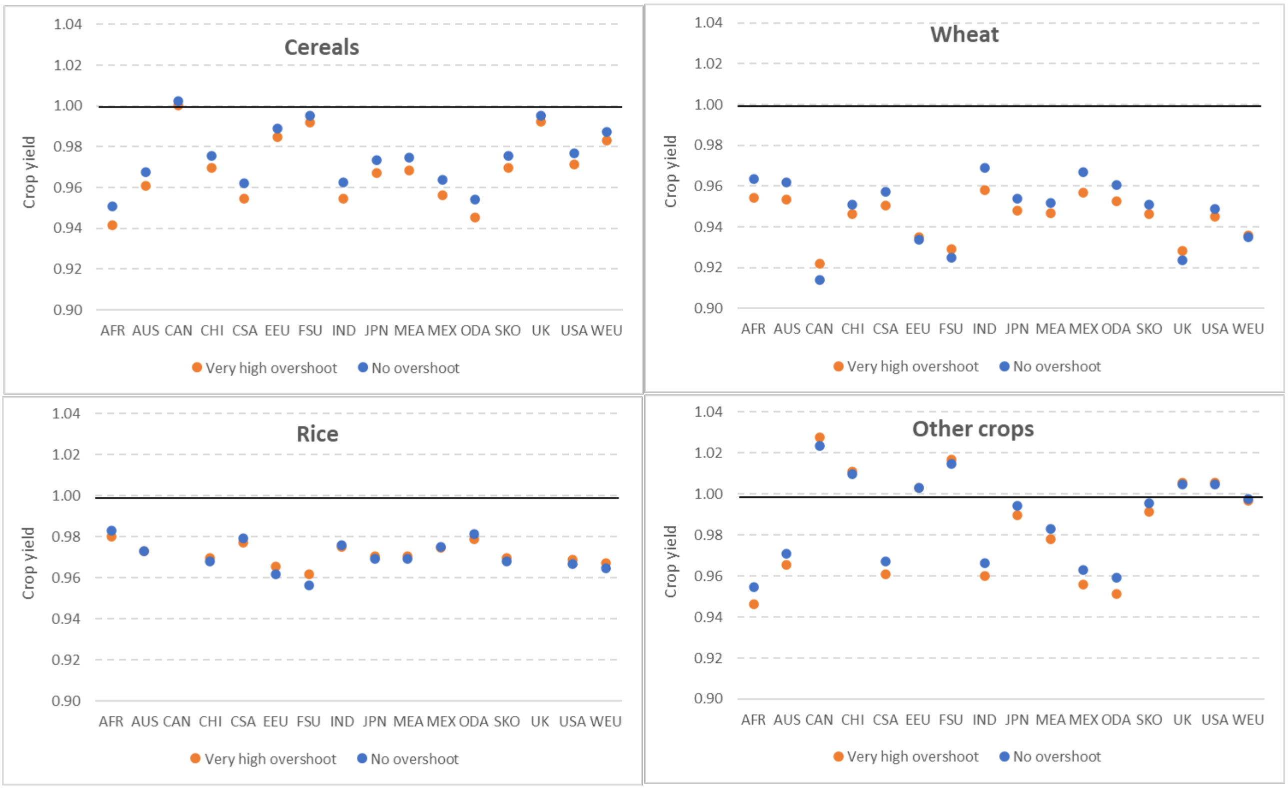


Figure 14. Relative change in regional crop yields in 2050 due to overshoot. Assumed warming levels in 2050 are 1.5 °C for the NO pathway and 1.77 °C for the VHO pathway. A counterfactual reference scenario with no climate change = 1. The regions are defined in Table 14.

The 'other crop' sector, which includes vegetables, fruits, oil seeds, sugar crops, and fibre crops (as well as other crops not classified elsewhere), represents a significant portion of total crop production—between 62% and 82% in 2020 (FAO, 2023). Therefore, this sector plays a crucial role in determining the overall impact on the agricultural sector. A higher temperature in the VHO pathway compared to the NO pathway implies that several regions may experience positive impacts in 'other crops' yields. Therefore, the overall effect on global GDP is positive and it grows with higher temperatures (Figure 16). However, the impact on global welfare, which we define as the change in real income, shows a declining trend in line with the rise in temperature. In fact, the overall effect on producers and consumers' income is negative. As the difference in temperature between both pathways is small (0.27 °C in 2050), the impact on GDP and welfare is expected to be marginal (0.13% and -0.38% with respect to 2020, respectively).

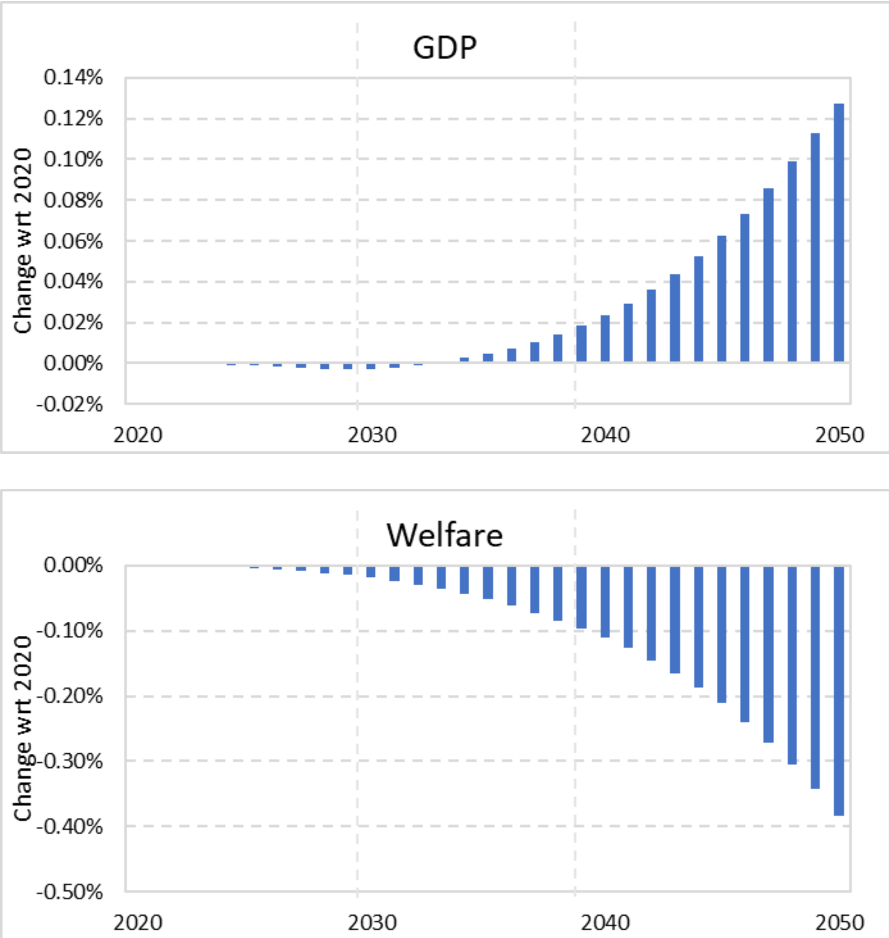


Figure 15. Change in global GDP and welfare due to overshoot that is calculated by the ENGAGE model. The VHO – NO pathways are shown with the change relative to the year 2020.

The global average masks regional effects. GDP declines are observed in China, India, and Other Developing Asia (Figure 17). While some of these regions, such as India and Other Developing Asia, experience a large additional decline in yields in VHO pathway compared to the NO pathway, other countries like China show positive yield impacts in the 'other crops' sector. This suggests that the overall regional economic outcome depends not only on the direct effect of climate change on crop yields but also on the indirect effect that climate change has on comparative advantages in food production.

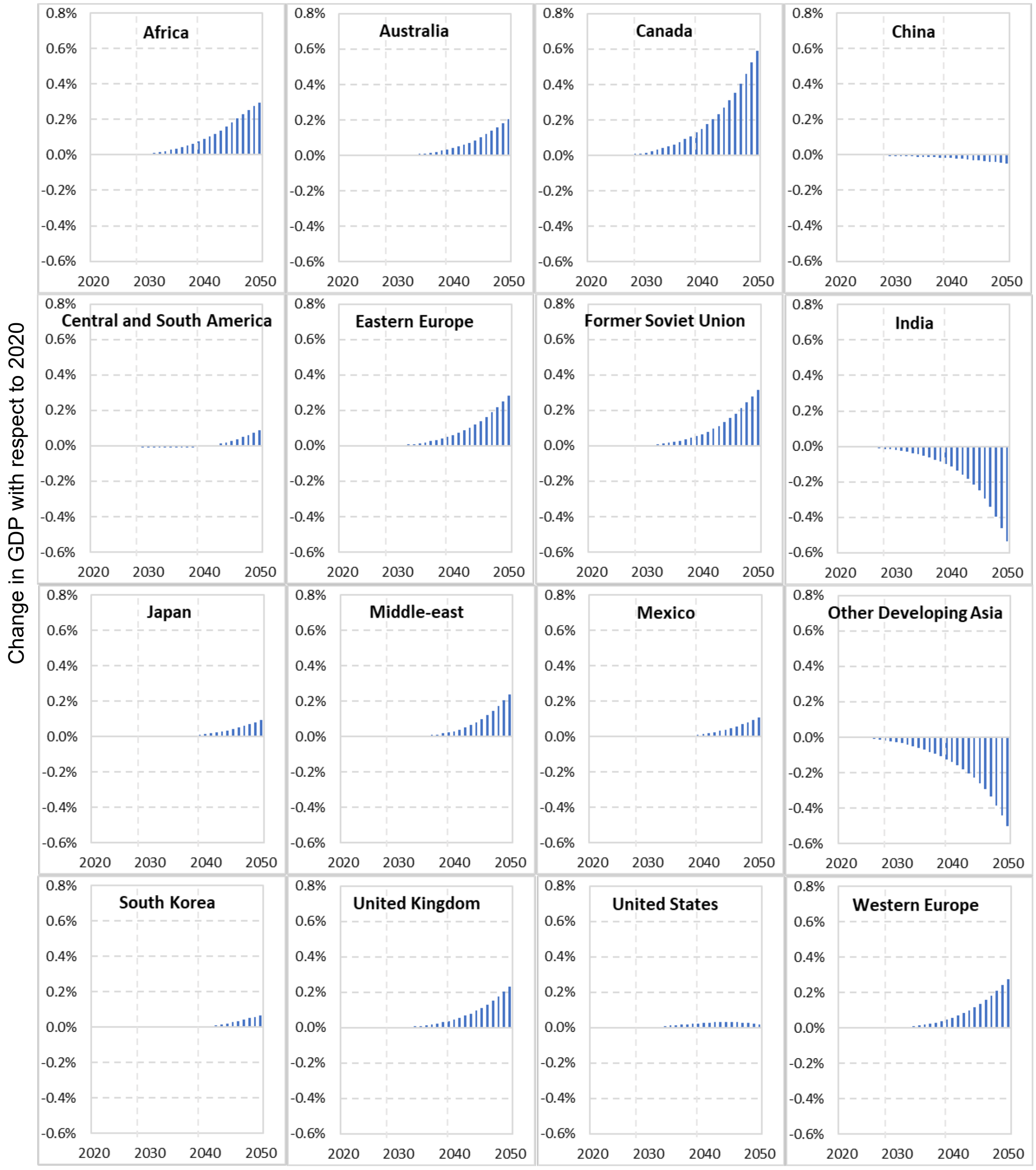


Figure 16. Change in regional GDP due to overshoot. The VHO – NO pathways are shown with the change relative to the year 2020.

In fact, production increases in regions with temperate climates and at far north latitudes (Canada, Eastern Europe, the former Soviet Union, the UK, and the USA). However, in these regions, the increase in exports exceeds the proportion of the increase in production (Figure 18). This means that farmers in regions where production increases may experience greater access to markets, while farmers in regions adversely affected by climate change (e.g. India, Africa, and Other Developing Asia) may lose their market share, as they face lower yields and greater competition from elsewhere.

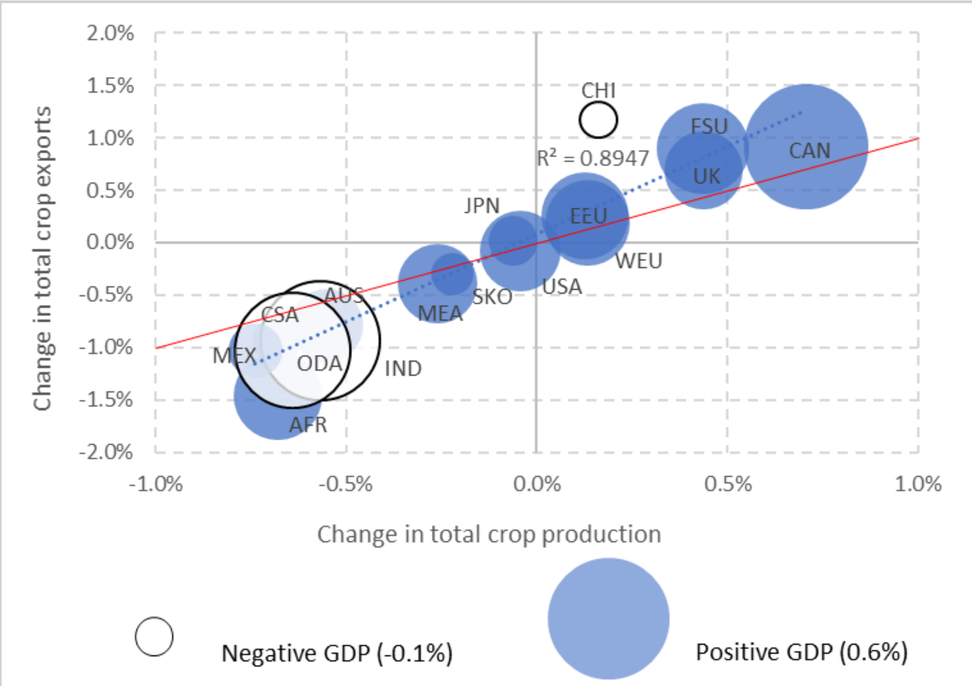


Figure 17. Changes in regional GDP, total crop production and total crop exports in 2050 due to overshoot. In each case, the difference between the VHO and NO pathways are shown. The red line represents a 45° line. GDP change is relative to the year 2020.

Compared to the NO pathway, under the VHO pathway, global production of all crops is expected to decline. As a consequence, global food prices are expected to increase by more than 1% for cereal grains (Figure 19). This implies that higher temperatures resulting from global warming will disproportionately affect vulnerable populations. Both their physical and economic access to food to meet their dietary needs will be impacted. As shown in Figure 16, the gains experienced by producers are outweighed by the losses incurred by consumers.

Moreover, food prices are expected to increase significantly in developing regions, including Africa, India, and Other Developing Asia (as shown in Figure 19). The price response is particularly strong for wheat and ‘other crops’. The larger the decline in production, the greater the increase in prices.

Figure 18. Change in regional crop commodity price and crop production in an overshoot. The differences between the VHO and NO pathways are shown.

5.3 Impacts of overshoot on fisheries

Warming oceans will affect the fish stocks and locations. Fishing communities in equatorial and tropical nations are more at risk than communities in temperate nations as fish displace towards the poles. However, as well as a change in location, the composition and size of fish will vary, as will their onshore-to-offshore and pelagic-to-demersal distribution. This would likely require changes in fishing gear and adaptative management strategies. Understanding the impact on fish is important for SDG14 (life under water) but also for SDG2 (zero hunger), with links to SDG3 (good health and well-being) and SDG5 (gender equality) as changes to fisheries affect food supply, healthy diets (some communities are reliant on fishing for their protein intake), job opportunities and how employment is split between genders. We used the Fisheries and Marine Ecosystem Model Intercomparison Project (FIShMIP) to access outputs of fish model projections looking at the impact of climate change on the fish biomass (FIShMIP, Lotze *et al.*, 2019, Tittensor *et al.*, 2021).

5.3.1 Methods

FIShMIP is part of the Intersectoral Impact Model Intercomparison Project (ISIMIP) and we used the ISIMIP portal to download the outputs. We decided to use the latest outputs (ISIMIP3b) since they use the CMIP6 models as forcing, and more specifically the outputs of the runs with the IPSL-CM6a-LR model as those were used by four of the fisheries models providing us with an ensemble from which we extracted mean fish biomass. The outputs we used were the total consumer biomass (i.e. the full fish biomass), and the consumer biomass in log10 weight bins separating the small and large fish (i.e. similar to bins on a histogram). The total consumer biomass was available for the four models that contributed to the project (APECOSM, FEISTY, BOATS and ECOOCEAN), while the binned consumer biomass was estimated for only two models (APECOSM and BOATS). We took the mean values of all models to provide a more nuanced outlook than just using a single model. Of the existing Shared Socioeconomic Pathways scenarios (SSPs) projections were only available for SSP5-8.5 and SSP1-2.6, providing us with the two extremes of the climate scenario spectrum. As for crop yields, data are not currently available for RCP1.9 so it is difficult to estimate the impacts of a NO pathway.

We used Figure 20 from the IPCC AR6 report to identify the timeline of when the overshoot happens and the level of warming. This Figure shows the level of warming for a range of SSP/RCP combinations. For the 2040–2050 decade, we can expect a 1.5 °C rise under SSP1-2.6 and a 2 °C rise under SSP5-8.5. Under SSP1-2.6, the temperature peaks at around 1.75 °C warming, depending on the model used, while SSP5-8.5 leads to warming of 4°C around 2080–2090. Consequently, for our analysis we used the years 2015–2024 as our “present time” 10-year reference time slice; 2040–2050 for 1.5 °C and 2 °C warming; and 2080–2090 for a 4°C warming and for the temperature persisting near 1.5 °C over the long term.

Our analysis had several limitations:

- Rather than looking at pelagic and benthic separately, we examined the full water column.[6] Further differences can be expected between species in these two groups.
- The FIShMIP results we used were based on the outputs of only one earth system model for the forcing. Earth system models produce varying projections for fish due to differences in the physics and biogeochemistry of ocean models.
- No fishing pressure is included in these model projections. Areas that are overfished will likely show a faster loss in biomass than projected here.

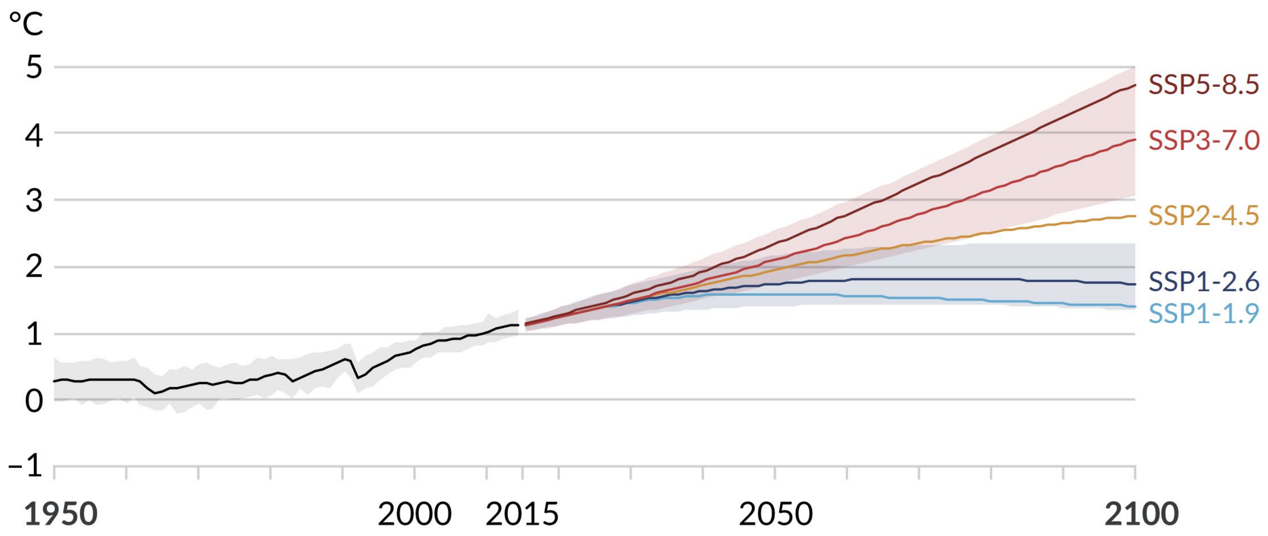


Figure 19. Global surface temperature change relative to 1850–1900. From Figure SPM.8 Panel (a) in IPCC (2021b).

5.3.2 Results

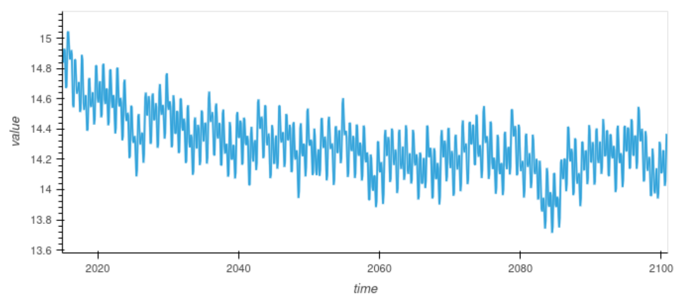
We produced four sets of ensembles: the total consumer biomass and the binned consumer biomass each for SSP1-2.6 and for SSP5-8.5. For each ensemble, we calculated the mean biomass and extracted the global trend (global biomass plotted against time), the zonal mean (mean biomass at given latitude showing the North-South biomass distribution at a set time in space) and map of present distribution and future anomalies (areas where biomass increases or decreases). For the files with the binned consumer biomass, these

[6] Pelagic fish swim in the deep sea. Benthic fish live near the sea bed.

were plotted/mapped for each bin to show the change in distribution/abundance depending on the size class.

The results and figures are collated for SSP1-2.6 in Table 15 and for SSP5-8.5 in Table 16.

Table 15. Change in fish biomass by following SSP1-2.6. Changes in the density of fish per sea column are shown, split into total consumer biomass (fish/m^2) and in bins of 1 g fish/m^2, 10 g fish/m^2, 100 g fish/m^2, 1 kg fish/m^2, 10 kg fish/m^2 and 100 kg fish/m^2. For each of these categories, there are plots of the global trend (global average of biomass plotted over time), the zonal mean (spatial average per latitude showing the distribution of biomass between poles), and a map (global distribution of fish as per their biomass and changes in future distribution expressed as anomalies between the present and the specified future time period. Note the y axes are set to the maximum and minimum in each case.

<table>
<tr><td colspan="5">SSP1-2.6</td></tr>
<tr><td>Biomass variable</td><td>Plot</td><td>“Present” (2014-2025)</td><td>2 °C Warming (2040-2050)</td><td>4°C warming (2080-2090)</td></tr>
<tr><td rowspan="3">Total consumer biomass (fish/m^2)</td><td>Global trend</td><td colspan="3">
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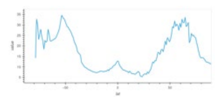
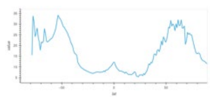
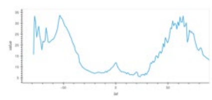
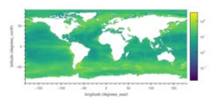
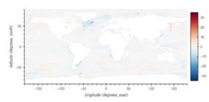
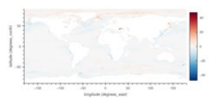
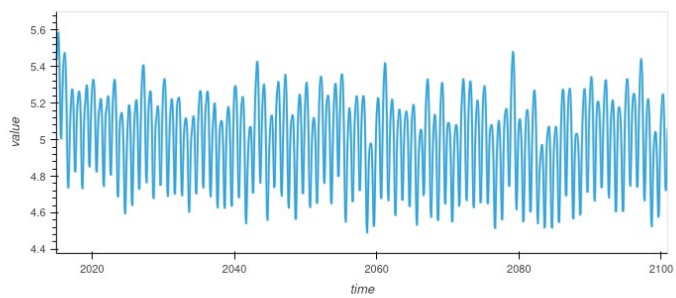
<tr><td>Zonal mean</td><td></td><td></td><td></td></tr>
<tr><td>Map</td><td></td><td></td><td></td></tr>
<tr><td>1 g fish/m^2 bin consumer biomass</td><td>Global trend</td><td colspan="3">
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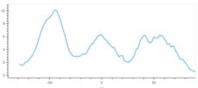
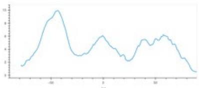
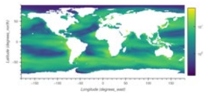
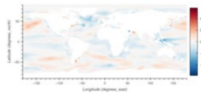
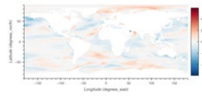
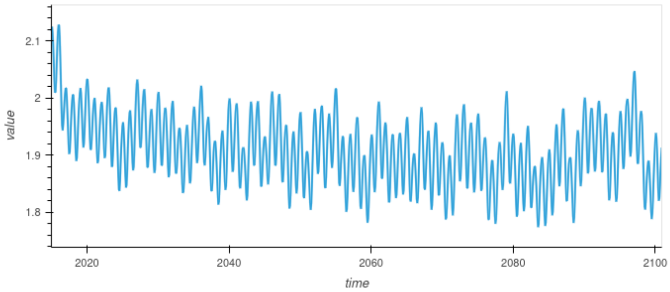
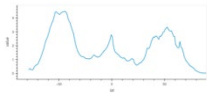
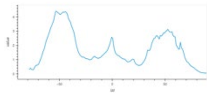
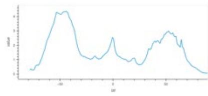
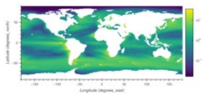
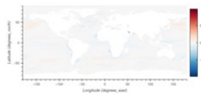
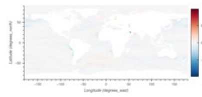
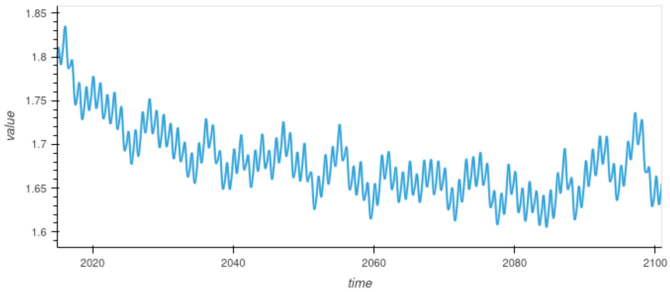
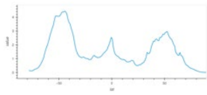
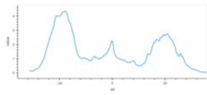
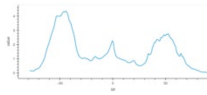
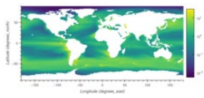
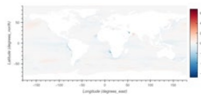
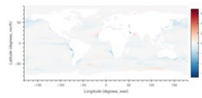
SSP1-2.6				
	Zonal mean	Change in fish biomass by following SSP5-8.5		
	Map			
10 g fish/m^2 bin consumer biomass	Global trend			
	Zonal mean			
	Map			
100 g fish/m^2 bin consumer biomass	Global trend			
	Zonal mean			
	Map			

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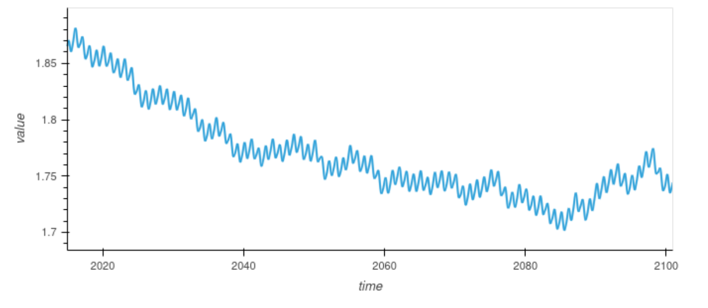
<tr><td rowspan="3">1 kg fish/m^2 bin consumer biomass</td><td>Global trend</td><td colspan="3">
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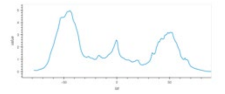
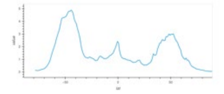
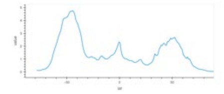
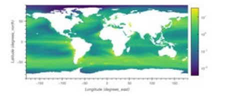
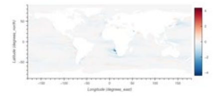
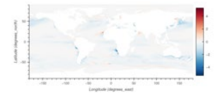
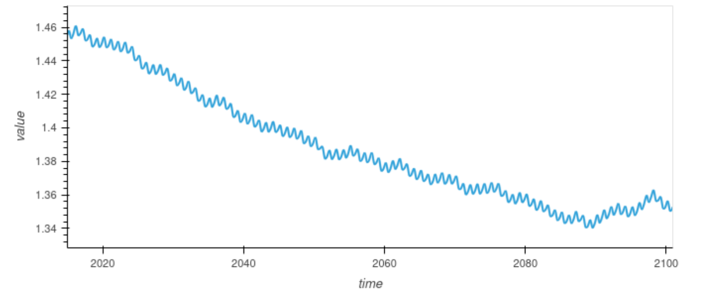
<tr><td>Zonal mean</td><td></td><td></td><td></td></tr>
<tr><td>Map</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">10 kg fish/m^2 bin consumer biomass</td><td>Global trend</td><td colspan="3">
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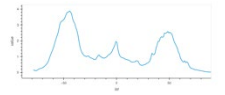
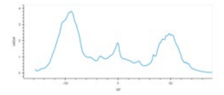
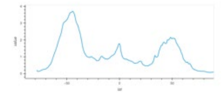
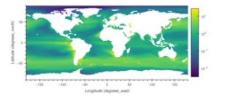
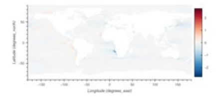
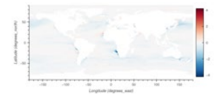
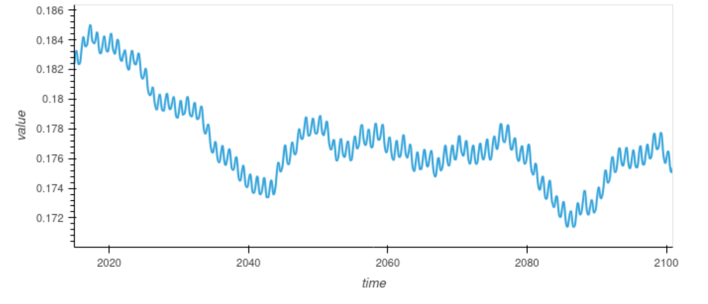
<tr><td>Zonal mean</td><td></td><td></td><td></td></tr>
<tr><td>Map</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">100 kg fish/m^2 bin consumer biomass</td><td>Global trend</td><td colspan="3">
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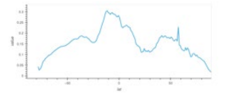
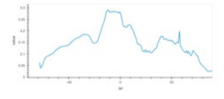
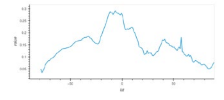
<tr><td>Zonal mean</td><td></td><td></td><td></td></tr>
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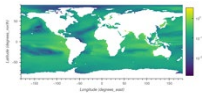
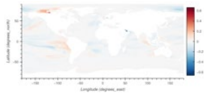
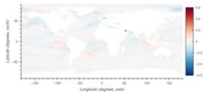
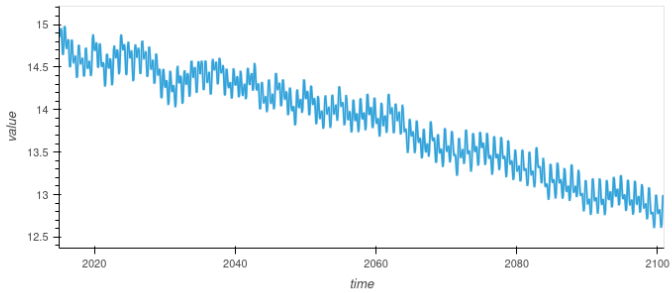
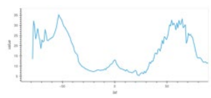
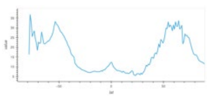
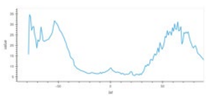
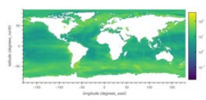
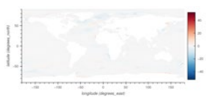
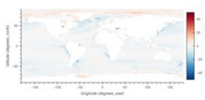
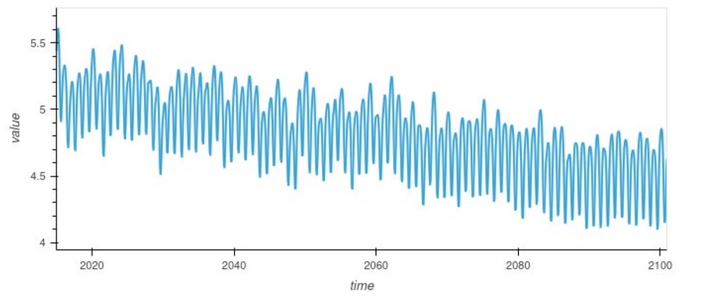
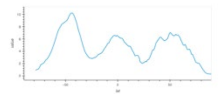
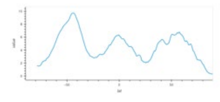
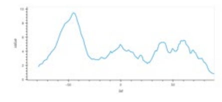
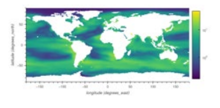
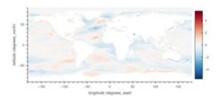
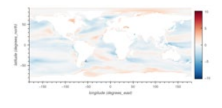
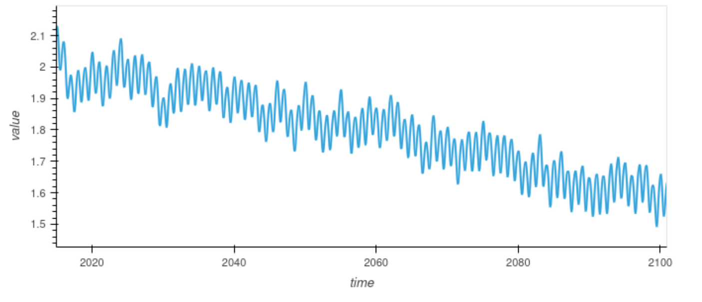
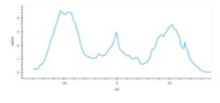
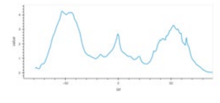
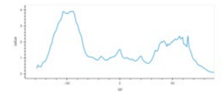
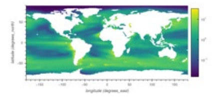
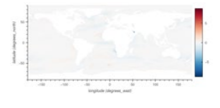
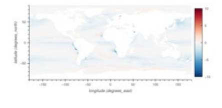
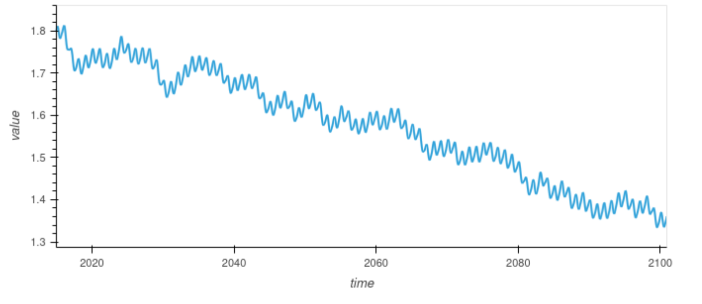
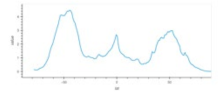
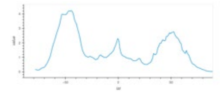
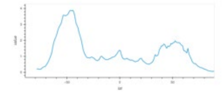
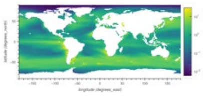
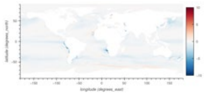
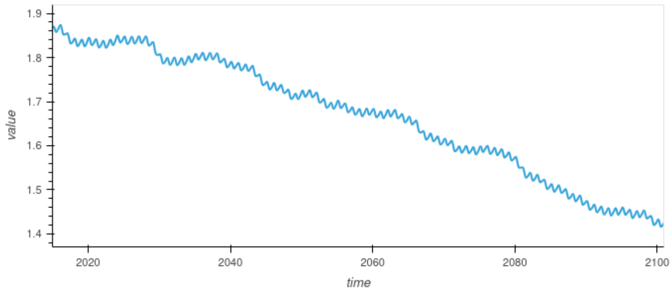
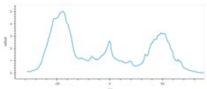
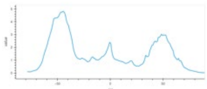
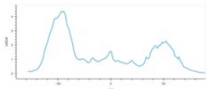
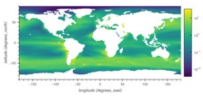
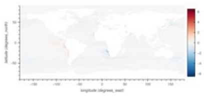
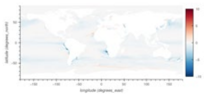
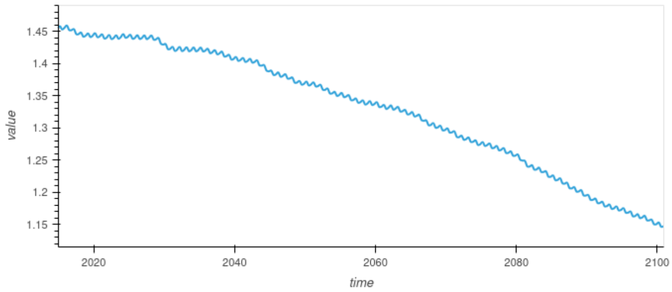
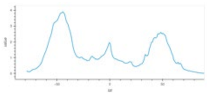
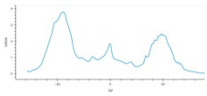
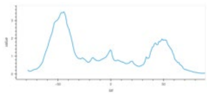
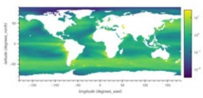
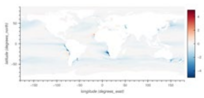
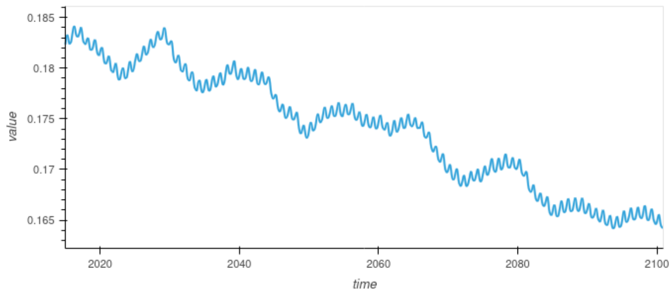
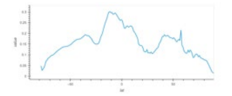
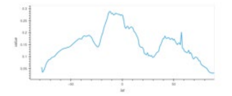
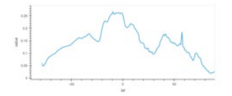
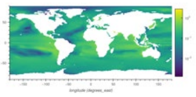
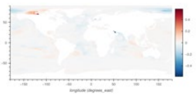
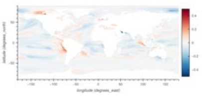
	Map			

Table 16. Change in fish biomass by following SSP5-8.5. Changes in the density of fish per sea column are shown, split into total consumer biomass (count/m^2) and in bins of 1 g fish/m^2, 10 g fish/m^2, 100 g fish/m^2, 1 kg fish/m^2, 10 kg fish/m^2 and 100 kg fish/m^2. For each of these categories, there are plots of the global trend (global average of biomass plotted over time), the zonal mean (spatial average per latitude showing the distribution of biomass between poles), and a map (global distribution of fish as per their biomass and changes in future distribution expressed as anomalies between the present and the specified future time period. Note the y axes are set to the maximum and minimum in each case.

SSP5-8.5				
Biomass variable	Plot	"Present" (2014-2025)	2 °C Warming (2040-2050)	4°C warming (2080-2090)
Total consumer biomass	Global trend			
	Zonal mean			
	Map			

SSP5-8.5				
1 g fish/m^2 bin consumer biomass	Global trend			
	Zonal mean			
	Map			
10 g fish/m^2 bin consumer biomass	Global trend			
	Zonal mean			
	Map			
100 g fish/m^2 bin consumer biomass	Global trend			
	Zonal mean			

SSP5-8.5				
	Map			
1 kg fish/m^2 bin consumer biomass	Global trend			
	Zonal mean			
	Map			
10 kg fish/m^2 bin consumer biomass	Global trend			
	Zonal mean			
	Map			
100 kg fish/m^2 bin consumer biomass	Global trend			

SSP5-8.5				
	Zonal mean			
	Map			

5.3.3 Global impact on total biomass

Under SSP1-2.6, the decreasing trends that are currently observed stabilise on a global scale and changes stay minimal between the “present” time slice and the end of the century. There is still a decline in biomass in some of the productive regions (negative anomalies) and an increase in the northern latitudes. The increase in biomass is mostly in areas with lower biomass at the outset so indicate a displacement of fish populations into these areas that were previously less suitable for those species. Areas that were more productive seem to only experience a reduction as original fish are displaced and not always replaced. Looking at the zonal mean for total biomass, the latitudinal distribution pattern is the same in all three time slices, indicating that the reduction in biomass is similar.

Under SSP5-8.5, there is a marked decrease in the total biomass throughout the century. The increase in loss follows the same pattern as for under SSP1-2.6 with little differences for 1.5–2 °C warming (SSP1-2.6 and SSP5-8.5, respectively). The zonal mean shows that the loss of fish biomass is particularly high around the equator.

5.3.4 Impact on the different size classes

For 1.5–2 °C warming (SSP1-2.6), larger size classes (from 1 kg) are most affected with a decrease in the Northern Atlantic and Northern Pacific as well as in equatorial regions. Outside of these areas, highly productive regions have an increase within their core habitat while areas of low productivity have a further reduction. This pattern is especially visible for the largest size class, indicating that for those, rather than a displacement we can expect a reduction of the distribution linked to a reduction in suitable habitats.

For 2–4°C warming (SSP5-8.5), all size classes show a decline and a marked loss in equatorial regions and subpolar regions. The changes observed for 1.5–2 °C warming are strengthened in these conditions for the larger size classes. For the smaller size classes, (100 g and under), there is a clear reduction in the tropical and subpolar areas while species redistribute poleward uniformly.

5.3.5 Summary

Changes in ocean temperature will cause a redistribution of consumer fish towards the poles, with a loss of biomass at the equator and at the poles. The overall loss of biomass is likely to be small for the overshoot pathways but will be greater than for the NO pathway due to higher oceanic temperatures for an extended period. The impact of continuing temperature increases, for example by failing to implement sufficient CO_2 removal from the atmosphere to return the global temperature rise to 1.5 °C, would be to further reduce fish biomass throughout the century. Not all size classes of fish would respond in the same way to climate change, so redistribution of various size class (and species) means that the fishing community might have to adapt or change their approach, particularly in tropical areas where total fish biomass would likely reduce.

6. Health impacts

There are a number of ways climate change may impact human health (Ebi *et al.*, 2021), which is the focus of SDG3 (good health and well-being). Effects can be direct, as high ambient temperatures can limit the body's ability to regulate core temperature and degrade sleep quality, leading to increased mortality and morbidity from cardiovascular and respiratory disease (Cheng *et al.*, 2019), kidney failure (Roncal-Jimenez *et al.*, 2015), adverse pregnancy outcomes (Zhang *et al.*, 2017b), greater emergency room visits and hospital admissions (Sohail *et al.*, 2020, Mason *et al.*, 2022) and mental health conditions (Liu *et al.*, 2021, Lee *et al.*, 2023). Indirect effects may occur following the incidence of wildfires (Grant and Runkle, 2022), flooding (Jackson and Devadason, 2019), and reduced productivity and labour supply (Ebi *et al.*, 2021, van Daalen *et al.*, 2022).

The extent to which these impacts are felt across the global population will depend on the degree of climate warming. Temperature-related mortality has increased at a rate of 15.1 (95% CI: 1.51–31.6) additional deaths per million inhabitants per decade between the years 2000–2020 (van Daalen *et al.*, 2022) under the current global temperature increase of 1.2 °C. These deaths are not distributed equally across the global population, which undermines the aims of SDG10 to reduce inequalities within and between countries. Anthropogenic climate change is responsible for <1% of the total number of deaths during warm seasons across North America and northern regions of Europe and Asia, whilst areas of South America, Southern Europe and South and Southeast Asia had higher mortality (Vicedo-Cabrera *et al.*, 2021). Within countries, heat-related mortality and morbidity is unequally distributed across different population groups. For example, evidence from regions of Spain (Sanchez-Guevara *et al.*, 2019, Salvador *et al.*, 2023), the USA (Koman *et al.*, 2019, Hsu *et al.*, 2021) and India (Ghumman and Horney, 2016, Ingole *et al.*, 2017) has shown socially-deprived individuals bear a disproportionate risk from exposure to high ambient temperatures and the associated heat-related mortality and morbidity burden.

Temperature-related mortality and morbidity are expected to increase proportionally with global temperature rise (Ebi *et al.*, 2018b). This means that an overshoot pathway will have higher health impacts than the NO pathway. Even if the global temperature rise is reversed following an overshoot, this does not mean the impacts felt at 1.9 °C are also reversible. Considerable increases in heat-related mortality represent one irreversible impact of overshooting with far-reaching consequences. Further impacts on human health may be mediated by droughts and floods (Drouet *et al.*, 2021) and reduced agricultural productivity (Meyer *et al.*, 2022), as discussed in Sections 4 and 5.

This section reviews the direct and indirect impacts of overshoot on health in Sections 6.1 and 6.2. It then examines lost co-benefits due to overshoot in Section 6.3 and the economic consequences of heat stress in Section 6.4.

6.1 Direct effects of overshoot on health

By 2050, a temperature increase of 0.3 °C would result in an additional 47% of India's population being exposed to heatwaves on an annual basis, equivalent to 66.8 million people, compared with a 1.5 °C warming scenario (Lejeune *et al.*, 2022). If this difference were to rise further, to 0.5 °C, these heatwaves are likely to be akin to the 2015 deadly Indian heatwave (Ebi *et al.*, 2018b) and more than twice as likely to occur (Mishra *et al.*, 2017). Across Senegal and Australia, an increase of 0.3°C in 2050 would result in an additional 50% and 36% of the national population, respectively, being exposed to heatwaves annually (Lejeune *et al.*, 2022).

Gasparrini *et al.* (2017) projected increases in heat-related mortality of 0.2%–1.9% across regions of America, Europe, Asia and Australia by the middle of the 21st century (2050–2059) between RCP4.5 and RCP8.5, for which the global mean surface temperature increase between 2046–2065 was 1.4 °C and 2 °C, respectively (IPCC, 2014b). Figure 21 shows the percent of heat-related deaths as a proportion of total deaths between 2050 and 2059, for 23 countries, adapted from Gasparrini *et al.* (2017), under RCP4.5 and RCP8.5. Notably, there are no heat-related mortality estimates across the African continent (Figure 21). Heatwave duration and frequency are predicted to be most severe in areas of West and Southern Africa under an overshoot pathway compared to a NO pathway (Drouet *et al.*, 2021), but there is a lack of epidemiological data from which to quantify mortality and morbidity between the different temperature scenarios in these areas (Harrington and Otto, 2020).

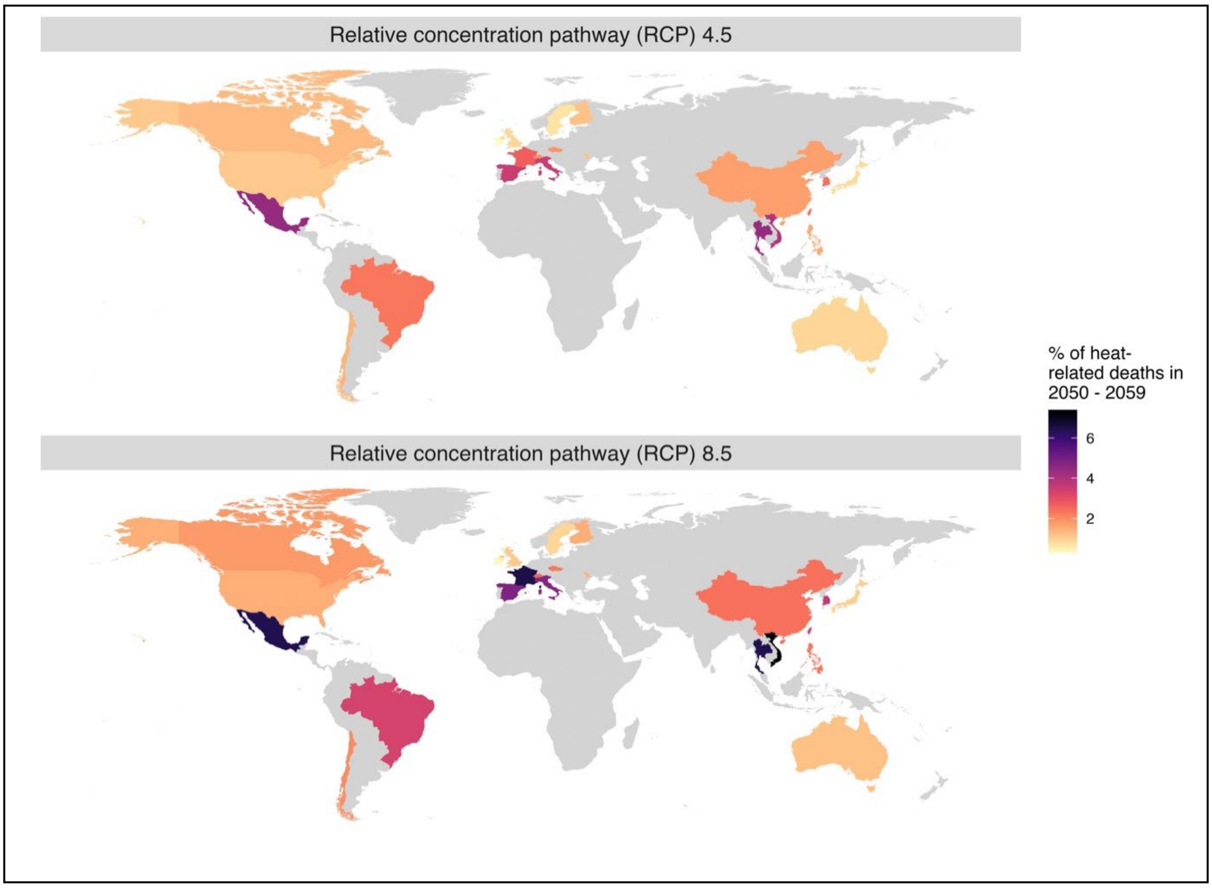


Figure 20. Heat-related deaths between 2050–2059 by country under RCP4.5 and RCP8.5. Colours represent the percentage of total deaths. The Figure shows estimates for 23 different countries across Europe, Asia, Australia and North and South America. Source: adapted from Gasparrini *et al.* (2017).

The estimates in Figure 21 are generally supported by the wider literature, where the burden of heat-related mortality and morbidity is expected to be greater if mean global temperature increase reaches ~2 °C by the middle of the 21st century versus 1.5 °C (Ebi *et al.*, 2018b). However, such projections depend on the integration of adaptation pathways such as additional cooling that may be achieved through changes to national infrastructure. The aforementioned Gasparrini *et al.* (2017) projected the impact of temperature-related mortality under the assumption of no adaptation or population change, but several studies have found heat-related deaths have continuously decreased over the last three decades despite ambient temperatures increasing (Chung *et al.*, 2017, Vicedo-Cabrera *et al.*, 2018). These declines in heat-related mortality may be explained by higher national adaptation, reduced population susceptibility and greater economic growth. Reductions in mortality and morbidity following national adaptation may attenuate risks due to infrastructural changes that happen simultaneously but independently from the changing climate (Vicedo-Cabrera *et al.*, 2018). However, as population susceptibility varies with the changing climate due to acclimatisation (Arbuthnott *et al.*, 2016), this mechanism may provide additional protection against heat-related health impacts by the mid-21st century in a high overshoot pathway.

The widespread adoption of residential air conditioning is one technological adaptation to climate change that is expected to result in heat-related mortality declines, particularly in middle-income economies where use is at present limited (Biardeau *et al.*, 2020). A multi-country analysis of air-conditioning and heat-related mortality in high-income countries suggested uptake of residential air conditioning explained 16.7%, 20.0%, 14.3% and 16.7% of the reductions is heat-related mortality observed between 1972–2009 in Canada, Japan, Spain and the USA, respectively (Sera *et al.*, 2020).

By 2040, adoption of residential air conditioning is expected to reach between 49%-69% in India; 43%-61% in Indonesia; 35–42% in Mexico and 65–85% in Brazil, with ranges dependent on moderate (RCP4.5) or vigorous (RCP8.5) climate warming (Pavanello *et al.*, 2021). The cooling demand required in the middle of the 21st century under RCP4.5 provides insights into future energy demands under a VHO pathway (IPCC, 2014b - Table 2.1). Meeting the residential cooling demand required in 2050s under higher emission scenarios is likely to pose significant challenges in low-income, low-latitude countries, such as India and Indonesia, placing considerable strain on the electricity grid infrastructure (Sherman *et al.*, 2022). Even in high-income countries where air conditioning use is already pervasive, exceeding the 1.5 °C threshold may lead to 8% more demand for air conditioning, heightening the risks of blackouts (Obringer et al., 2022). Co-occurring heatwaves and blackout events led to double the estimated heat-related mortality burden in three US cities (Stone *et al.*, 2023).

6.2 Indirect effects of overshoot on health

Food scarcity, from deaths of livestock and reduced labour productivity and crop production, is an indirect effect of global climate change of primary concern for population health, with implications for SDG2 (zero hunger) and SDG8 (decent work and economic growth). It is estimated that up to 5 million poultry died within a span of two weeks during the 2015 Indian heatwave (Pattanaik *et al.*, 2017). For a 1.8 °C temperature rise in 2050, labour productivity is expected to decline by 36% and 46% across Colombia and Brazil, respectively (Lejeune *et al.*, 2022), compared to a NO pathway. The largest declines would be seen across sub-Saharan Africa and South Asia under higher emission scenarios (Dasgupta *et al.*, 2021). Food insecurity, from reduced quality and quantity of crops, is expected to be higher in 2050 under a higher emission scenario (Hasegawa *et al.*, 2021), and can lead to malnutrition and diet-related non-communicable disease, such as diabetes and cardiovascular conditions (Fanzo and Downs, 2021). Health risks associated with food insecurity and malnutrition in 2050 are larger at 2 °C compared to 1.5 °C of warming (Ebi *et al.*, 2018a), and may exceed mortality and morbidity from population exposure to heat. Springmann *et al.* (2016) found climate-related deaths due to changes in diet and weight-related risk factors were 32% higher in 2050 under RCP8.5 compared with RCP4.5.

Climate overshoot scenarios may also indirectly impact the risk of vector-borne disease transmission (Ebi *et al.*, 2018b) The geographic range of a number of vectors, such as those for zika virus, dengue fever and malaria, is currently limited by cooler ambient temperatures (Rocklöv and Dubrow, 2020). A number of studies have concluded that the risk of malaria transmission is higher if the global temperature increase exceeds 1.5 °C due to the expanded geographic range of the Anopheles mosquito vector (Ebi *et al.*, 2018b). By 2050, the proportion of environmentally suitable land for malaria transmission will increase under RCP8.5 compared with RCP4.5 in China (Ren *et al.*, 2016) but decline in Sub-Saharan Africa (Semakula *et al.*, 2017). This highlights how the effects of higher ambient temperatures on vector-borne disease transmission may be nonlinear, a conclusion reached by a number of other studies (Ebi *et al.*, 2018b, Rocklöv and Dubrow, 2020). Whilst a higher mid-century overshoot may expand the spread of many vectors to more northern latitudes, it may decrease incidence in areas where vectors are already endemic, if the temperature increase inhibits vector survival and feeding.

6.3 Lost co-benefits due to overshoot

Decarbonising the global economy as early as possible would bring health co-benefits. The CS-N0W “Co-impacts of climate change mitigation” report examines three potential health benefits on a global scale:

1. Better air quality through less fossil fuel combustion.
2. Lower meat consumption that reduces dietary-related health issues. Most of the benefits would be realised in regions, such as Eastern Europe, that have high meat consumption.
3. Greater physical activity due to increased active travel that improves health.

Dietary and physical activity gains are assumed to occur as a result of behavioural change to reduce greenhouse gas emissions, but it would be possible, but more difficult, to decarbonise the global economy without realising these health benefits.

The LO, HO and VHO pathways would delay many mitigation actions by 5, 15 and 20 years, respectively. During those periods, these health co-benefits would not be realised in an overshoot compared to following a NO pathway.

The impacts on health of not decarbonising was carried out for the International Energy Agency (IEA) “Stated Policies” and “Sustainable Policy” scenarios (IEA, 2021), which until 2050 have similar but slightly lower temperature trends to the VHO and NO pathways, respectively, as shown in Figure 22. The methods used to identify the impacts in 2050 are documented in detail in the CS-N0W “Co-impacts of climate change mitigation” report.

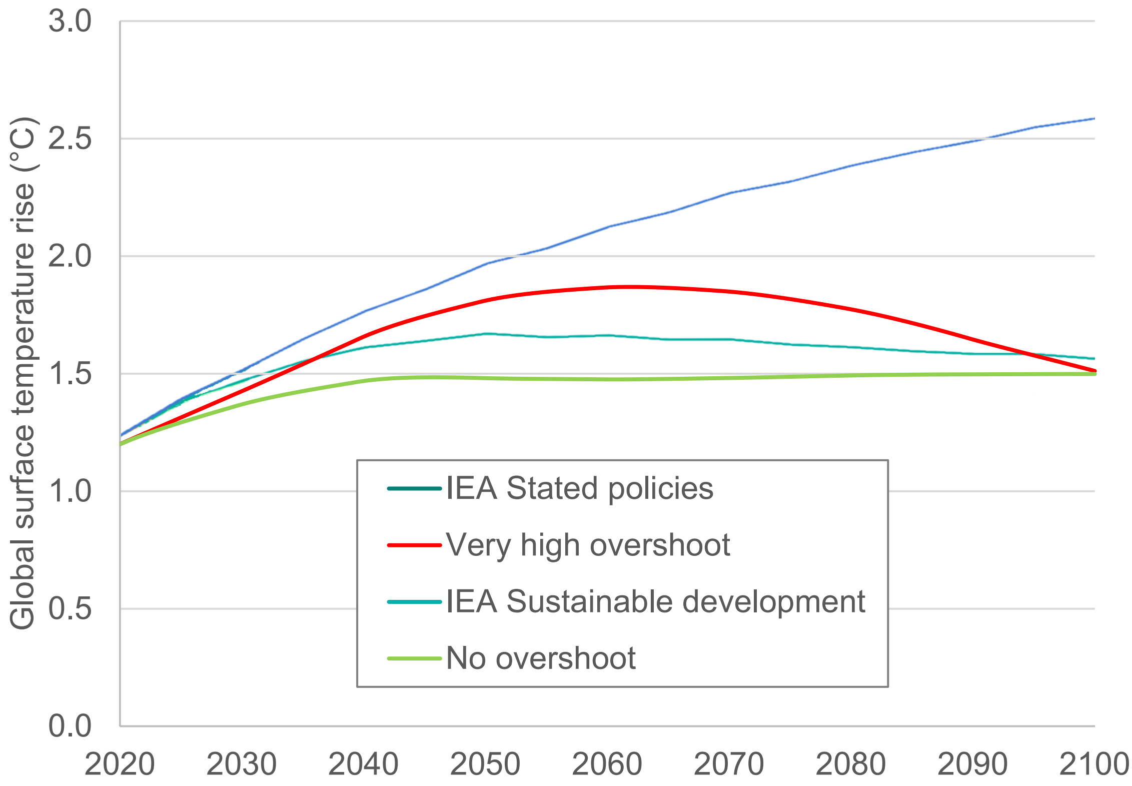


Figure 21. Global temperature pathways for IEA scenarios and the VHO and NO pathways. The IEA pathway data is from IEA (2021).

The increases in mortality in the year 2050 between the IEA "Stated Policies" and "Sustainable Policy" scenarios are shown for each health co-benefit, by world region, in Table 17. Improving diet has the largest potential benefit. Improved air pollution is particularly important in Asia, in which many cities have poor air quality. Physical activity by contrast has smaller potential benefits.

Table 17 shows only mortality in a single year. The VHO pathway has a much longer delay to mitigation actions than the other two overshoot scenarios, so mortality over the period to 2100 would be much higher. In Annex 3 of this study, the length of the delay is used as a proxy to estimate the loss of economic co-benefits through the total loss of life in each overshoot scenario. In practice, the relationship between the length of the delay and total mortality is unlikely to be linear as health impact calculations rely on estimating both exposure (for example to PM2.5 pollution in the case of the air pollution domain) and the age structure and health of the underlying population. For this reason, total mortality for each overshoot scenario is not projected here.

Table 17. Increased mortality in 2050 due to not realising mitigation co-benefits, by health domain and region in 2050. Units are deaths/100k population. Source: own analysis.

Region	Air Pollution	Diet	Physical activity
East & Southeast Asia	55	94	12
European Union	15	183	13
Latin America	15	142	5
North Africa & Middle East	18	141	14
Other Europe	28	268	7
South & Central Asia	55	103	9
Sub Saharan Africa	10	53	2
USA and Canada	9	154	7
World	34	92	7

6.4 Economic consequences of heat stress

Changes in the frequency and intensity of extreme temperatures directly affect human health. These adverse effects on humans generate economic costs due to labour productivity decrease. Indoor and outdoor workers are exposed to high temperatures and humidity in workplaces, particularly in low and middle-income countries (IPCC, 2022a). The potential adverse effect of high temperatures on the human body and labour productivity is well known and documented (Kovats and Hajat, 2008). The estimated loss of labour capacity, supply, and productivity in moderate outdoor work due to heat stress ranges from 2%–14%, varying depending on the location and indicator (IPCC, 2022a).

In this section, we assess the economy-wide impacts of heat-induced labour productivity losses behind the temperature increase under the VHO and NO pathways.

6.4.1 Modelling approach

To quantify the economy-wide impacts of heat stress on labour productivity, we use the UCL ENGAGE model, which considers direct and indirect impacts of policy interventions spanning across sectors and regions. A brief description of the UCL ENGAGE model is provided in Section 5.2.1.

Heat stress reduces the ability of workers to operate during the hottest hours. Higher temperatures result in lower labour productivity levels and economic outputs. Country estimates on the impact of heat stress on the productivity of labour in the agriculture, industry and services sectors are used to assess the economic impact to 2050 for the VHO and NO pathways. Heat stress estimates are linked to the global mean temperature, so do not consider extreme heat events.

The impact of heat stress on labour productivity is based on Roson and Sartori (2016). The authors estimate heat damage functions for three sectors: agriculture, manufacturing and services, for a given increase in global temperature. They estimate the percentage of a typical working hour that a person can work, assuming the remaining time is rest, using the average monthly "wet bulb globe temperature".[7] The heat stress impact on labour productivity is calculated using these damage functions in ENGAGE as a decline in the productivity of labour. All other assumptions remain unchanged.[8]

Some limitations of our modelling approach are:

- Heat stress impacts are based on a single study. The results are heavily influenced by this choice. Uncertainty on the impact of heat stress on labour productivity should be captured by including additional estimates, potentially derived from a variety of methodologies and diverse data sources.
- The damage functions of ENGAGE use local temperature changes for 140 countries from Roson and Sartori (2010) to estimate the change in labour productivity. We used the global temperature increase computed by the TIAM-UCL model as the damage function temperature. This implies that all regions experience the same warming level, which is inaccurate as local temperatures vary widely for a given global temperature level.
- As with most global economic models, ENGAGE includes very aggregated sectors and regions. This is a limitation of the model that average out local effects.

[7] The wet-bulb globe temperature is a measure of environmental heat as it affects humans. It accounts for air temperature, humidity, radiant solar heat and ventilation.
[8] The modelling of the VHO and NO pathways are described in detail in Dodds et al. (2024), section 4.

6.4.2 Insights

In the VHO pathway, higher temperatures will exacerbate existing challenges and intensify the impact of heat stress on the labour force, particularly in developing regions with high outdoor labour concentrations and inadequate climate-controlled conditions. An additional 0.27 °C of warming in 2050, compared to the NO pathway, will adversely affect business and economic growth worldwide. Global GDP steadily declines to -0.32% in 2050, compared to the 2020 level (Figure 23).

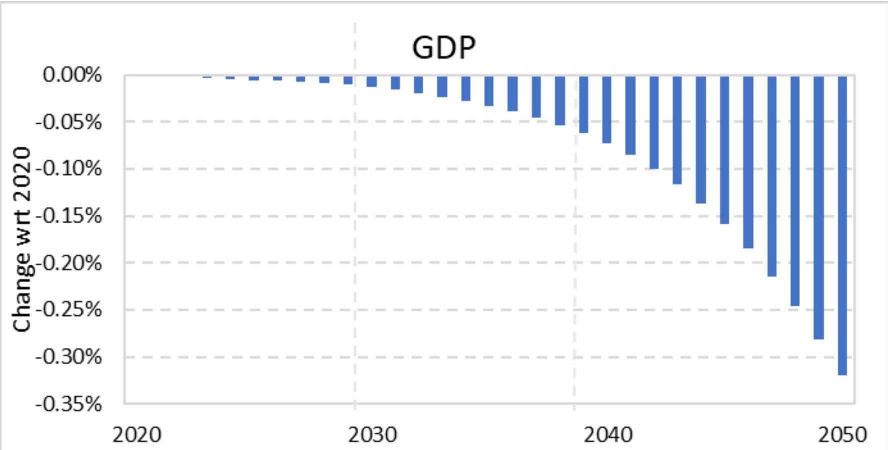


Figure 22. Change in global GDP due to overshoot. The differences between the VHO and the NO pathways are shown with changes relative to the year 2020.

The impacts of climate change on labour productivity and GDP are unevenly distributed across regions, with developing regions, such as Africa, Central and South America, India, the Middle East, and Other Developing Asia, experiencing the more severe impacts (Figure 24). An increase of 0.27 °C in the global temperature in 2050 in the VHO pathway compared to the NO pathway could potentially reduce Africa's GDP by 1.4% and India's GDP by 1.1% by 2050.

The influence of heat stress on labour productivity is not uniformly distributed across all sectors. Workers in the agricultural sector, who are predominantly outdoors and highly exposed to weather conditions, are likely to experience substantial productivity losses. Similarly, individuals employed in industries with hot indoor environments are also more susceptible to productivity losses compared to those in the service sector. The difference in impacts across sectors is evident in Figure 25. The impacts on production and trade in the agricultural sector are larger than those in the industry and service sectors. India and Other Developing Asia (primarily Southeast Asia) have an increase in the production and trade of agricultural products. The main reason is that both regions have a relatively lower decline in agricultural labour productivity than other regions. That is, although the productivity levels of these two regions are the largest for a specific temperature increase, the percentage change in productivity between the VHO and NO pathways is smaller in these two regions compared to other regions. However, this positive impact on agriculture is more than offset by the negative impact on the industry and service sectors.

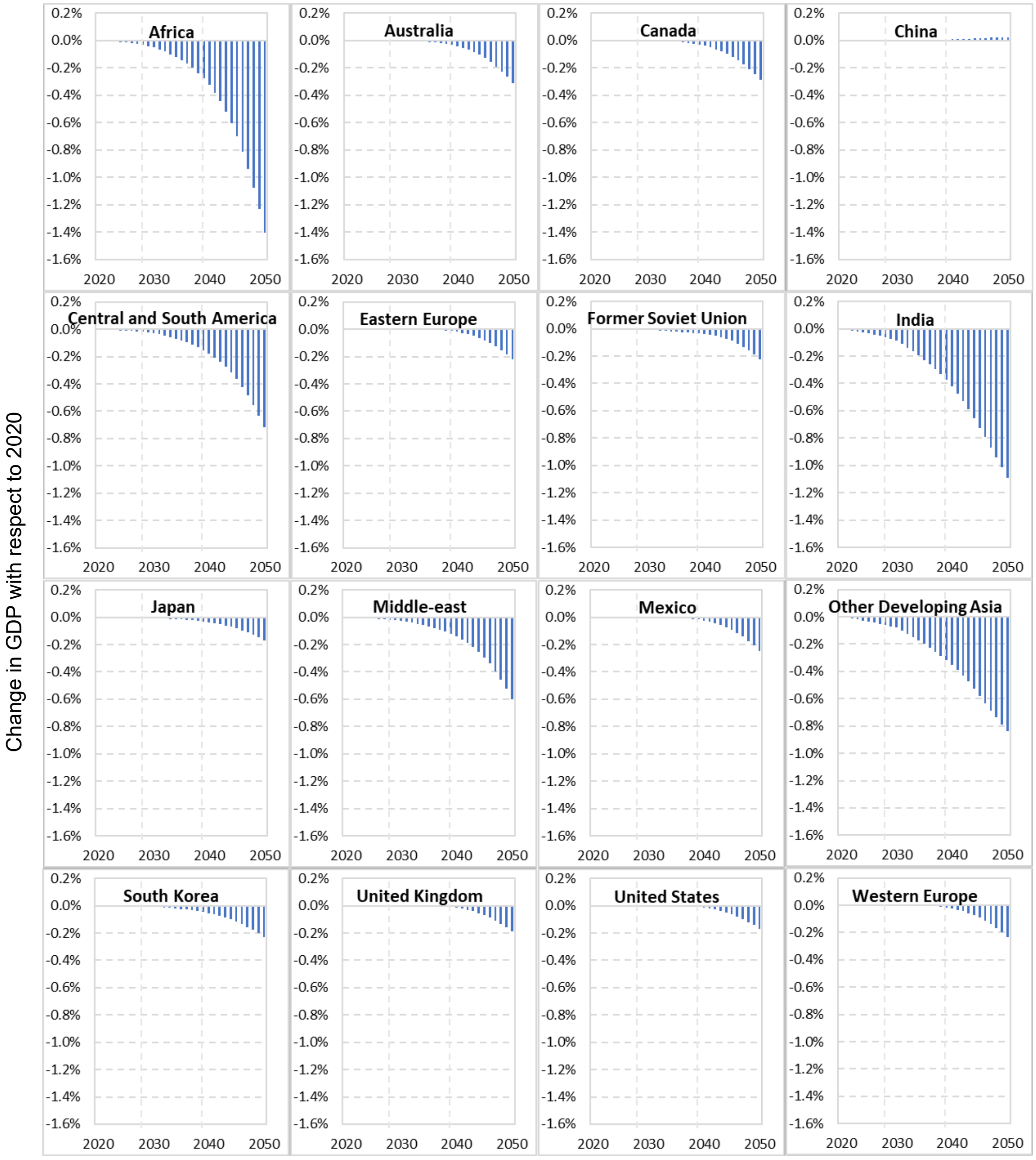


Figure 23. Change in regional GDP due to overshoot. The differences between the VHO and the NO pathways are shown with changes relative to the year 2020.

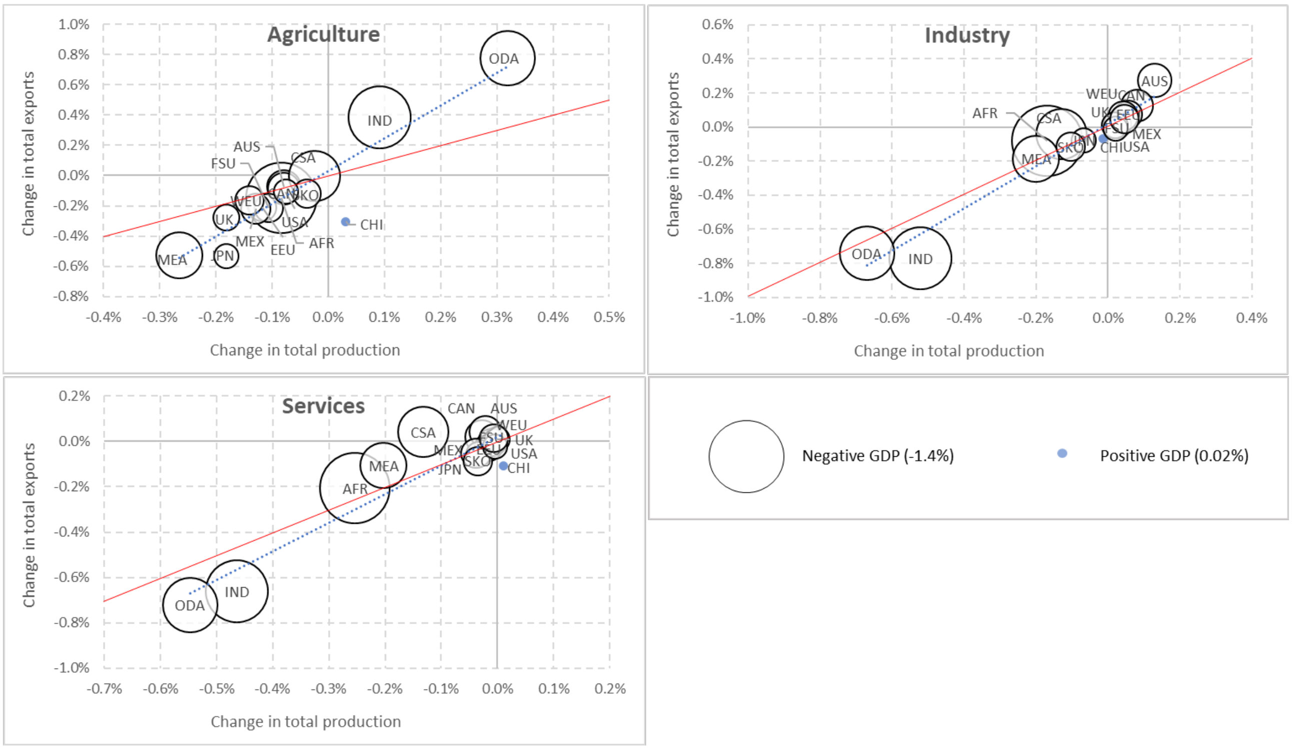


Figure 24. Change in regional GDP, total crop production and total crop exports in 2050 due to overshoot. The differences between the VHO and the NO pathways are shown with the change in GDP relative to the year 2020. Red lines represent 1:1 changes. Blue lines show actual changes as measured using linear regressions. The circle areas indicate the magnitude of GDP loss in each region. Graphs shown the agriculture (PDR, WHT, GRO, A_F), industry (A_F, MIN, PPP, CRP, NMM, I_S, MPR, IND, COA, OIL, GAS, P_C) and services (NUP, CFP, WIP, HYP, OFP, OTP, SOP, TnD, SER, TRN) sectors, with the model sub-sector codes listed in brackets.

As the global economy contracts due to a reduced labour productivity worldwide in the VHO pathway, the global production and price of agricultural and industrial goods slightly decrease. However, as trade does not alleviate demand or supply constraints in the service sector, its prices slightly increase (Figure 26).

Generally, price changes correspond to changes in production. A larger decrease in production leads to a greater price increase in the service sector, or a smaller price reduction in the agricultural sector.

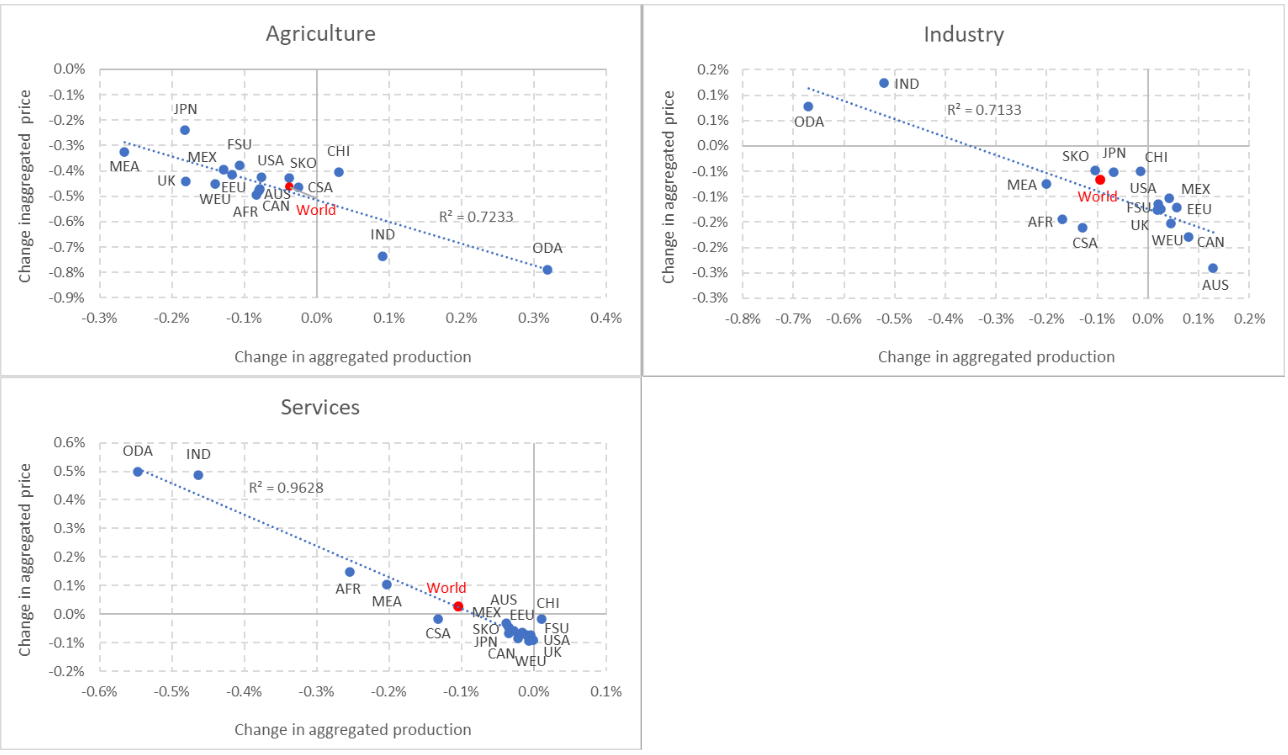


Figure 25. Change in regional aggregated price and aggregated production due to overshoot. The differences between the VHO and the NO pathways are shown.

7. Impact on affordable and clean energy

The energy sector is the largest producer of anthropogenic greenhouse gas emissions globally. Most of these emissions are caused by fossil fuel combustion. As a result, any change in future pathways is driven by changes in the energy sector. Hence there are substantial differences in energy between the NO and VHO pathways, particularly in the period to 2050, and these would have important implications for SDG7 ("ensure access to affordable, reliable, sustainable and modern energy for all") and wider economic and social systems.

This section first examines how fossil fuel and biomass consumption might change in VHO and NO pathways, then considers electrification of the economy and energy efficiency (SDG7.3) and renewable energy deployment (SDG7.2). The focus then changes to the impacts of climate change on electricity generation and on the resilience of the energy system more generally. We finish with a discussion of the impacts on access to and the affordability of modern energy services (i.e. electricity and clean cooking) (SDG7.1).

7.1 Methods

Two methods have been used in this section.

First, for Sections 7.2 to 7.4, outputs have been extracted from the TIAM-UCL energy system model for the NO and VHO pathways. The development of these pathways and the underlying assumptions are discussed extensively in Annex 1 of this study so are not discussed here. These are presented as previous studies of the impacts of climate change on energy and have not considered overshoot pathways.

Second, for Sections 7.5 to 7.8, a rapid scoping review has been conducted to examine the impacts of climate change on renewable and affordable energy. The methodology employed was a review of reviews, focusing exclusively on review studies on this subject. A search was conducted on the Scopus database (an extensive, interdisciplinary research database) using specific keywords detailed in Table 18. For example, to find review studies on the impacts of climate change on hydropower, the search terms "climate change", "impacts", "projections", "scenarios", "hydropower", "hydroelectricity", and "hydro" were used. Searches were conducted using the Scopus electronic database between 25th May and 26th June 2023.

A selection process was applied to identify relevant review studies that served as the primary material for the review. The selection process involved assessing each study's title, abstract, and relevance to the topic. The focus was on comprehensive reviews that addressed various impacts and thoroughly analysed the relationship between climate change and renewable and affordable energy.

In addition to the methods described above, when relevant review studies were identified, their reference lists were also examined to find additional pertinent studies. This approach, often referred to as "snowballing," allowed for the identification of studies that specifically investigated the impacts of climate change under scenarios of global warming up to 2 °C.

Upon finalizing the selection of studies, an in-depth review of each paper was conducted using NVivo software. This qualitative data analysis tool was used to code relevant text that discussed the impacts of climate change on renewable and affordable energy. This approach allowed for systematic data extraction and ensured all pertinent information was captured. The coded text was analysed to draw out significant themes from the literature.

Table 18. Search terms used for the rapid scoping review to examine the impacts of climate change on renewable and affordable energy.

Search term 1: “climate change"

Search term 2: “impacts” OR “projections” OR “scenarios”

Search term 3 (by section header):

- Thermal and nuclear power plants: "thermal energy" OR "thermal power"
- Hydropower: “hydropower” OR “hydroelectricity” OR “hydro”
- Wind power: "wind power" OR "wind energy" OR "wind resource" OR "wind resources" OR "wind farm" OR "offshore wind" OR "onshore wind" OR "wind turbine" OR "wind turbines"
- Solar power: "solar power" OR "solar energy"
- Energy system resilience: "electricity infrastructure" OR "energy infrastructure" OR "electricity transmission" OR "energy transmission" OR "electricity distribution" OR "energy distribution" OR "electricity stability" OR "energy stability" OR "electricity storage" OR "energy storage" OR "energy system collapse" OR "electricity system collapse" OR "energy supply" OR "energy demand" OR "electricity supply" OR "electricity demand" OR "energy system resilience" OR "energy system risk" OR "energy system vulnerability"
- Energy access and affordability: "access to electricity" OR "energy access" OR "universal access" OR "without access" OR "access deficit" OR "access gap" OR "energy insecurity" OR "energy poverty" OR "fuel poverty" OR "energy affordability" OR "thermal comfort"
- Clean cooking fuels and technologies: "clean fuels and technologies for cooking" OR "access to clean cooking" OR "clean cooking"

7.2 Fossil fuel and biomass consumption

Energy pathways from a range of global and national integrated assessment models have shown that fossil fuel use must be heavily curtailed to meet the Paris goals (IPCC, 2022c). The VHO and NO pathways from TIAM-UCL are typical. Figure 27 shows that substantial reductions are required in both pathways over the century in order to achieve a global temperature rise of no more than 1.5 °C in 2100. Yet the transition in the two pathways is quite different.

To avoid overshooting, fossil fuel use is reduced by 20%, and coal use by 60%, in the NO pathway from 2020 to 2030, and then there are further steady reductions over the following decades. In contrast, the VHO pathway has slightly increasing fossil fuel to 2040, as higher energy demands are partly met by increased natural gas consumption, before very steep reductions after 2060 beyond what is required for the NO pathway to bring the global temperature rise back to 1.5 °C. It is not clear whether such steep reductions would be politically and technically feasible in practice. The continued high fossil fuel use in the period to 2050 would have a substantial impact on air quality, as discussed in Section 6.3.

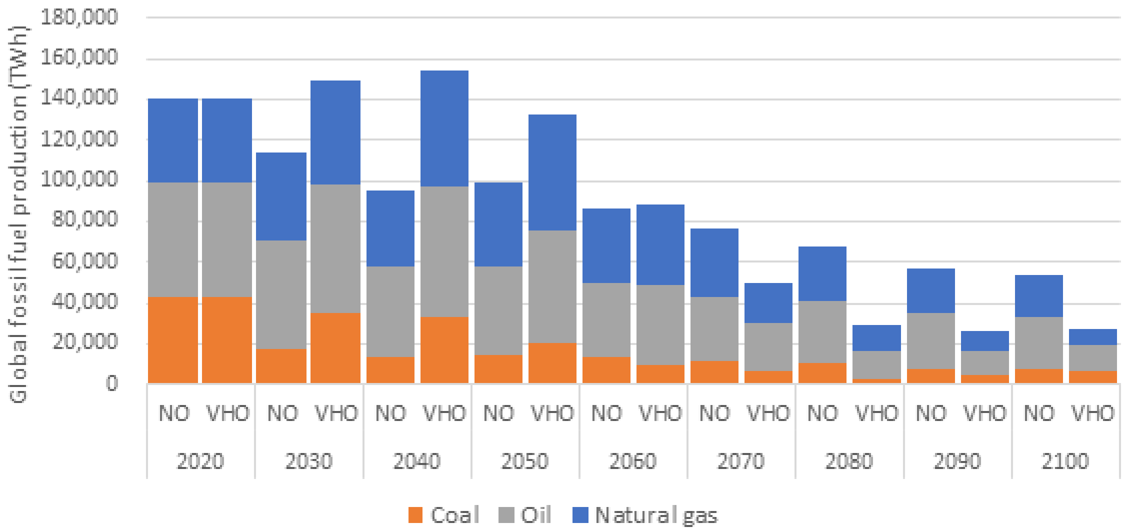


Figure 26. Global fossil fuel production in the NO and VHO scenarios from the TIAM-UCL model

Both of the TIAM-UCL scenarios have substantial deployments of carbon dioxide removal (CDR) technologies. These are discussed in detail in Annex 2 of this study, where the feasibility of achieving the required deployment rates in the VHO scenario in particular is questioned. In particular, the availability and sustainability of the substantial amounts of biomass required in the energy system of both pathways for CDR are discussed in Annex 2 so are not considered further here.

A small number of NO pathways using little CDR have been identified in the IPCC AR6 scenarios database (Byers *et al.*, 2022), but these require very steep cuts in fossil fuel use of 6% per year to 2030 and a much higher rate of electrification of the economy. Hence the NO and VHO pathways from TIAM-UCL should be considered examples of potential pathways rather than targets.

7.3 Rate of energy system electrification

Electrifying heat, transport and industry is a key strategy to reduce fossil fuel use, so decarbonising later in the VHO pathway would be expected to lead to lower rates of near-term electrification. Figure 28a shows that electrification is much higher for the NO pathway in the period to 2050, particularly in industry, than for the VHO pathway.

Electrification of the economy is a key contributor to SDG7.3 (“By 2030, double the global rate of improvement in energy efficiency”). Figure 28b shows that electricity consumption is substantially higher in Africa in the period to 2050 in the NO pathway, particularly in the residential and industry sectors. However, the model is not able to show whether this represents an increase in consumption for populations that already have access to electricity, or an increase in access to electricity (SDG7.1), or both. Despite increased electrification in a NO scenario, electrification of the economy in Africa is projected to be slower than in other regions (Figure 29) due to the high cost of capital and the lack of existing capacity to scale up the low-carbon electricity industry. Early and rapid action on electrification of the economy in most world regions is required to avoid an overshoot, and this would make a substantial contribution to increasing energy efficiency (SDG7.3).

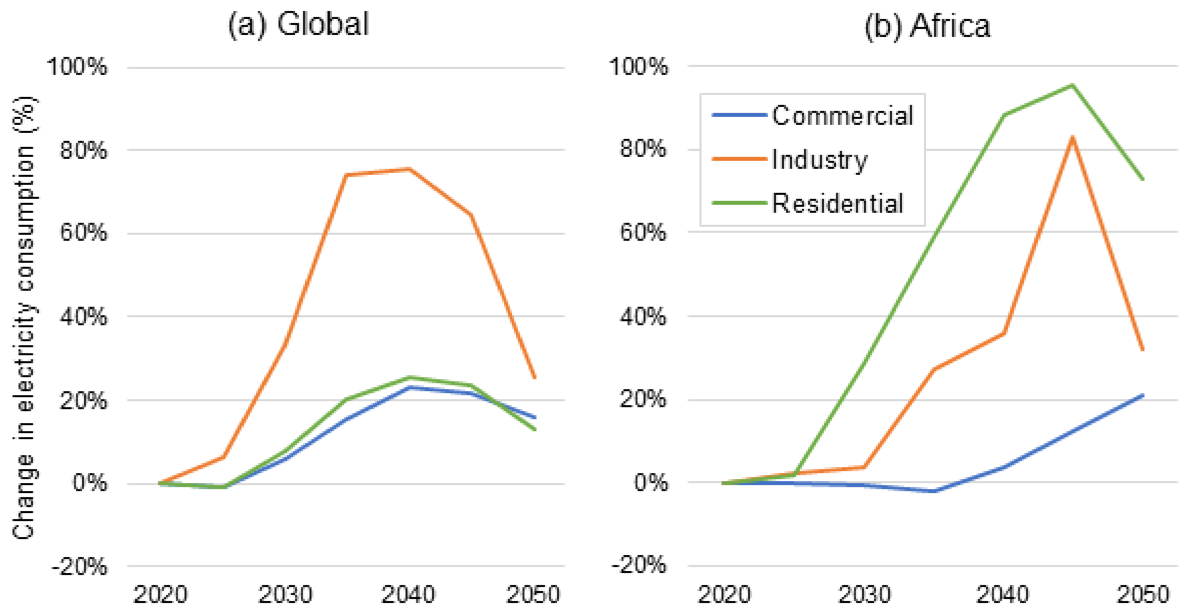


Figure 27. Change in electricity use in end-use sectors in the NO pathway compared to the VHO pathway, from the TIAM-UCL model. (a) shows global changes and (b) shows changes in Africa. “Commercial” represents commercial and public sector buildings, but not industry

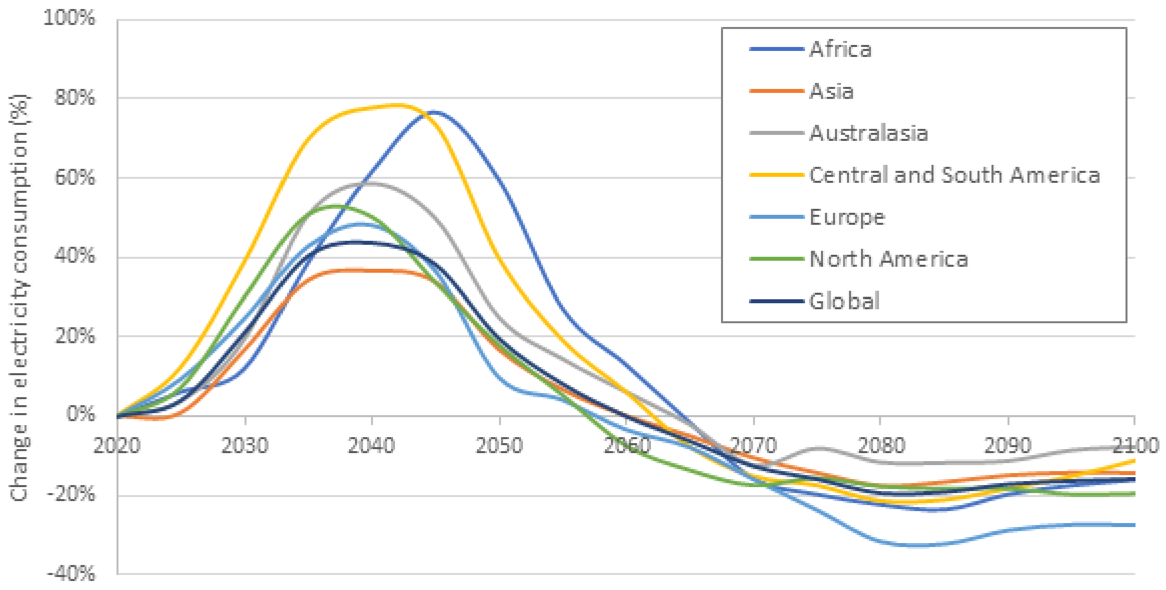


Figure 28. Change in electricity consumption in world regions in the NO pathway compared to the VHO pathway.

7.4 Rate of renewable deployment

SDG7.2 aims to increase substantially the share of renewable energy in the global energy mix by 2030. In the NO and VHO pathways, wind and solar generation make substantial contributions to decarbonising the global electricity supply and increasing electrification of the global economy. Figure 30 shows that wind and solar generation are scaled-up rapidly in the NO scenario in the period to 2060, but more slowly in the VHO pathway. After 2060, however, the need for further electrification of the economy and additional demands for CDR (for DACCS) causes the VHO pathway to use much higher deployments of renewable generation than is necessary for the NO scenario. This contributes to the higher cost of the VHO scenario after 2050 (Annex 3 of this study) and potentially reduces the deliverability of this pathway.

Models such as TIAM-UCL tend to implicitly assume that climate change will not affect electricity generation plants. Yet thermal and nuclear power stations require substantial quantities of water for cooling, hydropower is dependent on precipitation and evaporation rates, and wind and solar generation are weather-dependent, as is biomass growth and decay.

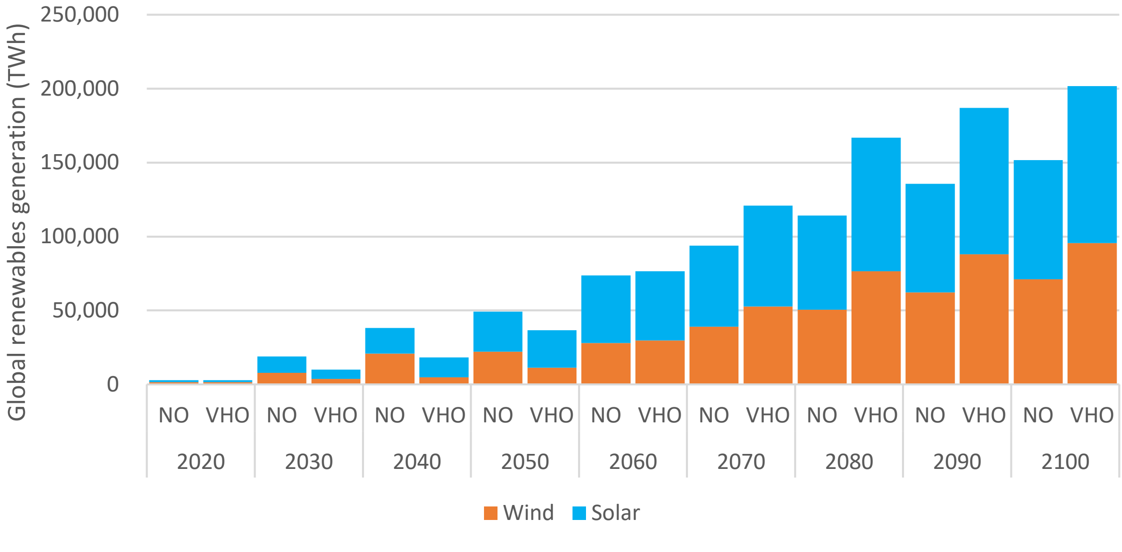


Figure 29. Global renewable generation in the NO and VHO pathways from wind and solar PV.

7.5 Impacts of overshoot on electricity generation

Numerous studies have focused on the impacts of high levels of climate change on renewable energy. Substantially fewer studies have examined the impacts when limiting climate change below 2 °C. An exception is Gernaat *et al.* (2021), who used four General Circulation Models (GCMs) to evaluate the impact of climate change on global renewable energy potential, comparing the RCP2.6 and RCP6.0 scenarios. They found that under the RCP2.6 scenario, which assumes lower levels of climate change, the impacts on renewable energy potential are less than under the RCP6.0 scenario. However, the energy system effects under both scenarios are comparable due to the larger share of renewables in the total energy system under RCP2.6, making it more susceptible to small climatic changes. They caution that the results for solar PV, wind energy, and hydropower under the RCP2.6 scenario remain uncertain.

Here we review the evidence for the effects of climate change under low warming-scenarios for thermal and nuclear plants, hydro, wind and solar power, energy system resilience, access to, and affordability of, energy. Biomass production is examined in detail in Annex 2 so is not reviewed here.

7.5.1 Thermal and nuclear power plants

Some thermal and nuclear power plants use seawater, but many rely on river water abstractions. They require large quantities of water at a sufficiently low temperature. Temperature is important as returning water (discharges) from power plants heat the river water locally and many aquatic organisms perish if the river temperature exceeds certain thresholds.

A global temperature rise of 2 °C could significantly impact thermal energy production in Europe. Tobin *et al.* (2018) concluded that thermoelectric power plants, which rely on river water for cooling, are expected to experience negative changes in power generation across all European countries. The magnitude of these changes could be three times greater than those for wind and solar PV generation because wind and PV technologies do not require cool water or air for cooling. Furthermore, the impacts of global warming on thermoelectric power generation are more severe in Southern Europe than in Northern Europe, leading to disparities among European Union countries.

Emodi *et al.* (2019) conclude that thermal power plants in most regions may experience a decline in capacity factor due to global warming, which will decrease the availability of cooling water for thermal plant operation. Changes in precipitation patterns and glacier melt due to climate change could lead to either a shortfall in power output due to reduced precipitation or increased power production due to glacier melt.

On a global scale, under the RCP2.6 scenario, the annual capacity of thermoelectric power plants is projected to reduce by 7% in the 2050s, compared to only 1.2% for hydropower plants (van Vliet *et al.*, 2016b). These reductions are primarily due to constraints in the availability and temperatures of water resources required for cooling thermoelectric power plants. These findings underscore the potential challenges that climate change could pose to the sustainability of thermal energy production.

7.5.2 Hydropower

Several studies have examined the impacts of climate change on hydropower under the RCP2.6 scenario, which represents a future where global warming is limited to 1.5–2 °C above pre-industrial levels. In India, Ali *et al.* (2018) project that all hydropower projects will experience a warmer and wetter climate, leading to increased precipitation, streamflow, and hydropower production. However, significant warming could result in a decline in streamflow and hydropower production in May-June for snowmelt-dominated projects. In China, the impact of climate change on hydropower generation under the RCP2.6 scenario is significant, especially in the southern regions, indicating that hydropower in the south of China has higher sensitivity to climate fluctuation than that in the north (Fan *et al.*, 2020). Globally, van Vliet *et al.* (2016a) expect gross hydropower potential to increase by 2.4% for the 2080s compared to 1971–2000, with the most substantial increases expected for Central Africa, India, Central Asia, and the northern high-latitudes. In Germany, RCP2.6 could lead to an overall reduction in hydropower potential, especially in many areas of Northern Germany, but never greater than 20%, with minor changes and no clear trend in production expected (Koch *et al.*, 2015).

7.5.3 Wind power

A growing body of evidence underscores the significant role of wind power in Europe's energy transition. Climate change could potentially enhance wind resources in some regions. However, our understanding of how climate change affects wind power in other parts of the world still needs to be improved. Notably, there are substantial knowledge gaps in wind power studies in Australia and Africa (Russo *et al.*, 2022). These regions, with their diverse climatic conditions and unique geographical features, should be a focus of future studies where wind power is planned to be widely deployed.

If global warming does not exceed 1.5 °C, noticeable changes in wind power generation potential are projected for Europe, with an increase in wind speed of around 4 m/s, particularly over Germany and over and downwind of Scotland (Hosking *et al.*, 2018). The most significant load factor, a measure of the actual output of a turbine compared to its maximum potential output, is generally seen in winter, with values exceeding 20% over the onshore area of the UK (Hosking *et al.*, 2018). Based on a review of 75 scientific studies examining projected wind resource changes due to anthropogenic climate change, Jung and Schindler (2022) conclude that the impacts of climate change on wind patterns, and consequently on wind energy generation, are predicted to be highly heterogeneous across both different geographical regions and different climate change scenarios (Ruffato-Ferreira *et al.*, 2017). Wind speeds are expected to increase in some areas and decrease in others, leading to a spatially-varied impact on wind energy potential (Bonjean Stanton *et al.*, 2016, Jung and Schindler, 2022). For example, for RCP1.9, the wind energy potential in Europe is projected to increase, especially in the Northern and Eastern parts. However, Southern Europe may experience a decrease in wind energy potential. In contrast, for RCP 2.6, the wind energy potential in Europe is expected to decrease, particularly in the Northern and Western parts. In contrast, an increase in wind energy potential is projected for Southern Europe. This geographical disparity could lead to an imbalance among countries in terms of the effects of climate change on wind power generation.

On a global scale, Lei *et al.* (2023) compared the SSP2-4.5 climate change scenario, which overshoots 2 °C, with a carbon-neutral scenario similar to SSP1-1.9, which aligns with not overshooting 1.5 °C. By 2040–2049, the SSP2-4.5 scenario predicts an increase in wind power in the tropics and southern subtropics but a decrease in the northern mid-high latitudes. However, under the carbon-neutral scenario, the pattern of wind power change shifts, particularly enhancing wind power in Asia, with Eastern China increasing from 2% under SSP2-4.5 to 5% under the carbon-neutral scenario. Conversely, the wind power increase in West Africa is 6% under SSP2-4.5 but only 3% in the carbon-neutral scenario. Furthermore, according to Lei *et al.* (2023), the carbon-neutral scenario improves the temporal stability of wind power in most studied regions, including the Eastern United States, Western Europe, India, and Eastern China, compared to the SSP2-4.5 scenario, which predicts less stability in Eastern United States and India but greater stability in Western Africa and Eastern China. These findings highlight the potential benefits of global carbon-neutral policies for the stability of renewable generation.

7.5.4 Solar power

Solar power is less studied than other forms of renewable energy concerning the impacts of climate change, despite it being the second most selected renewable energy source in decarbonisation strategies (Russo *et al.*, 2022). Solar production increases with fewer clouds and less atmospheric aerosol (Danso *et al.*, 2022). Reducing fossil fuel combustion will reduce atmospheric pollution and hence reduce atmospheric aerosol (Section 6.3). On the other hand, global warming will increase the water content of the atmosphere so could increase cloudiness. Geoengineering initiatives to cool the planet, for example by injecting sulphur into the stratosphere, could also reduce incoming solar radiation (Bednarz *et al.*, 2023).

Hou *et al.* (2021) focused on the impacts in Europe under SSP1-2.6. They projected an increase in solar PV capacity factors in continental Europe, with a substantial increase in central Europe in summer and the most substantial overall increase in PV electricity generation around the Mediterranean in winter. This mitigation scenario is projected to improve the climatic conditions for PV, leading to approximately 5% more power generation than today.

On a global scale, Lei *et al.* (2023) compared an SSP2-4.5 scenario that overshoots 2 °C with a carbon-neutral scenario similar to SSP1-1.9 (Lamboll *et al.*, 2021). Lei *et al.* (2023) report that under the carbon-neutral scenario, compared to the SSP2-4.5 scenario, solar PV potential is projected to increase in Eastern China, return to historical levels in India and Western Africa, and increase slightly Eastern United States and Western Europe. They explain that this enhancement is primarily driven by increased surface downwelling shortwave radiation, not temperature, particularly in Asia. The authors also report that the reduction in aerosol optical depth resulting from decarbonisation improving air quality in carbon-neutral scenarios contributes to increased solar PV potential. Moreover, they report that the temporal variability of solar PV potential is expected to decrease under carbon-neutral scenarios in most regions, improving the reliability of this renewable energy source. Lei *et al.* (2023) conclude that strong mitigation policies that aim to limit global warming to below 2 °C could enhance solar power generation and improve its reliability and stability.

High ambient temperatures can adversely affect the performance and lifespan of solar panels. As temperatures rise above 25 °C, the efficiency of solar panels decreases by approximately 0.5% per degree, leading to a potential reduction in optimal efficiency on particularly hot days when demand for cooling peaks (Skoplaki and Palyvos, 2009). Furthermore, elevated temperatures can accelerate the degradation of solar panels, shortening their effective lifespan. However, these impacts can be mitigated through proper installation and maintenance, such as ensuring adequate ventilation and using materials designed to withstand elevated temperatures. As global temperatures rise due to climate change, these findings underscore the importance of considering temperature effects in the design, installation, and maintenance of solar energy systems.

7.6 Energy system resilience

Climate change will impact energy transmission, demand, infrastructure, and generation capacity, even if global warming does not exceed 2 °C. However, the effects tend to be less severe than scenarios with higher temperature rises. A review by Craig *et al.* (2018) of climate change impacts on the USA power system cites Chester *et al.* (2015) who estimate that average summertime transmission line capacity could reduce across the U.S. by 2% under RCP2.6 by mid-century, with the Midwest seeing the most significant reductions. Craig *et al.* (2018) also cite Larsen *et al.* (2017), who estimate that energy generation in the USA will need to increase by 1% by mid-century to satisfy growing energy demand caused by warming air temperatures under RCP2.6. Bartos *et al.* (2016) found that under IPCC scenario B1 (a low global emissions scenario), by mid-century (2040–2060), climate change may reduce average summertime electricity generating capacity by 1 GW, with potentially disruptive impacts occurring in California and the desert Southwest. Ryan *et al.* (2016) investigated the effects of climate change on power distribution pole networks between 2015 and 2070 across five Australian cities. They estimate that the number of electricity distribution pole failures caused by wind will increase from 9,500 under no climate change to 12,300 under IPCC scenario B1. The observed increase in wind failure rates is due to advanced decay of poles and increased wind speed. These studies collectively highlight climate change's significant and varied impacts on various aspects of the energy sector, underscoring the need for proactive adaptation and mitigation strategies.

7.7 Energy access and affordability

SDG 7.1 aims to ensure universal access to affordable, reliable, and modern energy services by 2030. The latest "Tracking SDG7: The Energy Progress Report" (IEA *et al.*, 2023) estimates that there are 675 million people who lack access to electricity in 2021 and a further 2.3 billion people without access to clean cooking fuels and technologies. While progress is being made, the current pace is slow to meet this Target.

Few studies explicitly project the impacts on access to modern energy services of global warming up to 2 °C degrees of change. Dagnachew *et al.* (2018) analysed the trade-offs and synergies between achieving universal electricity access and climate change mitigation in Sub-Saharan Africa. The study found that climate change mitigation policies could negatively impact energy access by increasing energy prices. However, efficiency improvements from global climate policy (i.e. SDG 7.2) could offset the additional electricity generation needed to achieve universal access. The study also found that climate policy could stimulate the expansion of renewable off-grid systems, leading to 10 million more people connected via off-grid systems under a scenario that combines a target of universal access with a global climate policy that aims to limit global warming to 2 °C above pre-industrial levels, in comparison to a scenario that achieves universal access in the absence of any international climate policy.

A comprehensive review by Jessel *et al.* (2019), which examined over 100 scientific studies, explores the relationship between energy affordability and climate change. They concluded that climate change exacerbates both direct and indirect health impacts of energy insecurity, defined as the "inability to meet household energy needs adequately". Jessel *et al.* (2019) found that climate change can worsen fuel shortages, indirectly affecting health by increasing fuel costs and making energy sources unaffordable and inaccessible.

The study highlights several health consequences of energy inaccessibility, including increased rates of infectious diseases, hygiene-related illnesses, and pneumonia. As climate change intensifies, it strains energy systems, causing power outages and interruptions in energy services. Extreme weather events, such as polar vortices, can be particularly problematic, leading to power outages and even deaths from hypothermia.

Jessel *et al.* (2019) emphasise that as energy becomes more expensive and the wealth gap widens in the USA, poorer households will struggle to afford adequate household energy. The proportion of income spent on energy bills could increasingly differ between wealthy and low-income families. The study also notes that climate change-related energy insecurity could affect anyone, regardless of socioeconomic status, as severe weather events, such as power outages, can lead to acute energy insecurity, and more frequent heatwaves can significantly increase energy demand.

The study suggests that energy insecurity, especially acute, may become more widespread as climate change worsens. Despite these findings, Jessel *et al.* (2019) identify a significant gap in the literature: only a third of the sources reviewed address energy insecurity. This finding indicates a need for further research on the impacts of climate change on energy vulnerability.

7.8 Clean cooking fuels and technologies

Only a few studies investigate the impacts of climate change for up to a 2 °C temperature rise on access to clean cooking fuels and technologies (e.g. Dagnachew *et al.*, 2018, Pachauri *et al.*, 2021). The studies generally indicate that climate change and climate mitigation policies could significantly impact the achievement of universal access to clean cooking fuels. By exacerbating economic and social challenges, climate change could indirectly hinder efforts to achieve universal access to clean cooking, potentially leaving up to 820 million people in Sub-Saharan Africa reliant on traditional biomass cookstoves by

2030 (Dagnachew *et al.*, 2020). Climate mitigation policies, while necessary for global warming targets, could inadvertently slow the transition from traditional biomass to modern fuels for cooking and heating by increasing energy prices (Dagnachew *et al.*, 2018). However, these policies could also stimulate efficiency improvements and the expansion of renewable off-grid systems, offsetting some of the additional electricity generation needed for universal access.

Despite these potential benefits, the SDG 7 Target of universal clean cooking access by 2030 could remain out of reach under an ambitious climate mitigation policy scenario, particularly affecting low-income households in Africa, developing Asia, and Latin America (Pachauri *et al.*, 2021). Pachauri *et al.* (2021) also suggest that the aftermath of the COVID-19 pandemic could push many people back into extreme poverty, making cleaner burning cooking fuels more expensive and out of reach for many. In South Asia, the urban poor could be particularly affected by rising gas prices under climate mitigation policy scenarios, with dependency on solid fuels for this group almost doubling. Directing green and climate funds and revenues from carbon pricing to the clean cooking sector could be a strategy to increase financing to this sector. That study also suggests that recent technological advances and new payment and financing models could help clean cooking services reach even low-income households. However, this would require considerable investment, capacity, and commitment to upscaling.

Dagnachew *et al.* (2020) further highlight that unless radical improvements are made concerning the affordability and efficiency of clean cooking technologies, as well as an exceptionally rapid installation of modern fuel infrastructure, traditional biomass (firewood and charcoal) will have a significant share (67% in their scenario) in the cooking energy mix for decades to come. Improved and advanced biomass cookstoves could play an essential role as interim solutions in the transition, especially in rural areas.

These findings underscore the need for coordinated actions, enabling policies, scaled-up finance, and the integration of energy access programs with climate mitigation and environmental programs.

7.9 Summary

To avoid overshooting, fossil fuel use would need to reduce by 20%, and coal use by 60%, in the NO pathway from 2020 to 2030, and then further steady reductions would be required over following decades. Electrification of many processes in industry, buildings and transport would be necessary, powered by a massive expansion of renewable generation.

Overshooting could reduce production from thermal and nuclear power plants by 7% in 2050 due to warmer river temperatures. Changes in hydropower potential would vary across the world according to changes in precipitation in an overshoot, but the aggregated global hydropower potential would be similar. Changes in wind power speeds are expected to vary between regions and to change within regions as global temperature continues to increase. Solar PV generation would reduce due to slower reductions of fossil fuel use, greater cloud cover and higher temperatures. Overshooting would also reduce transmission capacity in summer and could increase distribution infrastructure failure due to faster pole decay and more intense storms.

Climate change, including overshoot, is projected to increase energy insecurity worldwide. It could also indirectly hinder efforts to achieve universal access to clean cooking.

8. Climate impacts on poverty and migration

SDGs 1 and 10 have targets to reduce poverty and inequality, respectively. The range of climate change impacts reviewed in the previous chapters are expected to affect poorer people and poorer countries more than richer people and countries. This means that climate change is likely to increase poverty and inequality. Section 8.1 examines the potential impacts of overshoot on poverty and inequality.

One potential consequence of changing and more variable weather is climate-related migration. However, it is very difficult to attribute migration to climate change as there are a range of other social drivers, and it is even more difficult to project how migration might change in the future with climate change. Section 8.2 reviews the evidence.

8.1 Climate impacts on poverty

The most recent global estimates from the World Bank are that 701 million people remained in extreme poverty in 2019 (World Bank, 2024). It is estimated that 70 million people worldwide were pushed to extreme poverty during the COVID-19 pandemic (World Bank, 2021b). Moreover, the recovery from the pandemic has been uneven, in favour of the richest economies who recovered at a faster speed than the middle- and low-income economies, increasing global inequality as measured by the Gini index (World Bank, 2021a) to around 0.63 in 2020.[9] The subsequent rise in energy and food prices, triggered by conflict and climate shocks, has intensified the post-pandemic recovery challenges and amplified poverty crises globally (World Bank, 2021b).

Climate change is expected to pose an additional burden to poverty reduction efforts worldwide. Vulnerable communities, particularly those in low-income countries will bear most of its effects, exacerbating existing inequalities. Climate change will significantly affect vulnerable populations in diverse ways. Intensified extreme weather events can disrupt livelihoods and damage infrastructure in low-income regions. Crop failures, water scarcity or floods, and reduced agricultural yields will impact rural communities and increase food prices. Health risks may escalate due to changing disease patterns and heat stress. Moreover, displacement from agricultural areas and those affected by rising sea levels could put pressure on urban systems, creating instability (IPCC, 2022b).

In this section, we explore the implication of the VHO and the NO pathways on global income distribution and poverty levels. We do not attempt to measure the resulting income distribution and poverty levels due to climate change impacts based on these pathways. Instead, our focus is on understanding the anticipated evolution of income distribution and poverty levels behind the economic development in both the VHO and NO pathways. Our analysis focuses on the demographic and economic development inherent to these pathways.

[9] The Gini index (or coefficient) is statistical metric that represents income inequality. A value of 0 represents perfect equality, while 1 represents absolute inequality (where a single individual has all income).

8.1.1 Overview of the GlobPov model

We use the global income distribution and poverty module (Calzadilla, 2010), which we call GlobPov. GlobPov is based on the methodology and database used by PovcalNet, which, in 2022, was replaced by the Poverty and Inequality Platform (PIP) (World Bank, 2024). PIP is an interactive computational tool that offers users quick access to the World Bank's estimates of poverty, inequality, and shared prosperity. PIP provides a comprehensive view of global, regional, and country-level trends for more than 160 economies around the world. PovcalNet and PIP allow the replication of the calculations made by World Bank researchers for estimating the magnitude of absolute poverty in the world. They also enable estimations of various poverty and inequality measures under different assumptions and using alternative country groupings.

GlobPov uses survey data in grouped form from PIP to estimate the parametric specifications of the underlying Lorenz curve using the same functional forms that are used in PIP. Once the Lorenz curves for each country have been estimated, the principal inputs to compute the poverty measures are the poverty line, the mean income/consumption and the population.

The main outputs from the GlobPov module (Calzadilla, 2010) are the Gini index, the number of poor people, the headcount index of poverty,[10] the poverty gap index, the squared poverty gap index and the elasticities of these poverty measures with respect to the mean of the distribution and the Gini index. Additionally, GlobPov represents graphically the Lorenz curve,[11] the income distribution function and the cumulative distribution function for each country as well as regional and global figures. GlobPov provides poverty and inequality indicators for 167 countries.

8.1.2 Modelling approach

To replicate the poverty estimates made by the World Bank in 2019, we use the new international poverty line set to \$2.25 a day (equivalent to \$68 per month) and the monthly

[10] The headcount index of poverty is the share of the population whose income is below the poverty line.

[11] Lorenz curves are a graphical representation of income inequality, plotting the fraction of income against the fraction of households.

average income/consumption per capita from the surveys expressed in 2017 PPP terms. PPP rates account for differences in domestic prices, enabling a comparison of international welfare. We use population numbers from PIP.

The projections of poverty and income distribution to the year 2050 are based on the economic growth and population behind the VHO and NO pathways that were developed using the ENGAGE model in Annex 3 of this study. The regional population and GDP per capita growth are used to update each country's income distribution function, while keeping fixed the poverty line. In this process, we make two important assumptions:

1. The survey-based real private income/consumption per capita in each country will grow at the same rate as the real GDP per capita.
2. The Lorenz curve for each individual country does not change. That is, economic growth is distributionally-neutral, keeping within-country inequality constant.

To exclude the effects of inflation, constant prices are used for calculating growth rates.

These two assumptions are limitations of this analysis, as the influence of economic growth on global poverty and inequality ultimately depends on how the income is distributed across the population and how this distribution changes over time. Another limitation of this analysis lies in its narrow focus on poverty changes driven solely by variations in real GDP per capita and population growth. We do not consider the impact of targeted policies aimed at poverty alleviation or equitable income distribution. For instance, the strategy of governments employing overshoot as a means to postpone mitigation efforts while prioritizing other socioeconomic goals, such as poverty alleviation, remains unexplored in this analysis.

8.1.3 Insights

Our results suggest that the number of people living in extreme poverty is expected to decline to around 130–160 million in 2050 (Figure 31). The average annual rate of decline for the 2020–2050 period is similar to the rate observed during the 2009–2019 period: 5% per year. As highlighted by the World Bank (2021b), the goal of ending extreme poverty by 2030 would not be achieved in this scenario. Efforts would be required to reduce inequality in the poorest countries to approach this target.

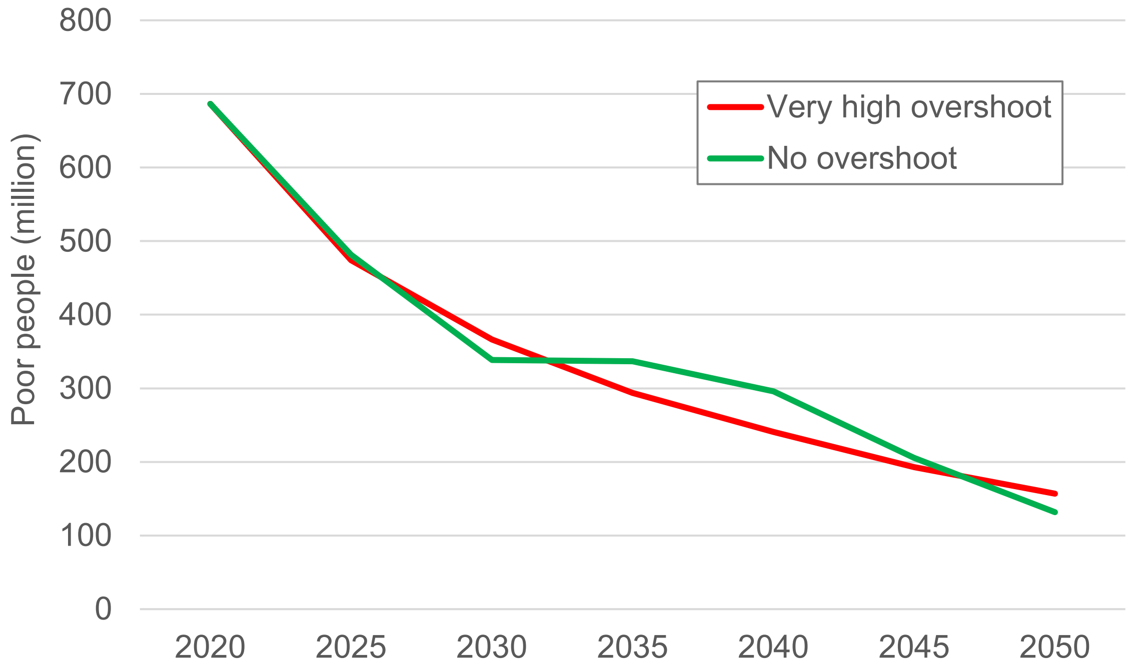


Figure 30. Number of people in extreme poverty by decarbonisation pathway.

Globally, the headcount index declines from 9.2% in 2020 to around 1.8% and 1.5% in 2050 for the VHO and NO pathways, respectively. Most of this decline is due to steady reduction in extreme poverty rates in Africa, the Middle East and India (Figure 32).

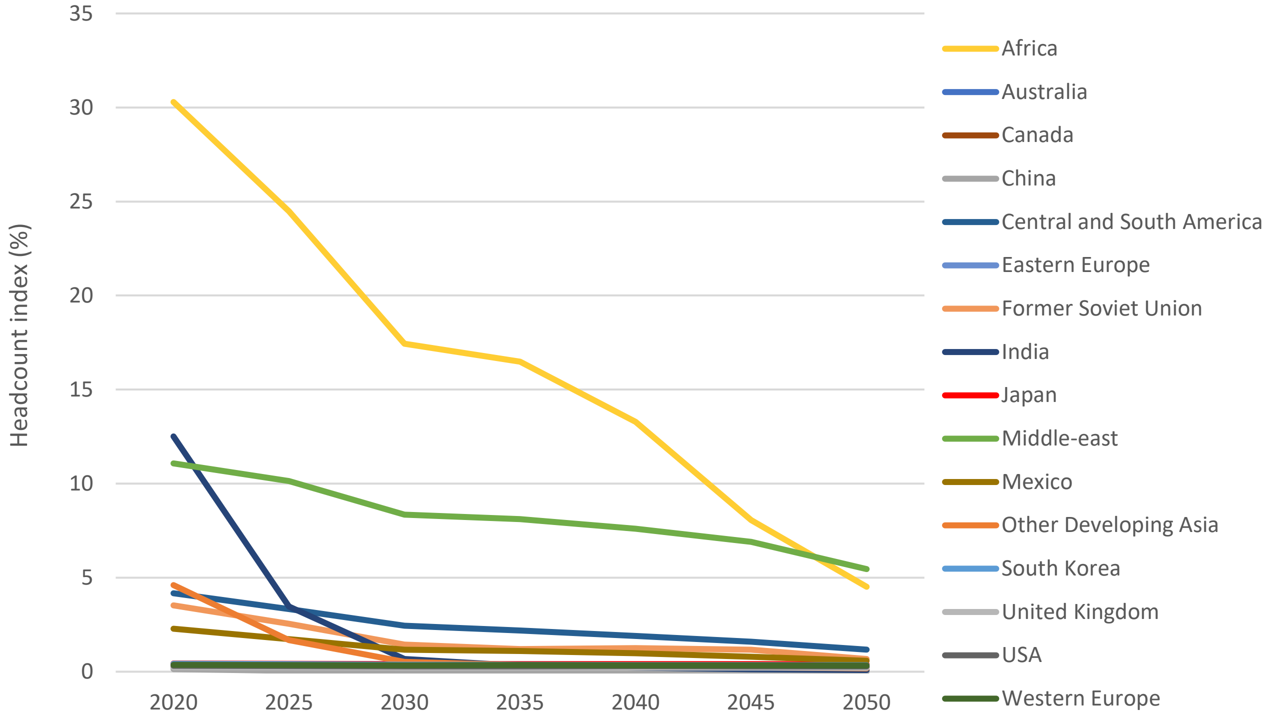


Figure 31. Headcount index of extreme poverty by region for the NO pathway.

The global poverty trajectories in Figure 31 align with projected economic development in the VHO and NO pathways. This means that more ambitious policy actions taken to achieve more stringent decarbonisation targets to avoid overshoot would result in higher global GDP and lower global poverty levels in 2050 in the NO pathway, while the VHO pathway has lower poverty levels in 2035–2040. But as the difference between the two pathways is so small compared with the total reduction in poverty, the principal insight is that both a NO and VHO pathway should lead to substantially lower poverty and following either pathway would make little difference to the final number of people in poverty.

Our modelling results suggests that an overshoot pathway might result in an additional 25 million people being pushed into extreme poverty by 2050 (Figure 33). The majority of these individuals are located in Africa. The dynamic economic trajectories of the VHO and NO pathways lead to both gains and losses in terms of poverty during the period from 2020–2050. Africa, India, Southeast Asia and the Middle East are the most vulnerable regions.

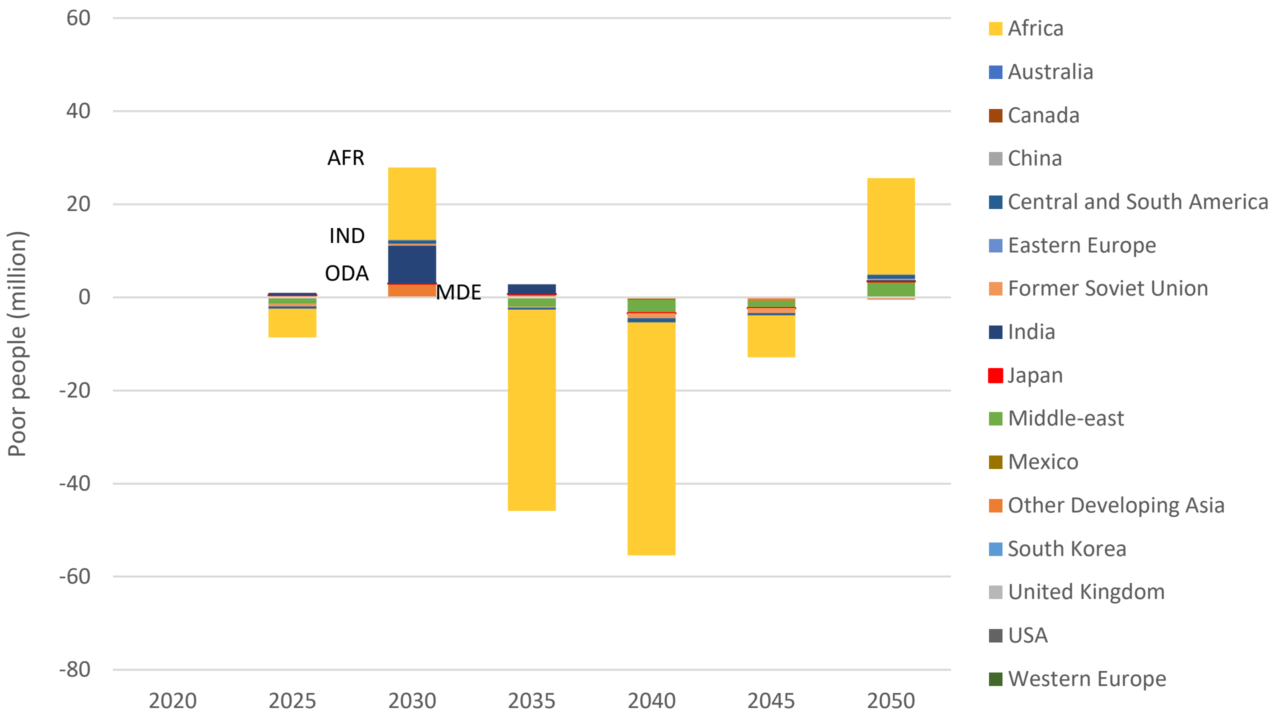


Figure 32. Change in the number of people under extreme poverty by region due to overshoot. The differences between the VHO and the NO pathways are shown.

Within Africa and the Middle East, Congo, Nigeria, Yemen, Madagascar, Mozambique, Tanzania and Malawi account for more than two-thirds of the additional 25 million people who could be pushed into extreme poverty by 2050 due to an overshoot pathway. All these countries, including Syria and Yemen, have high vulnerability to poverty associated with variations in economic growth.

8.2 Climate impacts on migration

Climate change has been recognised as an important driver for migration in the Agenda for Humanity and by the 2016 United Nations Summit for Refugees and Migrants, the Global Compact for Migration and the Global Compact on Refugees. SDG 10.7 has a target to "facilitate orderly, safe, and responsible migration and mobility of people, including through implementation of planned and well-managed migration policies".

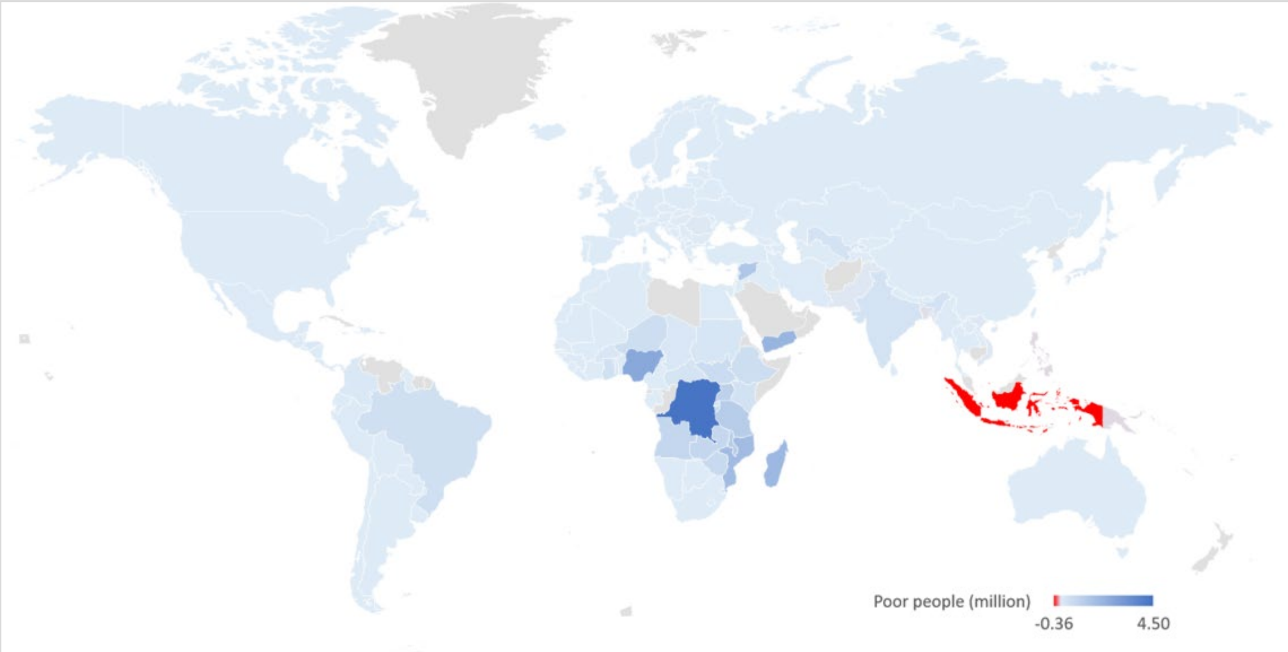


Figure 33. Change in the number of people under extreme poverty in 2050 due to overshoot. The differences between the VHO and the NO pathways are shown.

The global temperature rise of 1.1 °C by 2020 (IPCC, 2023) has been linked with a higher frequency of extreme events. The Internal Displacement Monitoring Centre (IDMC) (2022) estimates that 32.6 million people were displaced due to disasters in 2022. The impact of climate change on current and potential future migration has received international attention. In 2018, the World Bank estimated that three regions (Latin America, sub-Saharan Africa and Southeast Asia) would create 143 million more climate migrants by 2050, if no action were taken (World Bank, 2018a). Myers (2002) projected that 200 million people could migrate, based on populations being affected by sea level rise, flooding, storms, precipitation changes and droughts. However, confidence in projections of mobility flows is low due the complexity and range of causes that affect the decision to migrate (IPCC, 2014b). Nevertheless, Fussell *et al.* (2014) highlight the importance of identifying regularities in environment-migration relations to improve the development of future migration scenarios, which could be enhanced by global surveys of environmental change and migration. Kniveton *et al.* (2008) stress the need for interdisciplinary assessment (including fields of sociology, development studies, economics, geography, informatics and climate science) when studying climate change impact on migration and potential future flows.

It is important to understand the extent to which climate change contributes to current and future migration flows. There are many dimensions to examine for this assessment, such as how climate change may affect mobility via climate-related events and long-term climatic variability. Also, assessing the level of vulnerability among population groups is crucial in understanding the composition of migration flows. Heterogeneities across countries and regions are expected due to different exposure levels to climate change, but also different mitigation and adaptation strategies.

Selby and Daoust (2021) provide a comprehensive summary of findings on the impacts of climate change on migration flows and identify the key issues as climate-migration pathways, long-term climatic variability, environmental pull factors, adaptation and mitigation policies and a review of suggestions on estimates and projections. They highlight that climate-related shocks can be associated with both an increase and decrease in relocation, and movements tend to be mainly internal, but it is not clear if they are temporary or permanent. Populations' characteristics also affect migration flows; for example, young people in countries/regions which rely on agricultural production have a higher probability of migration after climate-related shocks. The role of adaptation, especially in the agricultural sector, is also highlighted, in terms of mitigating displacement pressures. According to this review, more evidence is needed to assess the impact of long-term climatic variability, and whether people tend to move to areas with preferable climatic conditions. Through an analysis of adaptation and mitigation, they conclude that policies related to flood, coastal and agricultural protection reduce migration pressures.

Selby and Daoust (2021) conclude in a review that there is not a robust global estimate for the number of people displaced due to climate change or a clear upward trend. There are forecasts for future migration caused by flood, weather fluctuations, sea-level rise and long-term warming, but not for environmental pull factors and adaptation or mitigation. However, projections vary significantly and are sensitive to assumptions about potential adaptation policy.

8.2.1 Principal drivers of migration

The intention to migrate due to environmental stress has several potential contributing factors. The International Organisation for Migration (IOM) (2022) proposes four drivers:

1. Migration at less advanced stages of gradual environmental change. During early stages of environmental degradation, farmers start to lose earnings and may move internally or internationally. This is often temporary movement.
2. Migration at advanced stages of gradual environmental change. Persistent environmental degradation leads to some business closures and loss of income. Previously temporary migration might need to become permanent but obstacles such as socioeconomic status can arise and make migration irregular.
3. Migration due to extreme environmental events such as natural or industrial disasters. Such events are not always related to climate change, but have been associated with tsunamis, earthquakes and floods.
4. Migration due to large-scale development and land conservation. This is often temporary displacement due to infrastructure works

Climate change and land degradation drivers of migration include elevated sea level causing coastal flooding, changes in storm and cyclone frequencies, changes in precipitation causing river flooding, fire, changes in agricultural productivity, increases in temperature and heat-related stress, and higher emission concentrations (Black *et al.*, 2011). The effects on agricultural productivity appear to be very important in relation to migration. Falco *et al.* (2019) empirically investigates this argument, using panel data of 100 countries from 1960 to 2010, and find that negative shocks to agricultural productivity related to climatic fluctuations significantly increase emigration from developing countries, with a strong impact in poor countries but lower impact in middle income countries.

8.2.2 Impact of climate shocks on migration

Climate-related extreme weather events have been associated with migration flows but there is mixed evidence in terms of the direction of this association. Such shocks tend to increase migration due to their negative impact on agricultural production and income. On the other hand, they tend to prevent migration flows due to constrained capabilities of households via reduction of resources. Floods, storms, droughts, and short-term temperature and precipitation fluctuations have been found to affect migration flows.

Evidence of the impacts of flood events are mixed. Countries in Africa appear vulnerable to floods and subsequent food-induced displacement, following Kakinuma *et al.* (2020). Hydrological disasters (floods and mass movement) are found to increase the rate of migration, based on panel data analysis which captures migration from developing countries to the main OECD destination countries (Drabo and Mbaye, 2015). On the other hand, floods are overall associated with reduced internal migration flows in Tanzania, based on survey data, which might be related to policies focusing on resilience (Ocello *et al.*, 2015). Similarly, Chen and Mueller (2019) show that Bangladeshi flows to neighbouring South Asian countries decline after flooding and precipitation-related events.

Storms**,** overall, seem to impose pressure on migration in the Bay of Bengal, but the impact on migration is mixed (Selby and Daoust, 2021). For the Philippines, one standard deviation increase in normalised death rates from typhoons is related to a 0.17% increase in outmigration, based on inter-provincial migration panel data (Bohra-Mishra *et al.*, 2017). Hurricane events are found to increase migration by about 6% based on a fixed effects panel regression of Central American and Caribbean countries from 1989 to 2005 (Spencer and Urquhart, 2018). On the other hand, Drabo and Mbaye (2015) concluded that overall migration has not been significantly affected by storms based on panel data analysis of developing countries from 1975 to 2000.

Many studies of droughts have focused on East Africa and Southeast Asia, and to a lesser extent Central America, the Caribbean and Southern Asia. Dallmann and Millock (2017) find 1.5% of interstate migration is due to drought frequency in India, based on panel data analysis. The event history study of Gray and Mueller (2012a) concludes that men's labour migration rate increases but women's short-distance and marriage-related movement decreases due to drought, which demonstrates how the impacts can vary according to population and social characteristics. Owain and Maslin (2018) suggest that climatic variability has had limited or no influence on movements in East Africa during the last 50 years, with population change, economic growth and political instability being the main contributing factors. However, they suggested that severe droughts were a contributing factor for international migration. Entwisle *et al.* (2020) concluded that droughts had minimal impact on out-migration in Northeast Thailand.

The effects of short-term temperature and precipitation changes on migration have attracted a lot of attention. Evidence is mixed in terms of the relationship between short-term temperature fluctuations and migration. An increase in temperature tends to increase permanent outmigration in a province-to-province based study in Indonesia (Bohra-Mishra *et al.*, 2014). Quantitative evidence from Pakistan also shows that heat stress tends to increase men's long-term migration driven by negative impacts on farm and non-farm income (Mueller *et al.*, 2014). At the global scale, Backhaus *et al.* (2015) suggest, on average, a positive relationship between temperature and migration based on panel data analysis for 142 countries from 1995 to 2006. They also identify a positive relationship between precipitation and migration, but with weaker impact compared to temperature. Using a panel data analysis from 1960 to 2000, Beine and Parsons (2017) conclude that climate variability affects individuals' financial constraints more than their preference to migrate. Nawrotzki and DeWaard (2018) stress the importance of heterogeneity in the relation between climatic variability and inter-district flows in Zambia due to varying levels of vulnerability. Issa *et al.* (2023) provide a comprehensive scoping review on the relationship between heat and migration. They conclude that most of studies find a negative impact of heat from heat stress, heat-related disease and premature mortality in migrants compared to non-migrants. They also find that heat may affect migration patterns in terms of the intention to migrate, risk during relocating, and effect of heat when migrants are settled.

Overall, the effects of temperature fluctuations appear to affect migration flows to a greater extent than precipitation fluctuations. Some studies show insignificant or inconsistent evidence regarding the association between precipitation and migration. Mueller *et al.* (2020) find that migration decreases with precipitation in Botswana and Kenya while it increases with precipitation in Zambia, based on census data for a 22-year period. Evidence shown by Gray and Wise (2016) suggests that precipitation has a weak and inconsistent relationship with migration in a study of Kenya, Uganda, Nigeria, Burkina Faso and Senegal.

8.2.3 Impact of climate shocks on the type of migration

Kaczan and Orgill-Meyer (2020) present evidence based on a review of studies that suggests that climate related events, such as floods, droughts and temperature extremes tend to be related more to long-distance internal migration than local or cross-border migration. Another review of studies from Hoffmann *et al.* (2020) concludes that the impact of weather fluctuations on migration is greater for internal flows than international ones. There is no clear pattern on the duration of migration after climatic shocks. The impact of weather fluctuations tends to be mainly temporary; for example, Etzold *et al.* (2014) conclude that labour migration in the Kurigram district of Bangladesh is mainly driven by precipitation-related seasonal hunger. Radel *et al.* (2018) also stress the importance of short-term migration when studying Nicaraguan data to examine the role of labour migration in smallholder production. On the other hand, some studies conclude that the impact of weather variability and weather extremes is related to long-term or permanent migration. These include Call and Gray (2020), who find that although short heat spells increase temporary migration from Ugandan households, long-term heat stress increases permanent migration via the impact on agricultural livelihoods. Similarly, Mueller *et al.* (2014) show that heat stress causes an increase in the long-term men's migration in Pakistan.

Another interesting dimension to examine is the extent to which migration flows depend on characteristics of the population. Younger people are more likely to relocate in response to climate change events. Baez *et al.* (2017) analyse census data from eight countries of Northern Latin America and the Caribbean and conclude that 35% of the sample who moved across provinces within each of the countries were from the youngest group (15–25) while just 9% of it were from the oldest group (56–65). Mastrorillo *et al.* (2016) examine inter-district bilateral migration flows during 1997–2001 and 2007–2011 in South Africa, conditioning on various characteristics including age. They find the strongest climatic variability impact on young migrants (15–30).

Several studies have found that poorer households are more likely to relocate in response to a range of weather events:

- Storms: Loebach and Korinek (2019) for Nicaragua after Hurricane Mitch.
- Floods: Gray and Mueller (2012b) for rural Bangladesh, stressing differences for women and poorer households.
- Drought: Gray and Mueller (2012b) for rural Ethiopian highlands
- Weather fluctuations: Gray and Bilsborrow (2013) for rural Ecuador.

On the contrary, after Hurricane Mitch, wealthier households were more likely to migrate than small business owners in Nicaragua (Loebach and Korinek, 2019).

Education and skills are also important factors. In a study of rural India, Sedova and Kalkuhl (2020) find climate migration primarily involves low-skilled workers who depend on agricultural production. Ocello *et al.* (2015) consider migration as a potential reaction to droughts and floods among individuals with no education, in a study of internal migration in Tanzania. On the other hand, Drabo and Mbaye (2015) show that floods and drought are related to increased migration to high-income destination countries among highly educated people. Xu *et al.* (2021) indicate that people of higher formal education are more likely to move from rural to urban areas after precipitation changes, while people of lower formal education tend to move from one rural area to another.

Occupation is another characteristic which has received significant attention in the literature. Households depending on agricultural production appear to be more affected by weather fluctuations than others in Bangladesh (Carrico and Donato, 2019) and rural India (Sedova and Kalkuhl, 2020). However, if farm households are attached to places and communities, then this attachment forms a barrier to migration after climatic shocks. This could explain why only 6.5% of rural coastal Bangladeshi people have migrated, mainly domestically and temporarily, in response to environmental stressors (Bernzen *et al.*, 2019).

8.2.4 Impact of long-term climatic and related changes

Long-term climatic and related changes, such as sea level rise, a steady rise in temperature and long-term precipitation decline, may affect migration decisions, but there is generally little evidence to conclude about these relationships.

For sea level rise, many studies focus on small island states, but their research questions do not generally specifically examine the effect of sea level rise on migration. For example, Shen and Gemenne (2011) qualitatively examine migration from Tuvalu to New Zealand. Chen and Mueller (2018) find that inundation from sea level rise is not significantly associated with migration but increases in soil salinity affect aquaculture and internal migration from coastal Bangladesh. Chun (2014) examines vulnerability and household responses to environmental stressors in the Mekong Delta of Vietnam.

On the subject of long-term temperature changes, Cattaneo and Peri (2016), by analysing data of 116 countries from 1960 to 2000, find warming trends could impact agricultural productivity and increase the likelihood of migrating internationally or from rural to urban areas.

Raoul (2015) studied the extent to which glacial melting significantly affects migration and find limited impact on existing patterns, based on interviews with representatives in the Bolivian Andes. Long-term declines in precipitation have been associated with internal migration in sub-Saharan Africa, following Barrios *et al.* (2006). However, Beine and Parsons (2015) find no direct impact of long-term climatic factors on international migration in a multi-country panel data analysis from 1960 to 2000.

8.2.5 Projections of migration flows

Developing rigorous projections for migration flows associated with climate change is challenging. One would need robust estimates that disentangle the effects of climate change on current displacement in order to project future displacement. This is challenging because migration has many drivers.

An IDMC report by Anzellini *et al.* (2021) forecasts 392,000 people per year being potentially affected by internal migration in the Middle East and North Africa due to flooding, mainly from urban to peri-urban places. The risk of internal migration appears very high, especially in low-income countries in sub-Saharan Africa, South and Southeast Asia, Oceania, and Latin America, for which an IDMC report by Ginnetti and Milano (2019) suggests double flows by 2090 under RCP2.6/SSP1 and fivefold flows under RCP6.0/SSP4. Kam *et al.* (2021) forecast that river flooding could increase movements by between 110% (under RCP2.6/SSP1) and 350% (RCP6.0/SSP4) by 2090, especially in Central and Eastern Africa, Polynesia and the Indus River basin.

Studies on weather fluctuations and projected migration have mainly focused on long-term warming. Feng *et al.* (2010b) project that 1.4–6.7 million people could move internationally from Mexico by 2080 in response to changes in agricultural productivity due to increased temperature. Along these lines, Marchiori *et al.* (2012) suggest that annual displacement in sub-Saharan Africa may increase by 11.8 million people by 2099, responding to temperature fluctuations, with the range of 4–18.5 million depending on the level of climate change. Iqbal and Roy (2015) suggest precipitation variability may cause a 20% increase in net internal migration in Bangladesh by 2030 compared to 1990 through reducing agricultural productivity.

Sea level rise has been associated with about 168 million people per year being exposed to flooding by 2100 (Hinkel *et al.*, 2013). The extent of displacement that could follow is not clear. Nicholls *et al.* (2011) project that 72–187 million people could move from small island regions in the Caribbean, Indian Ocean and Pacific in response to elevated sea level by 2099 (assuming a temperature rise of 4°C or more by 2100), but that adaptation strategies could reduce displacement to just 41,000–305,000 people.

Missirian and Schlenker (2017) examine the relation between temperature and asylum applications to the EU between 2000–2014 and show that long-term temperature increase induces a rise in applications by 188% under RCP8.5. Barbieri *et al.* (2010) project the internal movement of 500,000 people in Northeast Brazil between 2025 and 2050 for a temperature increase up to 4 °C until 2070, because of the warming impact on yields and employment. Another study for Brazil by Oliveira and Pereda (2020) suggests that around 1 million people may move internally between 2040 and 2070 due to the impact of warming on agricultural productivity and wages.

Projections of future precipitation under different levels of climate change tend to be more uncertain than projections of future temperature, which makes projections about migration caused by the precipitation even more uncertain. Defrance *et al.* (2017) examine the impact on agriculture of a significant decrease in West African monsoon rainfall, significant Greenland ice melt and sea level increase up to 3 m under RCP8.5. This could lead to 360 million people living below the water threshold for sorghum cultivation in the Sahel area by 2100 and underpin large-scale migration. The impact of changes in precipitation on future migration has been examined in combination with other long-term changes. The World Bank's Groundswell report (Rigaud *et al.*, 2018) combines the impact of water stress, falling crop yields and sea level rise, and suggests that by 2050, internal migration within Sub-Saharan Africa, South Asia and Latin America will be between 31 million (under RCP2.6) and 143 million people (under RCP8.5), with a tendency to increase after then.

8.2.6 Conclusions

There is compelling evidence that climate shocks contribute to migration. Many studies suggest that movements tend to be internal to countries and there is little evidence about the typical duration of migration. The extent of vulnerabilities among population groups has caused variations in migration flows from some areas but the quality of evidence is again low. It appears that younger people are more likely to migrate compared to older people, and that countries and regions that greatly depend on agriculture are more exposed to climate-related events and therefore their populations are more likely to migrate. Adaptation policies are considered important tools for reducing migration. We have not reviewed “pull” factors, particularly for international migration, so their influence is not clear. It is very difficult to project future migration flows caused by long-term climate change.

9. Conclusions

We have examined the potential human system impacts caused by temporarily overshooting 1.5 °C using a review of literature and a range of models and other analyses.

9.1 Water-related impacts

Coastal flooding affects food production through salination while disasters cause infrastructure and livelihood damage, and loss of tourism. Impacts of flooding will increase over the next century as sea levels rise. The rate of increase will be higher for overshoot pathways.

Terrestrial precipitation is projected to vary in complex ways with global warming. Overall precipitation is expected to rise in some regions and fall in others as the temperature rises, yet in some regions these changes could reverse if the temperature rises further. More intense storms, floods and droughts are expected that will affect agriculture, drinking water and sanitation. Even where moderate floods may reduce in magnitude, larger damaging events are likely to increase in magnitude. These will start to reduce in magnitude as the temperature is reduced.

Changing precipitation patterns and more intense droughts, floods and storms will affect water availability for irrigation, and hence groundwater consumption, and also the quality of human water supplies and sanitation. Wetter conditions in some areas will damage infrastructure, disrupt water and sanitation services and jeopardise water quality. Drought will affect water supplies and sanitation. It will be more difficult to achieve safe water and sanitation in areas with increasing extreme weather.

9.2 Impacts on food, health and energy

Overshooting 1.5 °C would have only a small impact on most cereal yields globally but interannual yield variability could increase. Lower yields in Asia could lead to slightly higher food prices and lower GDP. Changes in ocean temperature will cause a redistribution of consumer fish towards the poles, with a loss of biomass at the equator and to a lesser extent at the poles. The overall loss of biomass is likely to be small for the overshoot pathways but will be greater than for the NO pathway due to higher oceanic temperatures for an extended period.

Overshooting will increase the frequency and intensity of heatwaves, which is expected to increase heat-related mortality and morbidity. However, declines in population susceptibility due to physiological acclimatisation and additional cooling measures such as air conditioning may result in a lower-than-expected health burden in an overshoot. Such adaptations are not always considered in epidemiological models but are found in historical data. Higher levels of food insecurity in an overshoot would increase malnutrition and might increase the risks from heat exposure. The estimated loss of labour capacity, supply, and productivity in moderate outdoor work due to heat stress ranges from 2–14%, varying depending on the location and indicator, and would worsen in an overshoot. An overshoot would also expand the spread of many vector-borne diseases to more northerly latitudes, but could decrease incidence in areas where vectors are already endemic.

Mitigating greenhouse gas emissions in a NO pathway would reduce air pollution, which would be particularly valuable in Asia where many cities have poor air quality. Dietary changes could also have very positive health outcomes. On the other hand, additional cooling from an overshoot could place considerable strain on the electrical grid infrastructure of middle and even high-income countries, increasing the risk of blackouts and consequent health impacts. This risk would be amplified by lower production from thermal and nuclear power plants due to lower availability of cooling water, potentially lower solar PV generation, reduced transmission capacity in summer and increased distribution infrastructure failure. Higher climate change is expected to increase energy insecurity and access to clean energy services.

9.3 Poverty, inequality and migration

The number of people living in extreme poverty is expected to decline substantially from around 700 million in 2020 to around 130–160 million in 2050. Following either the NO or VHO pathway makes little difference to the number of people in poverty in 2050. Most of the differences between the two scenarios for the period to 2050 are for people in Africa.

Migration has a range of drivers including some made worse by climate change. Flooding is a key driver, but temperature rise and precipitation changes are also important. Most displacement to date has occurred within countries, often from rural to urban areas, rather than across borders. The likelihood of migration depends on the level of investment in adaptation measures, the characteristics of the population and the strength of local communities and institutions. It is very difficult to assess with any confidence the extent to which climatic changes have caused migration to date. It is even more difficult to project future changes as these are dependent on both uncertain future weather patterns and social factors.

At the outset of this study, we had an ambition to examine human system tipping points. This is challenging because all of the impacts we examine in this report can be at least partially mitigated through adaptation, and many also depend on wider social circumstances and on the strengths of local communities and institutions. While overshooting 1.5 °C would cause precipitation patterns to change, these changes would reverse, perhaps with a time lag, if the global temperature were subsequently reduced. The most likely permanent tipping points, as measured by permanent changes to populated areas, would be caused by floods, severe storms and by changes to precipitation in agricultural areas. Sea levels will continue rising slowly through the next century, increasing coastal floods, while changes to precipitation amounts or variability over extended periods (e.g. decades) in agricultural areas could also lead to permanent migration away from an area. These impacts are likely to be localised to particularly vulnerable areas in small islands and the tropics. If global warming were to continue beyond 2 °C then they would become much more widespread.

9.4 Future research priorities

Table 19 identifies some future research priorities for better understanding climate impacts on human systems.

Table 19. Future research priorities.

Area	Research priority
Coastal flooding: global drivers of extreme water level events	How extremes at sub-global level could vary with overshoot scenarios as these are the main drivers of severe damage that could prompt earlier adaptation. This could consider a chain of events from a physical driver to a hazard. It is particularly important to identify sensitive boundaries and tipping points associated with the overshoot, especially where a tipping point is not reversible.
Coastal flooding: regional impacts	Identification of impacts that are specifically linked with livelihoods (e.g. in low-income countries). Although sea-level rise is considered more in the far future and is a lesser priority compared with more immediate human needs, development paths should not lead to increased future risks that could be avoidable today. This is needed for all scenarios regardless of the timing or magnitude of overshoot.
Coastal flooding: adaptation	Methods and costs to adapt in a just way in the most vulnerable or sensitive areas (e.g. low-lying islands, deltas, developing nations) and the enabling mechanisms to do this. This is needed for all scenarios regardless of the timing or magnitude of overshoot.

Regional water stress	Crop models and climate models should be developed to include a wider variety of crops and agricultural systems to help identify sustainable food systems, for example: • Cultivation of appropriate drought-resistant cultivars for food and feed crops. • Switching human and animal diets to reduce pressure on water resources. • Improving efficiency of irrigation techniques while avoid a rebound effect (i.e. induced increased deployment of irrigation). • Facilitating governance for sustainable water resources management.
Clean water and sanitation	Our knowledge is principally based on case studies as clean water and sanitation issues are inherently local. There is a need for comprehensive surveys of the potential impacts of climate change on water and sanitation, and the potential for adaptation, particularly for low-income countries.
Direct effects of overshoot on health	Improve epidemiological databases in Sub-Saharan Africa to quantify heat-related mortality and morbidity under an overshoot pathway across the African continent. Incorporate technological adaptation and/or physiological acclimatisation into existing epidemiological models to better understand future health impacts from temperature overshoot.

Impacts on crop yields	Expansion of model development towards coverage of additional crops. This will enable the production of a variety of forecasts for crop yields to recognise different needs in terms of climate related resilience and management practices. Further exploration on adaptation and farm management practices to mitigate climatic pressure on identified crops.
Energy: Integrated and Holistic Assessments	Integration of assessments: few studies have attempted to integrate the assessments of impacts of climate variability and change (CV&C) on both the supply and demand of electricity. Holistic assessments: current studies often focus on specific locations or individual electricity infrastructure assets, neglecting a comprehensive assessment of future renewable installation capacity or national-scale impacts of CV&C. Uncertainty communication: future research needs to explicitly communicate uncertainties, particularly regarding the entire electricity provision chain and potential adaptation strategies.
Energy: Data and Model Improvements	Wind speed data and temporal resolution: future regional climate models should include more detailed information about near-surface wind speeds and higher temporal resolution for calculating wind resources. Model ensembles: to capture natural variability and reduce uncertainties, larger ensembles with a more diverse range of models, emission scenarios, and ensemble members are needed.

Energy: Long-Term and Climate Extremes Implications	Long-term climate change implications: further research is needed on the long-term effects of climate change on optimised energy systems, future energy technologies, and the costs and benefits of adaptation and mitigation measures. Climate change extremes: more sophisticated modelling and analysis methods are needed to assess changes in wet and dry extremes, which significantly impact hydropower potential.
Energy: Renewable Energy Diversification and Localised Approaches	Non-hydro renewable energy (RE) diversification: research should focus on non-hydro RE-based diversification, especially in countries heavily reliant on hydropower. Localised approaches: there is an urgent need for localised studies due to the variable impacts of climate change on a local scale.
Energy: Operational and Environmental Considerations	Energy demand and grid stress: the interplay between seasonality changes in streamflow and peak electricity demand must be considered for power grid planning and operations. Sediment loads and extreme flow events: the impact of sediment loads on hydropower plants, particularly related to extreme flow events, is under-researched.
Migration	Better understand the drivers of migration and mitigation options to prevent migration related to weather events.

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11. Quality assurance

Each part of the work was reviewed by a member of the CS-N0W consortium:

- Coastal flooding impacts: Robert Nicholls (University of East Anglia).
- Inland flooding impacts: Robert Nicholls (University of East Anglia).
- Regional water stress impacts on agriculture: Paul Dodds (UCL).
- Water stress and quality: Alison Kay (NERC CEH).
- Clean water and sanitation: Luisa Campos (UCL).
- Crop yields: Chrysanthi Rapti (UCL).
- Impacts of overshoot on land food systems: Paul Dodds (UCL).
- Impacts of overshoot on fisheries: Jeremy Blackford (NERC Plymouth Marine Laboratory).
- Health impacts: Paul Dodds (UCL)
- Impact on affordable and clean energy: Julia Tomei and Paul Dodds (both UCL)
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