Literature Review

Work package D1: Climate impacts at the global, regional and country scale

31/03/2022

UK Government

CS-NOW

Climate services for a net zero resilient world

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Acknowledgements

Richard Smithers and Chris Thorpe, Ricardo Energy & Environment, for a review of the work.

Publication date

31/03/2022

Version

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Referencing this report:

Warren, R., Jenkins, K., Price, J., Jenkins, R., Wright, R., He, H., Manful, D., Ferrini, S., Jones, M., Brown, S., and Smith, A. 2022. Literature review: climate impacts at the global, regional and country scale. Climate services for a net zero resilient world. UK Government.

About CS NOW

Commissioned by the UK Department for Energy Security and Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5 million research programme, that will use the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation ambitions.

CS-N0W aims to enhance the scientific understanding of climate impacts, decarbonisation and climate action, and improve accessibility to the UK's climate data. It will contribute to evidence-based climate policy in the UK and internationally, and strengthen 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)**.

Executive Summary

Climate-related risk is the product of exposure of vulnerable systems to climate-related hazard. The Literature Review and Searchable Inventory together provide an assessment of metrics that are strong indicators of climate-change risk that are projected to occur for global warming of 1.5°C to 4°C above pre-industrial levels. Many of the metrics quantify exposure to climate related hazard in the context of known sensitivity to changes in climate. Sectors covered are drought and water security, fluvial flooding, coastal flooding, agriculture and fisheries, natural ecosystems and biodiversity, fire, health (heat and disease), and direct, indirect and induced economic impacts. In cases where adaptive capacity is very limited, for example for biodiversity, these indicators are essentially direct indicators of climate-related risk itself (although in some cases i.e., for some species at lower warming levels humans may be able to reduce these risks).

This report provides a review of existing and emerging evidence on country and regional level climate-risk-related metrics, and how these metrics accrue with global warming of 1.5°C to 4°C above pre-industrial levels. Regions covered are Africa, Asia, Australasia, Europe, North America, Central and South America, Polar regions, and Small Islands.

In many cases, the climate change literature focuses on global or continental-scale projections rather than the country level. Where country-level studies exist, they can be disconnected, using different climate scenarios, baselines and/or different methodologies. Climate-related studies often generate large volumes of data, and extensive reports, making comparisons and cross-country analyses difficult. This review fills a gap between the large array of un-harmonised local or country scale studies and broader scale discussions in the IPCC reports.

This is beneficial as it enables comparisons across regions and countries; helps to highlight key knowledge gaps at the region and sector level; and by considering different warming levels can help decision makers understand the potential consequences of climate change that might emerge in countries if the goals of the Paris Agreement are not met, or the benefits of limiting warming to lower levels if they are met.

This review is accompanied by the Searchable Inventory of Global Climate Impacts. Users of the Searchable Inventory can access country level data from the Tyndall Centre projections of risk-related metrics and avoided damages from limiting global warming to a lower, as opposed to higher, level of average warming. The Inventory also includes data made available by Climate Analytics and the IPCC AR6 Working Group 1 Interactive Atlas.

The following sections provide a sub-set of key findings for each region, with full details outlined in the main body of the review. Reflective of the literature as a whole, many of the metrics discussed focus on the quantification of exposure of vulnerable human systems or ecosystems to changes in climate-related hazards, important to establish potential concerns regarding exposure to hazards.

Decision makers wanting to design and implement effective adaptation strategies can use the review and searchable inventory as a starting point, to indicate the priorities and need for such action, but as adaptation is extremely context specific, strategies need to be designed around the local context and sensitivities. Climate adaptation actions can then be identified and prioritised that reduce sensitivities, increase adaptive capacities and/or reduce exposure to hazards but this is beyond the scope of this work.

Africa

Changes to food availability and nutritional content of food will increase the number of people at risk of hunger and malnutrition. There is *high confidence* that Africa is projected to be the region hardest hit by impacts on **food security**. Across Africa, yield reductions for staple crops such as rice, wheat and maize are generally expected. Millions more people are projected to be at risk of hunger in Sub-Saharan Africa with warming of around 3°C.

Biodiversity loss due to climate change is projected to be widespread across Africa. There is *high confidence* that risk increases and adaptive capacity declines with higher levels of warming. With warming over 2°C the risk of loss of biodiversity increases and becomes more widespread, especially in Central, West and East Africa. Endemic species are projected to be particularly impacted.

Increases in aridity, hydrological and agricultural/ecological **drought** are projected across many regions of Africa. With 2°C warming, there is *high confidence* that North Africa is projected to see increases in aridity, hydrological and agricultural/ecological drought, west Southern Africa will face increased aridity and agricultural/ecological drought, and east Southern Africa is projected to become more arid.

There is *high confidence* that climate change poses a significant threat to African marine and freshwater **fisheries**. Impacts, such as reduced fish catch potentials, are projected to accrue with warming. Enhanced impacts are projected for tropical regions due to the vulnerability of coral reefs, a key habitat for a variety of commercial fish and invertebrate species, particularly at early life stages. There is *very high confidence* that more than 90% of warm-water coral reefs are projected to be lost at 2.1°C of warming.

Asia

There is *high agreement* in the literature that Asian **fisheries** are projected to be highly vulnerable to climate change. The effect of climate change on fish catch potentials differs in magnitude and direction of trend dependent on the region. Negative impacts are projected to be large in the Indonesian Sea and the Gulf of Thailand.

There is *high confidence* that climate change is projected to have adverse impacts to those whose livelihoods depend on coasts and their ecosystems. 12 of the top 20 countries exposed to sea-level rise and **coastal flooding** are in Asia, dominated by low-lying areas including delta regions. A large proportion of the global population exposed to sea-level rise and subsidence are in Asian countries.

Climate change is projected to alter the geographical range of malaria vectors and change the risk of malaria **infections** with high likelihood. Malaria incidence in northern China is projected to increase. Projected additional annual deaths showed a significant malaria increase in South Asia. In China the high-risk area for dengue transmission is projected to expand with warming, while in Nepal, climatically suitable areas for dengue fever are expected to expand.

Studies suggest India and China will face some of the greatest risks from exposure to **heat stress**. Parts of South-East Asia, including Vietnam, Thailand and the Philippines are some of the countries projected to face the greatest excess mortality from future warming. The areas of South Asia currently exposed to extreme heat are projected to expand with warming of 1.5°C, including across larger parts of India, Bangladesh, Thailand, and Cambodia.

Models suggest some of the largest increases in **fluvial flooding** are projected to be in Asia. Flood frequencies are projected to increase across large areas of South Asia, Southeast Asia and Northeast Eurasia. There is reported *medium confidence* in projections of regional changes in Asia.

The projected relative change in exposed population increases from 1.5°C to 3°C warming in most parts of the world, with Asia seeing the largest increase.

Australasia

There is *high confidence* that climate change will have profound effects on the **biodiversity** of Australasia, including some irreversible impacts, such as species extinctions. Mountainous regions, such as the south-east Australian Alps Bioregion, are particularly vulnerable. However, some native and invasive species may see increases in range due to climate change.

Droughts are projected to increase in Australasia due to climate change, particularly in Southern and Eastern Australia and New Zealand with *high confidence*. With ~2°C warming, Eastern Australia is projected to undergo increases in aridity and agricultural/ecological drought and Southern Australia is projected to undergo increases in aridity, hydrological and agricultural/ecological drought (*medium confidence*).

Climate change is already impacting **fisheries** in Australia, shifting the range of species poleward. For Australasia as a whole, fish catch potentials are projected to decline as temperatures rise. Studies suggest the most affected areas are the North Australian Shelf and Southwest Australian Shelf. Another impact on Australian fisheries already evident is the loss of key habitat-forming species, including the effects of extreme weather events driving rapid mortality of corals.

Extreme heat events are projected to become *significant* and substantially more common in Australia under 2°C warming versus 1.5°C warming. Dangerous humid heat thresholds, with the potential to affect **health**, are projected to be exceeded more frequently over the 21st century in Australia, with Northern Australia particularly vulnerable.

Australia and New Zealand are projected to experience *unprecedented* **fire weather** under future warming increments relative to the natural variability simulated for the pre-industrial period. Fire weather season length and the annual frequency of fire weather extremes are projected to increase in Southeast Australian forests, accruing with warming.

Central and South America

This region contains the most productive marine ecosystem for **fisheries** catch, which is the Humboldt Current System. Projections suggest that the worst impacts will be in the Eastern Tropical Pacific, including the Humboldt Current System, related to changes in El Niño Southern Oscillation (ENSO) (*very high confidence*). For Central and South America as a whole, fish catch potential is projected to decline as temperatures rise.

Agricultural production is projected to decrease due to climate change in Central and South America, including reduced climate suitability and yield for beans, coffee, maize, plantain, and rice (*high confidence*). Reductions in wheat yields of up to 50% are projected in South America in comparison to a 1980–2010 baseline with warming of around 4°C.

Droughts are projected to lengthen, intensify, and become more frequent in Central America with increasing levels of warming. Drought frequency and severity is projected to expand in southwestern South America (*high confidence*). With 2°C warming, the South American Monsoon subregion is projected to have increases in agricultural/ecological drought and Southern South America is projected to have increases in agricultural/ecological drought (*high confidence*).

There is *medium confidence* that the **biodiversity** of Central and South America, particularly within the region's biodiversity hotspots, is projected to be particularly negatively impacted by climate change. Andean species are likely to be particularly vulnerable due to the high levels of endemicity and their limited ability to adapt by dispersing into new areas as the climate warms. Much of the Amazon is projected to become climatically unsuitable as refugia for biodiversity, even with warming as low as 1.5°C.

Europe

Climate change is projected to decrease suitable climate space for many **species** and lead to northwards and upslope range shifts. Risks to terrestrial ecosystems are projected to increase with warming as exposure increases and adaptive capacity is limited, with southern Europe generally at greater risk than northern Europe (*very high confidence)*.

There is *high confidence* that climate change has already negatively impacted marine **fisheries** in Europe, particularly in the North Sea, Iberian coastal Sea and Celtic-Biscay Shelf. However, over-fishing, rather than climate change, is considered the largest impact on fisheries in Europe. For Europe as a whole, fish catch potential is projected to decline as temperatures rise.

Drought frequency and severity is projected to expand in some regions with climate change (*high confidence*). With warming of ~2°C the Mediterranean subregion is projected to see increases in aridity, hydrological and agricultural/ecological drought, while Northern Europe is projected to undergo declines in aridity (*high confidence*). One study projected that changes in drought area would affect up to 42% more of the population, with the Mediterranean region most affected.

Many countries in Europe are projected to experience unprecedented **fire weather** under future warming relative to the natural variability simulated for the pre-industrial period, including Bosnia and Herzegovina, Croatia, France, Italy, Portugal, Slovenia, Sweden, Switzerland and Ukraine. Projections for the fire-prone Mediterranean region of Europe show an increase in fire probability.

Some of the largest changes in fluvial floods globally are projected for Europe. By the end of the 21st century, mean annual precipitation and average discharge are projected to decrease in northern and southern Europe (*medium confidence*) and increase in north-eastern Europe. There is *high confidence* of an observed increasing trend of **fluvial floods** in Central and Western Europe.

Critical heat thresholds relevant for humans are projected to be exceeded for global warming of 2°C and higher in Europe. Countries in Southern Europe are projected to be exposed to excess mortality from **heat exposure** under future global warming of 1.5°C and above.

North America

For North America as a whole, fish catch potential is projected to decline as temperatures rise. Climate change is projected to intensify losses in North American **fisheries**, with declines in yield and poleward range shifts found by several regional studies (*high confidence*).

Drought frequency and severity is projected to expand in some regions with climate change (*high confidence*). This includes western North America, much of which is currently in what is termed a 'megadrought'. Northern Central America is projected to suffer increases in aridity (*high confidence*) and agricultural/ecological drought (*medium confidence*). There is *high confidence* that North-Eastern North America is projected to undergo a decrease in aridity.

There is *high confidence* that climate change will increase risks to the **biodiversity** of North America, with greater risks projected with greater levels of warming and very limited adaptive capacity. In North America, montane ecosystems, including the Appalachian Mountains biodiversity hotspot, are projected to be particularly vulnerable.

Under future projections of warming studies suggest an increase in mortality in southern and eastern counties in the USA, particularly for elderly populations. At 1.5°C parts of the East and

Southeast USA are projected to be exposed to moderate and high (in shade) occupational **heat exposure**, and above 2°C will be exposed to extreme heat stress.

Canada, Mexico and the United States have already experienced an unprecedented shift in **fire weather** relative to the natural variability simulated for the pre-industrial period. Substantial increases in future fire weather have been modelled for North American boreal regions and parts of the western US, with the largest increases in the northwest US. In Canada, fire weather conditions are projected to become more severe, by up to a factor of 4-5 during the peak of the fire season, in the late 21st Century relative to the late 20th Century, particularly in western Canada.

Some of the largest changes in **fluvial flooding** globally are seen in the United States. Fluvial floods are projected to increase in the United States and Canada (*medium confidence*). Annual maximum daily runoff is projected to increase during the 21st century, especially in the south-eastern United States and Pacific Northwest, and to decrease in the Rocky Mountains and northern Great Plains.

The region is threatened by hurricanes, and local subsidence can enhance the rate of relative **sea-level rise**. Protection against extreme events is comprehensive, including hard defences, early warning systems and the ability to clear up after a disaster strikes, yet this is still insufficient for major hazards. Sea-level rise may mean large numbers of people move landward as housing is threatened (*medium confidence*). By 2100, the number of people at risk could potentially double in a non-mitigation scenario compared with a mitigation scenario.

<u>Small Islands</u>

Small islands in the Pacific suffer **coastal flooding** largely due to compound effects from high tides coinciding with e.g., cyclones. There is *high confidence* that tropical cyclones are already impacting small islands and will continue to do so. There is *very high confidence* that atolls are particularly vulnerable to rising sea-levels, including the associated effects of ground salinisation that can impact ground water.

There is *high confidence* that small island states are extremely vulnerable to sea level rise, freshwater stress and extreme weather events such as cyclones, which will impact their **food security**. Although many small island states are likely to be more impacted by changes to fisheries than crop production.

Island **biodiversity** is projected to be particularly vulnerable to climate change due to geographic isolation, high endemicity, and typically narrow ranges and small population sizes of many species. Climate change is projected to significantly affect the biodiversity and ecosystems of small islands (*high confidence*). A review of previous studies found that 100% of endemic species from islands examined faced extinction with increasing levels of warming.

Tropical and sub-tropical islands face health risks from vector-borne **diseases**, which are expected to increase with future climate change, and linked to hazards such as sea level rise and cyclones. The Caribbean region has a high probability of mosquito distribution, increasing the risk of contracting Zika. The changing climate is likely to alter the risk of water-borne diseases.

Small island countries are often inherently more dependent on **fisheries** for national income and food security than other countries. The direction of trends depends on the region and species, but tropical corals in the Pacific and Indian Oceans are projected to experience a 70-90% loss of coral reefs at 1.5°C of warming and 99% loss at >2°C (*high confidence*).

Polar Regions

High Arctic **biodiversity** is particularly vulnerable to climate change owing to high exposure to climate hazards and limited adaptative capacity. As warming continues, range shifts are projected to become more pronounced. One study suggests that the proportion of bird species threatened is highest in the Arctic and Southern Ocean. The encroachment of woody shrubs, reducing the area of tundra, is projected to continue with higher levels of warming (*high confidence*).

Contents

1. Introduction

This literature review and the associated Searchable Inventory were produced for the Department of Business, Energy and Industrial Strategy in response to their specific requests. Existing and emerging evidence on the accrual of country level climate change risk with increasing global warming is reviewed. This information can inform decision makers about the levels of risk that might emerge in countries if the goals of the Paris Agreement are, or are not, met, thus potentially informing those seeking to explore implications of different levels of action on climate change mitigation.

It can also inform decision makers planning adaptation strategies within countries. However, decision makers wanting to understand risk in detail, particularly at smaller scales, would be advised to explore the relative sensitivity of systems in which they are interested, and to combine the large-scale top-down analysis made available here with detailed bottom-up studies of sensitivity and adaptive capacity on the ground. This is because this review is global in scope and therefore tends, in common with the majority of the peer reviewed literature, to focus on quantification of exposure to climate change related hazard as this is a key driver of risk than can be relatively easily quantified in a harmonised fashion at large scale.

The Literature Review and Searchable Inventory together provide an assessment of metrics that are strong indicators of climate-change risk that are projected to occur for global warming of 1.5°C to 4°C above pre-industrial levels. Climate-related risk is the product of exposure of vulnerable systems to climate-related hazard (Figure 1). The reader is referred to Table A1.1 of Appendix A, where the definitions of the terms exposure, vulnerability and risk used by the Intergovernmental Panel on Climate Change (IPCC) may be found.

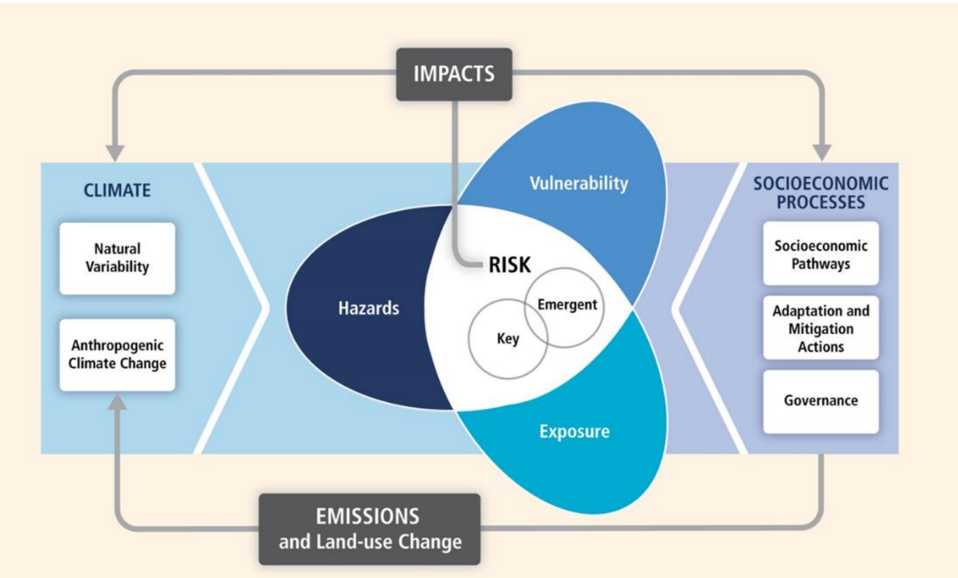


Figure 1: Schematic of the interaction among the physical climate system, exposure, and vulnerability producing risk. Risk of climate-related impacts results from the interaction of climate-related hazards with the vulnerability and exposure of human and natural systems. Changes in both the climate system (left side) and socioeconomic processes (right side) are central drivers of the different core components (vulnerability, exposure, and hazards) that constitute risk. Reproduced with permission from Oppenheimer, Campos and Warren, et al., 2014.

The literature, and in particular the Tyndall Centre, have both produced projections of a large range of indicators, most of which project changes in the exposure of vulnerable human systems or ecosystems to changes in climate-related hazard. Strictly speaking, risk cannot be fully quantified unless the vulnerability of the systems are also taken into account, and full analysis of vulnerabilities is in general extremely challenging. Vulnerability includes aspects of both adaptive capacity and sensitivity (see Table A1.1 of Appendix A).

Quantifying spatial vulnerability to each climate related hazard on a global scale is beyond the scope of this work, and indeed beyond the state of the art within the literature. An important way in which vulnerability manifests is the ability or not to adapt. Yet the scope of this review, and the accompanying Searchable Inventory, is such that there was a requirement to exclude adaptation, except in those few cases where it is generally considered in the literature that a certain level of adaptation is inevitable, as in the case of coastal flooding, where significant extensive flood defences already exist and are anticipated to be maintained. Therefore, in the absence of adaptation, exposure to changes in climate-related hazards do provide a strong indicator of climate change risk itself, although variation in the innate sensitivity of exposed systems is not included.

Also included in the Searchable Inventory is information about changes in climate-related hazard itself, including many of those produced by the recent IPCC AR6 Interactive Atlas (Gutiérrez et al., 2021). This is of interest so that readers can understand how the climate-related hazards themselves are projected to change, since the exposure related metrics are also affected by assumptions about the magnitude and spatial distribution of population changes, which are an extremely strong driver of exposure related metrics in human systems. Inevitably, the geographical distribution of an exposure metric might look very different from that of the corresponding climate-related hazard,

Within the Tyndall Centre projections, a single time-evolving spatially explicit population scenario is assumed for the 21st century (corresponding to the Shared Socioeconomic Pathway SSP2 (Riahi et al. 2017)) for all warming scenarios explored. Hence aspects of vulnerability related to human population size and distribution, although not quantified, remains constant across the scenarios and this harmonisation of assumptions about changes in population enhances the comparability of the exposure estimates across different countries.

SSP2 is by definition a scenario which was originally derived by considering what a world with a medium level of challenges to adaptation, and to climate change mitigation, might look like. However, the resultant population scenarios are now widely used in combination with a wide range of possible climate change scenarios and adaptation scenarios, and the use of SSP2 in the Tyndall Centre projections should not be interpreted as implying that a medium level of climate change mitigation or adaptation has been applied. Rather, a level of global warming is combined with a time evolving population scenario and there are no specific mitigation actions assumed for any particular level of warming, and similarly no adaptation is assumed as previously mentioned.

Users of the Searchable Inventory may access Tyndall Centre projections of absolute levels of exposure, changes in exposure and percentage changes relative to an observed baseline period. In addition, the inventory calculates the percentage avoided change in the metric that results from limiting global warming climate change to a lower, as opposed to higher, level of average warming: these percentages are more robust to uncertainties in regional climate change projection, use of alternative impact models, model parameters, and other factors.

For comparison, some examples of model projections originating elsewhere are also included, specifically those made available by Climate Analytics via their online Climate Impact Explorer Tool (http://climate-impact-explorer.climateanalytics.org/). Most of these metrics are additional to those produced by the Tyndall Centre. For example, economic damage from fluvial floods and tropical cyclones; fraction of population exposed to crop failures, heatwaves and wildfires; and land fraction exposed to fluvial floods, crop failures, heatwaves and wildfires. Change in crop yields are also included for comparison to metrics produced by the Tyndall Centre in the Searchable Inventory. The metrics from Climate Analytics are based on data from the global databases ISIMIP (The Inter-Sectoral Impact Model Intercomparison Project) for biophysical system and extreme event metrics, and CLIMADA (CLIMateADAptation) for direct damage metrics. Importantly, these metrics do not consider socio-economic change, assuming population and GDP remain fixed, and assume no additional adaptation.

This literature review is a companion to the Searchable Inventory. Appendix A contains methodological details on the basis and details of these simulations. Further information about the methodology may be found in the Topical Collection 'Accrual of Climate Change Risk in Six Vulnerable Countries' in the journal *Climatic Change* and in Warren et al (2021, 2022).

The review provides an aggregation of current understanding of risk-related indicators including changes in climate-related hazards and exposure to these hazards across sectors at the regional level. The review is inevitably limited in scope and does not encompass the full range of all published peer reviewed literature and computer simulations but fills a gap between the large array of un-harmonised local or country scale studies, and broader scale discussions in IPCC reports. However, the review does not claim to encompass the full range of all published peer reviewed literature or data, which would be beyond its scope.

The review also places the data contained within the Searchable Inventory in the context of the wider and more extensive literature and range of computer model simulations, including those presently emerging from IPCC AR6 WGI and WGII. The Appendix provides information about key methodological assumptions, and an assessment of the uncertainties and levels of confidence that can be associated with the projections found in the inventory.

Assessment of metrics is provided for each sector and region at global warming levels of between 1.5°C and 4°C above pre-industrial levels. In some cases, these projections are associated with particular time slices at which this warming is reached, and in other cases, not, as the literature allows. For some metrics, the literature allows a discussion of implications of alternative assumptions about socioeconomic futures.

Regions covered are Africa, Asia, Australasia, Europe, North America, Central and South America, Polar regions, and Small Islands. Sectors covered are drought and water security, fluvial flooding, coastal flooding, agriculture and fisheries, natural ecosystems and biodiversity, fire, health (heat and disease), and direct, indirect and induced economic consequences. Direct and indirect economic consequences are also highlighted within each sector where applicable.

2. Literature Review

2.1 Drought and Water Security

Introduction

Drought can have major impacts on biodiversity, agriculture and food security, water security, people and economies. There is *high confidence* that drought frequency and severity will expand in some regions with climate change. This includes the Mediterranean, western North America and south-western South America. Drought hazard, exposure, and resultant socio-economic impacts are likely to increase with every degree of warming, with a general picture of increasing drought risk with every degree of global warming. When considering the effects of climate change on drought, it is important to distinguish between meteorological drought, which is dependent only upon in situ climatology and land use and caused by periods of low precipitation; agricultural drought (also including ecosystems, which also often factors in soil moisture and duration of drought); and hydrological drought, which is also affected by runoff from upstream locations and leads to a reduction in water supply. The IPCC AR6 Working Group I (Seneviratne et al., 2021) reported that projections of climate change effects on these different forms of drought are consistent in many regions, but that there are also significant differences in some geographic regions and in the confidence in projections of future drought. Furthermore, increasing levels of aggregation (e.g., across countries and regions) can also mask some of the confidence and probability of drought as areas projected to become wetter offset areas becoming drier when aggregated together. Drought metrics include the area and number of people exposed to drought; the mean probability of a given month in a year being in drought and the number of months in drought. Satoh et al. (2021) noted that the diversity of drought indices used in assessments of current and future drought is a key limitation for comparing drought assessments. The ISIMIP project modelled soil moisture drought (i.e., the total moisture stored in soil within the root zone), which is shown in the Climate Analytics climate impact explorer.

Water security can be defined as 'the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability' (UN-Water, 2013). Water security metrics include both physical (related to the quantity of water) and socio-economic components (including demand for water). In addition to drought, the Searchable Inventory also includes a measure of the number of people exposed to water stress as another measure of water security. One of the most commonly used measures of water scarcity is the 'Falkenmark indicator' or 'water stress index'. This method defines water scarcity in terms of the total water resources that are available to the population of a region; measuring scarcity as the amount of renewable freshwater that is available for each person each year. If the amount of renewable water in a country is below 1,700 m^3 per person per year, that country is said to be experiencing water stress; below 1,000 m^3 it is said to be experiencing water scarcity; and below 500 m^3, absolute water scarcity. Gosling and Arnell (2016) also use the WCI (Water crowding index) and a threshold of <1000 m^3/person/year to indicate water stressed cells. However, they also combine it with the WSI (water stress index), which is not done in the projections shown in the Searchable Inventory.

Africa

The IPCC Working Group 1 Interactive Atlas shows that drought has increased in North Africa, showing an upward trend without attribution in aridity, hydrological drought, and agricultural/ecological drought over recent decades. Southern Africa shows an upward trend without attribution in hydrological and agricultural/ecological drought. There are no observed data in the IPCC Atlas for any other parts of Africa. Observed increases in the number of months of drought have led to increases in human migration from rural to urban areas in Senegal (Nawrotzki and Bakhtsiyarava, 2017). In the Serengeti, drought is known to alter wildlife migration patterns that can impact tourism (Kilungu et al., 2017). Drought has been associated, in part, with tree mortality in the Congo Basin (McNicol et al., 2018; Tyukavina et al., 2018). In the 2014-2016 extreme drought event, wild grazers declined by 60%, and the remaining populations were reliant on drought refugia (Abraham et al., 2019).

With the equivalent of 2°C warming, North Africa is projected to see increases in aridity, hydrological and agricultural/ecological drought with *high confidence*. In Southern Africa, the Western subregion is projected to undergo increases in hydrological drought with *medium confidence;* and aridity and agricultural/ecological drought with *high confidence*. West Africa is projected to become more arid, with increasing drought duration with warming of 2°C (Sylla et al., 2016; Zhao and Dai, 2016; Klutse et al., 2018; Ukkola et al., 2020). Drought extent in the Volta River Basin is projected to increase from 24% to 34% with an increase from 2°C to 2.5°C (Oguntunde et al., 2017). The Eastern subregion of Southern Africa is projected to become more arid (*high confidence)*, with *medium confidence* in projected increases in hydrological and agricultural/ecological drought. Madagascar is projected to have increases in agricultural/ecological drought (*medium confidence)*. Data for other parts of Africa shows *low confidence* in the direction of change. Satoh et al. (2021) compared different metrics and models of drought and found a decrease in soil moisture or runoff drought frequency is projected despite an increased precipitation drought frequency for Northeast Africa.

Asia

Droughts are projected to increase in likelihood across West, Central and South Asia. Prudhomme et al. (2014) found that most Asian countries are expected to experience increases in the land area under hydrological drought by the end of the century under a high warming scenario. The IPCC Working Group 1 Interactive Atlas projects increases in aridity in West Central and East Asia (*medium confidence)*. Data for other parts of Asia shows *low confidence* in the direction of change. While this means that there cannot be a direct comparison with the Tyndall projections for India and China in general, there is data for projected decreases in areas with permanent snow/ice in the Tibetan Plateau in the IPCC Atlas and this is generally in agreement with projections for large increases in drought in areas with snow/ice in India and China that were reported in the Searchable Inventory (Price et al., submitted). Satoh et al. (2021) compared different metrics and models of drought and found differences in the sign of change between different forms of drought in India with warming. Soil moisture or runoff drought frequency is projected to decrease, while precipitation drought frequency is projected to increase.

Australasia

There is *high confidence* that droughts will increase in Australasia as a result of climate change, particularly in southern and eastern Australia and New Zealand. The IPCC Working Group 1 Interactive Atlas shows observed increases in aridity, hydrological, and agricultural/ecological drought with no attribution in Southern Australia. With ~2°C warming, Eastern Australia is projected to undergo increases in aridity and agricultural/ecological drought (*medium confidence)*. Southern Australia is projected to undergo increases in aridity, hydrological and agricultural/ecological drought (*medium confidence)*. The other subregions in Australasia are reported as *low confidence* in direction of change. Kirono et al. (2020) compared drought metrics for Australia and found significant increases in all drought hazard metrics examined except frequency. However, there were differences in the magnitude of the projected changes between the drought metrics, with the Standardised Soil Moisture Index (SSMI) projecting larger changes from the baseline with warming. Satoh et al. (2021) compared different metrics and models of drought and found a decrease in soil moisture or runoff drought frequency is projected despite an increase in precipitation drought frequency for Northern Australia.

Central and South America

Droughts are projected to lengthen, intensify and become more frequent in Central America with increasing warming. The IPCC Working Group 1 Interactive Atlas shows observed increases in agricultural/ecological drought (no attribution) in North-Eastern South America and increases in aridity (no attribution) in South-Western South America. With 2°C warming, Southern Central America, Northern South America, North-Eastern South America, and South-Western South America are projected to have increases in aridity and agricultural/ecological drought (*medium confidence)*. The South American Monsoon subregion is projected to have increases in aridity (*medium confidence)* and increases in agricultural/ecological drought (*high confidence)*. Southern South America is projected to have increases in agricultural/ecological drought (*high confidence)*. There is *low confidence* in the direction of change for other parts of Central and South America. The results are generally in agreement with the data for Brazil in the Searchable Inventory, and also reflect issues with aggregation over large areas with differing signs of change in different parts of the region. Other research on drought in Central and South America found that drought may also lead to gender inequity. One study found that, in Colombia, drought was associated with migration in men, floods associated with migration in women (Tovar-Restrepo and Irazábal, 2013).

Europe

The IPCC Working Group 1 Interactive Atlas shows *medium confidence* in attribution of the upward trend in hydrological drought in the Mediterranean subregion, and an upward trend in agricultural/ecological drought (no attribution) for Western-Central Europe. With future warming of ~2°C, the Mediterranean subregion is projected to have increases in aridity, hydrological and agricultural/ecological drought (*high confidence)*. The Western-Central European subregion is projected to undergo increases in hydrological and agricultural/ecological drought (*medium confidence)*. Northern Europe is projected to undergo declines in aridity (*high confidence)*. Data for other parts of Europe shows *low confidence* in the direction of change. Samaniego et al. (2018) used an ensemble of hydrological and land-surface models to project changes to soil moisture droughts in Europe and projected increases in drought area of 40% (±24%), which would impact up to 42% (±22%) more of the population, with the Mediterranean region most affected. These results, where comparable (e.g., not including aridity) are in line with the Tyndall projections in the Searchable Inventory.

North America

The IPCC Working Group 1 Interactive Atlas shows observed increases in aridity (no attribution) across Northern Central America. Western North America shows observed increases in agricultural/ecological drought (attribution with *medium confidence)*. With warming, Northern Central America is projected to show increases in aridity (*high confidence*) and agricultural/ecological drought (medium confidence). Western North America is projected to have increases in hydrological and agricultural/ecological drought (*medium confidence)*. Central North America is projected to see increases in aridity and agricultural/ecological drought (*medium confidence)* while Eastern North America is projected to show a decrease in aridity (*medium confidence*). North-Eastern North America is projected to undergo a decrease in aridity (*high confidence)* with North-Western North America projected to undergo an increase in aridity (*medium confidence*). Data for other parts of North America shows *low confidence* in the direction of change.

Small Islands

Small islands are already regularly experiencing water shortages and droughts and these are likely to increase with warming. The risk to small island states will increase with rising temperature, changing rainfall patterns, sea level rise and population changes. There is limited data in the IPCC Working Group 1 Interactive Atlas for small islands, which only considers the Caribbean and Pacific Islands. With ~2°C warming, there is projected to be increases in aridity and agricultural/ecological drought in the Caribbean and increases in aridity in the Pacific islands (all, *medium confidence*). This is supported by other studies. In the Caribbean, an ~1°C temperature increase (1.7° to 2.7°C, SSP2) is projected to lead to a 60% increase in the number of people experiencing severe water resources stress (Schewe et al., 2014; Karnauskas et al., 2018). Across the different drought metrics (such as population exposed, or the probability of months being in severe drought), higher warming levels lead to greater risk from drought.

Summary

An additional 350 million people are projected to be exposed to drought driven increases in water scarcity with 1.5°C warming, increasing to 410 million at 2°C, both with uncertainty ranges of approximately half of the value (Liu et al., 2018). Severe droughts are associated with health problems from both overheating, and direct and indirect water access issues in both humans and livestock (Hall and Crosby, 2020; Mamo, 2020; Rankoana, 2021). Water stress (shortage) and drought have been linked to several human diseases and to an increase in violence in some areas (Schachtel et al., 2021; Lundgren, 2018; Andersen and Davis, 2017; Kaffenberger et al., 2017; Ramesh et al., 2016; Epstein et al., 2020a). Increasing use of open water storage containers as an adaptation to drought can also lead to vector-borne disease outbreaks by facilitating the reproduction of certain species of mosquitos. Droughts have also been linked to increases in rates of suicide among farmers (Carleton, 2017; Edwards et al., 2015; Vins et al., 2015).

Drought projections are subject to a number of uncertainties, including an incomplete understanding of biosphere processes, challenges in constraining plant physiological responses to atmospheric CO_2 and data limitations. Another important research gap revolves around inherent uncertainties due to the choice of climate scenarios. The Searchable Inventory makes use of a widely used method for modelling drought that does not have high data requirements. The index used for drought hazard, SPEI12, was chosen because (i) it takes into account potential evapotranspiration as well as changes in precipitation; (ii) it can be readily calculated from the climate projection data available in this study; (iii) it is broadly used and facilitates comparison with other studies that use SPEI; and (iv) it has an explicit time-scale over which precipitation surplus or deficits are accumulated (Vicente-Serrano et al, 2010). Although it may be over-sensitive to increasing evapotranspiration in areas of high aridity (Cook et al., 2014), other approaches would rely on poorly known aspects such as soil characteristics and snow accumulation. Therefore, using alternative metrics to measure drought may lead to differences in the likelihood and severity of drought. In addition, the IPCC AR6 WG1 report (Douville et al., 2021) shows that changes in regional evapotranspiration remain uncertain. Satoh et al. (2021) compared multiple models and scenarios and found that choice of drought definition was the dominant source of uncertainty, particularly in the northern high-latitudes. Therefore, it is critical to understand the type of drought being assessed before comparing studies and projections. The definition of drought used can affect not only the magnitude of changes but also the sign of changes.

Similarly, using different metrics to measure water security may also lead to variations in the levels of risk. However, geographically, the areas of greatest risk are very likely to remain the same across the different metrics for drought. For water security, a different pattern of the areas that are projected to be most at risk could be found when comparing metrics that only consider physical water scarcity and those that also consider socio-economic and political factors which affect the exposure, sensitivity and adaptive capacity of human systems to water scarcity. For example, some parts of the northern hemisphere such as the USA and Southern Europe, experience high physical water scarcity but are not considered as at risk when other factors (such as water governance, quality and accessibility) are considered. By contrast, water availability may remain higher across some regions of Africa but water security will be low due to low water quality, accessibility and governance. A combination of metrics should be used to fully understand vulnerabilities, impacts and risks associated with climate change.

2.2 Fluvial Flooding

Introduction

This chapter and Appendix A.3 discusses the state of the art of fluvial modelling assessment work, the modelling tools employed, underlying data sets, and an overview of findings at the country, regional and global scale. The quantification of historical occurrences and trends and the identification of anticipated climate changes in a region are the key steps in most impact analyses. The section explores the impacts on fluvial flooding within each region and compares the findings from the Searchable Inventory with findings in other literature including the IPCC AR6 reports.

Africa

Li et al. (2016) reported the annual flood frequencies fluctuate during the period 1990-2014 with *medium confidence* in an upward trend in flood event occurrence. Tramblay et al. (2021) evaluated the drivers responsible for floods in Africa and concluded that flood occurrence is more strongly related to the annual maximum soil moisture than annual maximum precipitation. They also point out that the Africa region suffers from a lack of observed data in terms of precipitation, river discharge and more generally with regards to hydroclimatic data.

Under future climate scenarios, the extreme river discharge, as characterized by the 30-year return period of 5-day average peak flow, is projected to increase by the end of the 21st century (2070-2099) for the RCP8.5 (more than 10% relative to 1971-2000 period) for most of the African river basins (see Fig 1 in Dankers et al. (2014)). The present-day 100-year return floods can have a return period of 40 years with 1.5℃ and 2℃ of global warming (Alfieri et al. 2017) and 21 years for 4℃ warming (Hirabayashi et al. 2013; Alfieri et al. 2017).

Roudier et al. (2014) found overall the future projections in West Africa are very uncertain with no clear general pattern of future runoff evolution. Aich et al. (2016) reported *medium confidence* of projected increases in 20-year return flood magnitudes for the near future (2021-2050) compared with the base period (1976–2005) within the Niger river basin under RCP8.5. The other large river basin, the Volta, in West Africa shows *low confidence* of an increase in extreme peak flows (>Q75) by the 2050s and 2090s (Jin et al. 2018). A significant median change of flood magnitude for the Gambia river (-4.5%) and for the Sessandra (+14.4%) and Niger (+6.1%) are projected under several scenario between mid-century (2020-2060) and end of century (2061-2100) (Roudier et al. 2014). In East Africa, extreme flows are projected to increase for the region within the Blue Nile with *low confidence* (limited evidence) (Aich et al., 2014). However, uncertainty due to the climate scenario dominates the projection of extreme flows (Aich et al., 2014; Krysanova et al., 2017) for the Blue Nile and Niger river basins.

Asia

Dottori et al. (2018) found globally that the relative change in exposed population increases from 1.5°C to 3°C warming in most parts of the world, with Asia seeing the largest increase (confidence level of the average change is greater than 90%). Alfieri et al. (2017) reported the largest increases in flood risk in Asia. Hirabayashi et al. (2013) found the flood frequencies and risks increase across large areas of South Asia, Southeast Asia and Northeast Eurasia. The IPCC AR6 WGI Chapter 12 summarises regional changes in Asia. They report that the monsoon floods will be more intense in South Asia (*medium confidence*) (Nowreen et al. 2015; Babur et al. 2016; Mohammed et al. 2018). The total flood damage will increase greatly in river basins in South-East Asian countries under climate change and rapid urbanization in the near future (Dahal et al. 2019; Kefi et al. 2020). A changing snowmelt regime in the mountains may contribute to a shift of spring floods to earlier periods in Central Asia in future (Reyer et al. 2017) (*medium confidence*). The annual maximum river discharge can almost double by the mid-21st century in major Siberian rivers, and annual maximum flood area is projected to increase across Siberia mostly by 2–5% relative to the baseline period (1990–1999) under RCP8.5 scenario (Shkolnik et al. 2018) (*medium confidence*).

He et al. (2022) quantified impacts between 1.5°C and 4°C of global warming on flood risks in six countries including China and India. At 1.5°C warming, 66% and 92% of the major basin areas in China and India experience a decrease in the return period of 100-year return floods, rising to 81% and 96% respectively with 4°C warming. The decrease in return periods leads to increased human exposure to flood risks, particularly with 4°C warming, where exposure in the major river basin areas in China and India increases by 202% and 2765% relative to the 1961-1990 reference period respectively. Limiting warming to 1.5°C would avoid much of these increased risks, resulting in increases of 12 and 239%, respectively.

Australasia

In Australia, the streamflow observations during the time period 1975–2012 show that negative trends dominate in annual maximum flow and that stations with significant negative trends were mostly located in southern Australia (Gu et al. 2020). The observed decreasing trend in southern Australia can be attributed to the decrease of soil moisture, although an increase of flood magnitude is possible for very rare events. For the more frequent flood events, the increase of extreme precipitation is balanced by the decrease of soil moisture (Wasko and Nathan 2019).

Gu et al. (2020) project that decreases in floods in southern Australia will continue in a warmer future (*high model agreement*) with increasing magnitude and volume of floods in northern Australia (*high uncertainties*). The also pointed out the increasing flood events in northern Australia can be attributed to increasingly heavy precipitation conditioned antecedent catchment wetness and wetting soil moisture. In contrast, the drying climate in the north counters the effect of slight increases in heavy precipitation and hence decreases in floods are projected. The diametric changes in flood magnitude between northern and southern Australia are projected to be more evident in extreme (50-year) floods than small (5- and 20-year) floods (Gu et al. 2020).

The median projection for Northern and Eastern Australia is a ~5% and 15% reduction in mean annual runoff by 2046–2075 for RCP8.5, respectively, with a 10th to 90th percentile uncertainty range of -40% - +30% and -40% - +20% (Chiew et al. 2017). There is stronger agreement in the projections for declining runoff in the far south-west and far south-east where the large majority of GCMs project a drier future winter. The projection of declining winter rainfall is also supported by recent trends in the observations and explanation of change in the global scale circulation under warmer conditions causing a poleward shift in rainfall bearing weather systems in far southern Australia (CSIRO 2012; Post et al. 2014; P Hope et al. 2017). In the far south-west and far south-east, the mean annual runoff is projected to decline by 50% and 20% (with an extreme dry projection of -70%, -40%) respectively.

There is *medium confidence* that river flooding will increase in New Zealand. Projections for New Zealand indicate that the 1 in 50 year and 1 in 100 year flood peaks for rivers in many parts of the country may increase by 5 to 10% by 2050 and by more by 2100 (with large variation between models and emissions scenarios), with a corresponding decrease in return periods for specific flood levels (Gray et al.; Carey-Smith et al. 2010; McMillan et al. 2010; Ballinger et al. 2011).

Central & South America

Reyer et al. (2017) published a synthesis of climate change impacts in this region including floods. They found no consistent runoff projections for the Amazon basin due to the high variability of rainfall projections using different GCMs and uncertainties introduced by hydrological impact models. In Central America, there is *high agreement* on decreasing mean annual runoff and discharge, although the magnitude of the change varies (Milly et al. 2005; Maurer et al. 2009; Imbach et al. 2012; Arnell and Gosling 2013; Hidalgo et al. 2013; Nakaegawa et al. 2013; Schewe et al. 2013). Camilloni et al. (2013) projected an increase in frequency and duration of river flooding in a >3°C world in the Uruguay and Paraná basins. A decrease in mean runoff is projected for southernmost South America (Milly et al. 2005; Schewe et al. 2013).

According to the Tyndall research (He et al. 2022), decreasing annual total precipitation is projected in large areas of Brazil. But only a small portion of grids, mostly in central-west Brazil, show the 5 GCMs agree that the annual total precipitation will decrease in the 21st century. A large portion of Brazil shows a decrease with low to moderate agreement. Small areas in the north-west and south of Brazil show increasing precipitation with low to moderate agreement. A very similar spatial pattern can be observed in the changes of flooding return period. At 1.5 and 4°C warming, the projected median proportional area of major river basins in Brazil that experience a decrease in the return period of Q100 is 47% and 54%, respectively.

North America

There is limited evidence and low agreement on observed climate change influences for river floods in North America (Ranasinghe et al 2021). The IPCC AR6 Chapter 12 reports that the trends in streamflow indices are mixed and difficult to separate from river engineering influences, with large changes but little spatial coherence across the US. The central United States shows increasing frequency of floods but limited evidence of significant changes in the magnitude of flood peaks (Mallakpour and Villarini 2015). Flood magnitudes in the Southwest have been decreasing but increasing in the Northeast and north-central United States (Peterson et al. 2013). There is only weak evidence that the annual maximum gauge height records have been changing over the continental United States during 1985-2015 (Villarini and Slater 2018). The frequency of flood events has increased across most of the U.S. Midwest, which is mostly driven by precipitation and antecedent wetness conditions (Neri et al. 2019).

There is *medium confidence* that climate change will increase river floods over the United States and Canada but *low confidence* for changes in Mexico (Ranasinghe et al 2021). The annual maximum daily runoff is projected to increase during the 21st century, especially in the south-eastern United States and Pacific Northwest, and to decrease in the Rocky Mountains and the northern Great Plains (Villarini and Zhang 2020). Winter and spring will see the largest changes in extremes (Villarini and Zhang 2020). It seems the direction in the projected changes in runoff is mostly consistent between CMIP5 and CMIP6 projections. The results based on Villarini and Zhang (2020), using the CMIP6 model outputs, are consistent with what is reported by Dankers et al. (2014) using the CMIP5 model outputs. The exception is that the CMIP6 models project a slight increase in floods in the southwestern United States, while the CMIP5 models show a decrease in floods in this region. This may partially help to explain the decreasing projections of floods in large parts of North America found by Hirabayashi et al. (2013) and Arnell and Gosling (2016) which did not use the CMIP6 model outputs.

Europe

Based on the most complete database of European floods, Blöschl et al. (2019) found increasing floods in north-western Europe due to increasing autumn and winter rainfall; decreasing floods in medium and large catchments in southern Europe due to decreasing precipitation and increasing evaporation; and decreasing floods in eastern Europe due to decreasing snow cover and snowmelt, resulting from warmer temperatures. They also report that the regional flood discharge trends in

Europe range from an increase of about 11% per decade to a decrease of 23%. There is spatial and temporal heterogeneity of the observational record, but the flood changes they identified are broadly consistent with climate model projections for the 21st century.

Alfieri et al. (2015a) used an ensemble of EURO-CORDEX RCP8.5 scenarios to drive a distributed hydrological model and assessed the projected changes in flood hazard in Europe. By the end of the 21st century they report that both mean annual precipitation and average discharge are projected to decrease in southern Europe and to increase in north-eastern Europe, while in central Europe the ensemble of projections does not agree on a specific trend. At 4°C global warming, climate change alone could increase the socio-economic impact of river floods in Europe by 220% by 2080 (Alfieri et al. 2015b). However, their findings are different from trends reported in Hirabayashi et al. (2013) and Dankers et al. (2014), of decreasing extreme discharge peaks in eastern Europe but increases in Western Europe by the 21st century.

Small Islands

The IPCC AR6 WGI Chapter 12 summarises regional changes in Small Islands as follows. There is limited evidence on observed changes in river flooding in small islands. Long-term records in Hawaii indicate no clear trends in peak flow, except for the significant decrease in peak streamflow in Hawaii Island over the period 1967-2016 (Bassiouni and Oki 2013). Similarly, there is no significant trend in the frequency and height (after adjusting for average sea level rise) of river flood in Fiji over the period 1892-2013 (McAneney et al. 2017). There is *low confidence* on the direction of future change of river flooding in the small islands due to limited currently available literature. In Oahu, Hawaii, extreme peak flow events with high return periods are projected to increase by end of 21st century under RCP8.5, but there is also high uncertainty in these projections (Leta et al. 2018).

Summary

Under future climate scenarios, extreme river discharge is projected to increase by the end of the century (2070-2099) under the high-end emission scenarios for most African river basins. There is *low confidence* in the direction of future change of river flooding in Africa due to a lack of data.

Most research show Asia is the region at the highest risk of increasing fluvial flood risks and damages at all levels of warming.

Decreases in floods in southern Australia are projected to continue with a warmer future (high model agreement) with increases in the magnitude and volume of floods in northern Australia (high uncertainties). The diametric changes in flood magnitude between northern and southern Australia are projected to be more evident in extreme (50-year) floods than small (5- and 20-year) floods. There is *medium confidence* that river flooding will increase in New Zealand.

Extreme precipitation events and total rainfall are projected to increase over most of Southeastern South America and western Amazonia. In Northeast Brazil and eastern Amazonia smaller or no changes are seen in projected rainfall intensity, though significant changes are seen in the frequency of consecutive dry days.

There is *medium confidence* that climate change will increase river floods over the United States and Canada but *low confidence* for changes in Mexico.

There is *high confidence* of an observed increasing trend in river floods in Central and Western Europe and *medium confidence* of a decrease in northern and Southern Europe (Ranasinghe et al 2021).

There is *low confidence* on the direction of future change in river flooding in the small islands due to limited available literature.

Some key research gaps and limitations include that flood mitigation and adaptation measures are not often taken into consideration in large scale impact studies. Most studies do not consider non-climatic factors such as flood defences or dams etc. and can therefore lead to over/under-estimation of inundation areas and population exposure. Future studies could take into consideration flood protection levels to obtain more robust estimation. In addition, both current and future adaptation strategies for flooding can also affect the estimation. The FLOPROS dataset, which is an evolving global database of flood protection standards (Scussolini et al. 2016), could also add value to impact assessment by taking flood protection standards into consideration.

Landcover changes: Most studies use static landcover maps. Future studies should account for land use in the model parameterisation by using regionalisation techniques or other approaches.

Glacier runoff and snow melt: These are very important fluxes in mountainous regions but are not accounted for in most studies. In future studies, a global glacier model can be coupled to the modelling chain to account for glacier changes and the impacts on water resources and floods due to global warming.

Limited resources: To understand and quantify the risks associated with floods worldwide, at any location in the world remains a challenge. The necessary resources including time, budget and data for flood risk assessments are often limited. Especially if the full range of uncertainties need to be explored, it is very time-consuming to run multiple hydrological and hydraulic models driven by multiple climate model outputs. The latter often result in a compromised assessment due to the reduced scope.

Insufficient data or poor data quality: Various global datasets are available as open source and the vast amount of data is still increasing. Examples are digital elevation data from SRTM and MERIT Hydro; river networks from OpenStreetMap; and flow direction map from MERIT Hydro. However, it is often not straightforward to determine which dataset is most suitable for a global scale study or a specific region. This is a prevailing problem in Asia, Africa and South America as well as other areas of regions where observed data can be sparse or low quality.

Inconsistent protocols: It is important to highlight the need for more detailed basin, country or regional level studies similar to what has been undertaken in ISI-MIP but with more consistent uses of GCMs, models, time periods, population projections, and more importantly impact measures. The latter will allow a better comparison within and between countries, which can provide important scientific evidence to assist policy making.

Insufficient study on economic losses: Sauer et al. (2021) conducted an economic assessment based on multiple modelling assumptions and pointed out that the quantification of the contribution of climate change to observed trends in flood-induced economic damages is limited by an insufficient understanding of the observed damage time series and observational data. Both the direct and indirect flood damages are important, but especially the latter still forms a research gap. The study carried out by Yin et al. (2021) is a very valuable attempt in quantifying economic impacts of future fluvial flooding under climate change and socio-economic development. They discussed the importance of including socio-economic development when estimating direct and indirect flood losses, as well as the role of recovery dynamics, essential to provide a more comprehensive picture of potential losses that will be important for decision makers.

2.3 Coastal Flooding

Introduction

There is *high* confidence that sea-levels are rising, and this will affect virtually all coastlines worldwide. Coastal flooding metrics include the number of people exposed (assuming no adaptation), the number of people flooded (assuming adaptation), cumulative land loss due to flooding (assuming adaptation) and damage costs (assuming adaptation) (Haasnoot et al. 2021a; Arnell et al. 2019). Outputs presented here and in the Searchable Inventory use a global scale methodology following a bath-tub approach, so do not take account of local processes such as swell waves or run-up. Uncertainties in input databases include elevation, population and land use datasets. Hence regional and local processes are not well represented. A major uncertainty in modelling the impacts of sea-level rise is adaptation, which may be considered part of the vulnerability component of risk. Globally, adaptation is focused on dikes, yet a wide range of methods may be applied in practice.

The data in the Searchable Inventory uses many studies from the Dynamic Interactive Vulnerability Assessment (DIVA) modelling framework (Hinkel 2005; Hinkel et al. 2014; Vafeidis et al. 2008) which are aggregated to national level (variations may be expected along a nation's coastline depending on the magnitude of sea-level rise, topography, population and economics, amongst other factors). Other global impact studies use different input datasets meaning that outputs can be very different to those represented in the Searchable Inventory (see Appendix A4, Table A4.1). In particular, different modelling of adaptation, as a measure of vulnerability, means that impact metrics can be highly changeable.

This report and the Searchable Inventory (based on Brown et al. 2021 and Warren et al. 2022) considers the impacts of sea-level rise, as adaptation is considered. Supplementing this in this report is Arnell et al. (2019). Arnell uses outputs (people at risk assuming adaptation) from the DIVA modelling framework (including the same model and database version). Results are aggregated as close as possible to the IPCC regions used in this report, except small islands (mostly in Australasia) and polar regions (with their relative country) are available at the regional level in Appendix A4, Tables A4.2 – A4.7). Due to the similarity of input data, outputs are broadly similar to those in the Searchable Inventory. Risk based metrics that do not consider adaptation (e.g., land and exposed sea-level rise) have been analysed in other journal papers (e.g., Brown et al. 2018; Goodwin et al. 2018).

There is high confidence that damage and adaptation costs will vary between regions. For economic costs, Jevrejeva et al. (2018) used the same model (including the same model and database version) as most of the data in the Searchable Inventory, with Brown et al. (2021) offering an updated analysis with a larger number of climate and socio-economic scenarios, but drawing similar conclusions taking account of spatial and temporal uncertainties with different levels of warming. Parrado et al. (2020) used a slightly earlier version of the DIVA model and database to analyse the indirect economic costs of coastal flooding via an extended computable general equilibrium (CGE) model. The study finds that, without additional adaptation, all regions are projected to increase their public deficits or reduce surpluses compared to a 2005 baseline, under all scenarios (SSP2, SSP5, RCP2.6, RCP4.5 and RCP8.5).

Africa

Africa's coastal zone varies in length from a few hundred metres in mountainous areas to more than 100km in low-lying delta regions (Hinkel et al. 2012). Continental studies are limited (e.g. Hinkel et al. 2012; Arnell et al. 2019), with country and local impact studies growing in recent years, such as in Egypt (e.g. Frihy and El-Saye, 2013), Ghana (e.g. Appeaning Addo, 2015), Kenya (Ojwang et al. 2017), Morocco (e.g. Khouakhi et al, 2013), and South Africa (e.g. Kretzinger, 2012). Nations particularly at risk are those along lagoons and delta regions where rising sea levels will result in salinisation and flooding, such as the Nile, Niger and Volta. Cities with rapidly growing populations (e.g., Luanada, Lagos), plus western and eastern sub-Saharan nations are also at risk (Neumann et al. 2015; Kulp and Strauss, 2019). Emerging concerns relate to impacts on tourism (Fitchett et al. 2016, Snoussi et al. 2008; Sagoe-Addy and Appening Addo, 2013) and heritage (Vousdoukas et al. 2022). The major sources of uncertainty relate to the growing exposure and vulnerability.

Hazard: Flooding will be driven by rising sea-levels, cyclones (which are projected to decline in number but be more intense around Mozambique (Malherbe et al. 2013; Ranasinghe et al. 2021)), plus local subsidence especially in delta regions (Nicholls et al. 2021; Wöppelmann et al. 2013; Addo et al. 2018). Sea-level rise is also seen as key driver of risk.

Exposure: Population growth (Neumann et al. 2015) is seen as a major risk driver, as exposure is increasing. This amplifies pressures, such as in cities *(high* confidence). It is unclear precisely how risk will accrue with time as this is dependent on development.

Vulnerability: Adaptation, such as grey (building restorations) and green (dune restorations, beach nourishments, land raising) investments (Snoussi et al. 2008; Sagoe-Addy and Appening Addo, 2013; Brown et al. 2020) and ecosystem-based approaches can reduce impacts (also called Nature-based Solutions). There is *high* confidence that ecosystem-based infrastructure can reduce climate risks. Adaptation will become especially important around growing populations (where those that will be exposed to the risk may not yet live there) and in delta areas. Vulnerability may be reduced through increased financial resources, education and public awareness to manage adaptation needs (Ojwang et al. 2017; Sheriff and Koske, 2021; Etongo et al. 2021).

Arnell et al. (2019) reports potential impacts displayed in Table A4.2 in the Appendix. This indicates that even by 2050, socio-economic change is the main variation in the cause of impacts across the climate change scenarios. By 2100, impacts remain high as sea-levels continue to rise even with temperature stabilisation. Impacts are particularly high under SSP3 and SSP4.

Economically, Jevrejeva et al. (2018) reports that, assuming no additional adaptation, globally Benin and Egypt both factor in the top ten countries with the largest coastal flood costs (as a % of GDP) under the 1.5 and 2 ºC scenarios (SSP2). Parrado et al. (2020) find that in South Africa indirect macroeconomic effects of Sea-level Rise and coastal protection could impact public deficit, by 13 billion US$ by 2050 compared to the 2007 baseline, assuming no additional adaptation (SSP2, RCP8.5). In North Africa the impact on public deficit was estimated to be ~30 billion US$ by 2050, and in sub-Saharan Africa ~70 billion US$ by 2050. These changes are mainly driven by a reduction in GDP and consequently lower tax revenues without accounting for indirect impacts on wellbeing.

Further research includes enhanced elevation models for impact assessments (Karlsson and Aarnberg, 2011) and high-resolution data for small islands (Brown et al. 2020; Parodi et al 2020). Achieving adaptation whilst maintaining income and sustainable development, with an emphasis on an ecosystems-based approach will become increasingly important while considering inequality and fairness in society.

Asia

Impacts are dominated by low-lying areas including delta regions, which contain many cities that have expanded significantly in the last two decades. Country level studies into people affected by flooding, with more precise drivers and scenarios of change are more common with some nations, such as Bangladesh (Desantis et al. 2007), China (Fang et al. 2020), South Korea (Park and Lee, 2020), and Indonesia (Marfai and King, 2008). Nevertheless, some nations have very few studies of the impacts of sea-level rise, such as Pakistan (Akhtar, 2015), Kuwait (Neelamani et al. 2021) and Qatar (Al-Mannai, 2021).

Hazards: Extreme events driven by cyclone activity, where a small number but more intense number of cyclones are projected (Arias et al 2021). For example, Feng et al. (2018) projects that in a 2°C world compared with a 1.5°C world, a considerable rise in extreme sea-levels is projected to result along the Chinese coast. Subsidence can be as large a concern as sea-level rise in deltas, especially in cities (Nicholls et al. 2021; Cao et al. 2021) and can exacerbate impacts. There is a growing emphasis on understanding multi-hazard events, such as in cities (Gu et al. 2015), plus understanding the drivers of extreme sea-levels (Fang et al. 2021; Jevrejeva et al, 2016). Risks accrue through rising sea-levels, subsidence (Nicholls et al. 2021; Cao et al. 2021) and the projected increase in cyclone intensity (Arias et al 2021).

Exposure: 12 of the top 20 countries exposed to sea-level rise and flooding are in Asia (Neumann et al. 2015) including many in deltas (Edmonds et al. 2020; Nicholls et al. 2021). 70% of global population exposed to sea-level rise and subsidence (which often occurs in deltas) are in just eight Asian nations (Kulp and Strauss, 2015). Growing populations (Neumann et al. 2015; Haasnoot et al. 2021a) exposed to hazards and associated damages (Abadie et al. 2020; Hallegatte et al., 2013) are an increasing concern and one of the main ways that risk accrue (Neumann et al. 2015).

Vulnerability: As populations grow, protection may not have been considered during development, or be limited to sea-walls which only offer limited protection in subsiding areas. Sea-level rise may result in the displacement of people, such as in Bangladesh (Davis et al. 2018) and this has led to the development of the 100-year Bangladesh Delta Plan to ensure water and food security whilst reducing vulnerability to hazards. There is *high confidence* that climate change will have adverse impacts on those who livelihoods depend on coasts and their ecosystems.

Arnell et al. (2019) reports potential impacts displayed in Table A4.3 in the Appendix. This indicates that by 2050 there could be substantial variations in those flooded across socio-economic change scenarios and sea-level rise plus subsidence. Impacts are particularly high under the SSP3 scenario, and lowest under SSP5.

Jevrejeva et al. (2018) highlights Asian countries are predominant in the top ten countries with largest annual flood cost, assuming no additional adaptation, both in absolute and relative terms. China is projected to suffer the largest absolute annual flood losses. Brown et al. (2021) also highlights large potential losses in China, with sea flood damage costs, assuming no additional adaptation, in 2100 ranging from $8903bn at <1.5°C (50th percentile) to $10,952bn at 4.0°C (50th percentile) compared with the 1986–2005 baseline. Many of the costs are projected to occur occur even with lower rises of sea level, as would be expected from the <1.5°C scenario given the significant infrastructure investment and population in large delta regions. Parrado et al. (2020) find that countries and regions in Asia face high indirect macroeconomic effects of SLR and coastal protection investment. China faces the largest impacts globally, with estimates suggesting a change in public deficit of more than 500 billion US$ by 2050 compared to the 2007 baseline, assuming no additional adaptation (SSP2, RCP8.5).

Further work could include a growing emphasis on adaptation solutions, moving beyond sea walls, and a greater emphasis of ecosystem-based adaptation. In many areas, adaptation needs to focus on both sea-level rise and subsidence (Takagi et al. 2017) as large numbers of people could be exposed. Adaptation needs to be integrated with development at the time, rather than in retrospect. Simultaneously, basic coastal modelling is needed for national scale assessments in some nations as details of the impacts of sea-level rise is scarce.

Australasia

Australasia has identified impacts and more focused on adaptive solutions compare with other world regions.

Hazards: Local drivers include subsidence (Watson 2020; King et al. 2020) and sea-level rise. Where wind-speed increase, 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).

Exposure: Hotspots include cities, such as Sydney (Hague et al. 2020) or along the Gold Coast. Exposure has been identified within the road, rail, built environment, storm/waste and water supply systems (Ministry for the Environment 2021; Commonwealth of Australia 2018).

Vulnerability: There is *high* confidence that vulnerable populations include Aboriginal, Torres Strait Islanders and Tangata Whenua Māori. Adaptation to infrastructure and exposed assets is being considered, with adaptation pathways in development (Lawrence et al. 2018). A major shift is how to move away from defence strategies to more transformative methods (Jongejan et al., 2016), such as planning regulations, particularly in urban areas and construction of new infrastructure (Walsh et al. 2004, Dedekorkut-Howes et al. 2021), improving early warning system, plus household and community self-reliance (Astill and Miller, 2018).

Impacts may occur through compound events. In New Zealand, risks to ecosystems and the built environment, (Ministry for the Environment 2021), building on the nuisance flooding seen today. In New Zealand, a 1m sea-level rise means that built-land and asset exposure doubles for a 1-in-100 year event (Paulik et al 2020). With sea-level rise, coastal squeeze and wetland degradation are also projected to occur.

Arnell et al. (2019) reports potential impacts displayed in Table A4.4 in the Appendix. This indicates that by 2050 impacts are projected to be similar across all climate and socio-economic scenarios. By 2100, the potential range of impacts are more widespread with between 0.04-0.16 million people per year at risk from flooding.

As an aggregate, the high-income group of countries, including Australia and New Zealand potentially face large absolute coastal flood losses (after the upper middle income group), but if additional adaptation in the form of sea dikes is assumed then a large proportion of losses could be prevented, resulting in the lowest annual total flood costs of all World Bank income groups (Jevrejeva et al. 2018).

Further research could concentrate on relative costs and benefits of a broader range of adaptation strategies (Dedekorkut-Howes et al. 2021, Tarabi and Howes, 2020) and financial systems to support adaptation.

Central and South America

This is limited research in this region, with risk research more focused on the natural environment rather than people exposed. Hence there is *low* to *medium* confidence in risk.

Hazard: With climate change, cyclone intensity is projected to remain at similar levels over the Caribbean, with sea-levels being the main risk driver (Kleptsova et al 2021). Additionally, local sea-levels are enhanced during El Niño-Southern Oscillation (ENSO) events (Villiamizar) or due to swell waves (Andrade et al. 2013). Subsidence (e.g., Cartagena in Caribbean Colombia (Restrepo-Ángel et al. 2021) can enhance sea-level rise. Wave run-up during extreme events (Heidarzadeh et al. 2018) is also a concern.

Exposure: Mangroves, which cover 28% of the low elevation coastal zone in Latin America and the Caribbean (Spalding et al. 2011) are threatened (Nagy et al. 2019), as are tourist beaches (Rangel-

Buitrago et al. 2015; Cueto Fonseca et al. 2021, Villamizar et al. 2017) and fishing zones for local communities. Increased salinisation especially in delta areas due to the long tidal range and increased flood extent (Rojas et al. 2018) is a concern as a greater land area would be exposed to flooding. Tourist areas will be exposed, which if flooded have implications for income.

Vulnerability: There is limited information on vulnerability specifically related to sea-level rise. Adaptation constraints are linked with poverty, resource allocation, political will and also a lack of early warning systems (Nagy et al. 2019, Villiamizar et al. 2017). Adaptation is moving towards ecosystems, reef restoration early warning systems, enhancing adaptive capacity, education and disaster risk preparedness (Nagy et al. 2019; Leal Filho et al. 2018; Mercer et al. 2012; Reguero et al. 2018). National Adaptation Plans are developed, but not fully implemented (Nagy et al. 2019).

Arnell et al. (2019) reports potential impacts displayed in Table A4.5 in the Appendix. This indicates that by 2050, the number of people flooded remains similar across all scenarios except SSP3 which is higher. By 2100, impacts increase, particularly under SSP2 and SSP3 indicating that under these scenarios, socio-economic change is a more important driver of change than sea-level rise. Other studies with RCPs indicate increase in area flooded (Orejarena-Rondon et al. 2019), increased damage, increased beach erosion and number of people flooded (Vousdoukas et al. 2018, Giardino and Merz 2019).

In terms of economic losses, countries in Central and South America did not factor in the top 20 countries globally with greatest annual sea flood costs (SSP2, assuming no additional adaptation) (Jevrejeva et al. (2018)). However, Brown et al. (2021) report that sea flood damage costs in 2100 in Brazil, assuming no additional adaptation, range from 1.1% of national GDP at <1.5°C to 1.4% at 4.0 °C (50th percentile), equating to 120.1 and 152.8 million US$ per year respectively. However, Parrado et al. (2020) highlights that countries in Latin America and the Caribbean may face high indirect losses related to SLR and autonomous coastal adaptation, with a change in public deficit of more than 150 billion US$ by 2050 compared to the 2007 baseline, assuming no additional adaptation (SSP2, RCP8.5). This is primarily driven by a reduction in GDP and consequently lower tax revenues.

Further research includes basic country level and local level impact assessments, mainstreaming and diversifying adaptation (with finance) and centralisation of data (Jevrejeva) to enable improving adaptation decision making.

Europe

Europe’s coast comprises uplifting, rocky Scandinavian coasts, low-lying heavily protected coastlines of the North Sea, Mediterranean seas, open coasts and deltas, plus small islands. A major risk driver is the hazard where there is *high* confidence that an increase in sea-level rise will result in an increased risk to people and infrastructure with current adaptation measures. With continued investment in adaptation, risk has the potential to decrease with time.

Hazard: This includes erosion and flooding, and in some deltas areas, subsidence, mainly driven by sea-level rise (Hinkel et al. 2011; Antonioli et al. 2020), but also human activities. Changes in sea-ice cover will exacerbate impacts (Kont et al. 2018).

Exposure: Large number of people are situated in low-lying areas, but they are frequently protected. Whilst there is a continued investment and growth of exposed assets, there is a realisation that adaptation cannot happen everywhere and that some exposed areas will be lost to the sea.

Vulnerability: Most countries are now planning for sea-level rise to reduce vulnerability, but to different extents (McEvoy et al. 2021). Risk is reduced by protection where it is economically viable to do so (Lincke and Hinkel 2018, Tiggeloven et al. 2020), such as in densely populated areas of where there is significant infrastructure exposed. For instance, the low-lying Netherlands is highly protected. Venice and its lagoon, although subsiding is being protected by a barrage. Elsewhere, nature based solutions, such as wetlands and sand nourishment (Stive et al. 2013) are used to reduce wave height, this decreasing erosion and flooding. Accommodation measures, such as retrofitting of houses and early warning systems are increasing. Set-back zones (Linke et al 2020) and planned relocation is being increasing considered (Haasnoot et al. 2021).

Arnell et al. (2019) reports potential impacts displayed in Table A4.6 in the Appendix. This indicates across all SSPs, the number of people flooded assuming additional adaptation in 2050 remains similar across all scenarios as sea-level rise is similar. After 2100, the number of people flooded increases, mostly driven by rising sea-levels rather than population change.

Economically, Jevrejeva et al. (2018) highlights that a few countries in Europe are at high risk of large economic losses. Based on absolute losses, the UK features in the top ten countries with largest annual flood cost, assuming no additional adaptation. Annual losses are projected to be 241 million US$ per year at 1.5ºC and 383 million US$ per year at 2ºC (SSP2).

Further work could concentrate on a wider range of adaptation solutions, such as the practical base on nature-based solutions, methods of realignment and integration of the impacts of sea-level rise into spatial planning (Stokke et al. 2014).

North America

The northern Caribbean and east coast of the United States risks are already occurring and are worsened through extreme events (e.g. hurricanes), coinciding with high tides impacting large populations and properties on the coast (Fu et al. 2016; Wdowinski et al. 2016; Heberger et al. 2011).

Hazard: The region is threatened by hurricanes, and locally subsidence can enhance the rate of relative sea-level rise (Eggleston and Pope 2013). In Canada, localised glacial isostatic adjustment means land rises, offsets sea-level rise.

Exposure: Sea-level rise may mean large numbers of people move landward (Hauer et al. 2020; Hauer 2017; Hauer et al. 2016) as housing, including affordable housing (Buchanan et al 2020) is threatened resulting in economic losses and property damage (Weiss 2011; Johnston et al. 2014) *(medium* confidence).

Vulnerability: Protection against extreme events is comprehensive, including hard defences, early warning systems, preparedness, structural measures, community-led adaptation and the ability to clear up after a disaster strikes. Yet this is still insufficient for the major hazards. There is a growing emphasis on green adaptation (Fu 2020, Fu et al 2017), with the number of vulnerable people and assets being significantly reduced if natural ecosystems can remain intact (Arkema). In Canada, planned retreat is also being considered (Saunders-Hastings 2020).

Impacts have been felt though nuisance flooding in the United States which could increase by 55 ± 35% in 2050 under RCP8.5 (Moftakhari et al. 2015). Additionally, there are threats to water supply (e.g. Texas, part of California) impacting on agricultural and coastal communities (Anderson and Al-Thani 2016; Hoover et al. 2017; Rahini et al. 2020) plus flooding from groundwater (May 2020). Wetlands and forests are also at risk (Brown et al. 2019) and aggravated by extreme events today such as La Niña (Desantis et al. 2007; Raabe and Stumpf 2016), and projected to be squeezed or migrate landwards as sea-levels rise (Borchert et al. 2018). There are local concerns in Canada about increased flooding and erosion risk (Radosavljevic et al. 2016).

Arnell et al. (2019) reports potential impacts displayed in Table A4.7 in the Appendix. This indicates the number of people at risk from flooding in 2050 is similar across all scenarios. By 2100, the number of people at risk could potentially double in a non-mitigation scenario compared with a mitigation scenario. Impacts could more than double from 2050 to 2100 due to significant population growth. Under a SSP3 scenarios, impacts are less than the other SSP scenarios in 2100. Thus, sea-level rise has the potential to be a larger driver of impacts in 2100.

Based on absolute losses, Jevrejeva et al. (2018) reported that the USA would feature in the top ten countries with largest annual flood cost, assuming no additional adaptation. Annual losses were projected to be 394 million US$ per year at 1.5ºC and 446 million US$ per year at 2ºC (SSP2). In relative terms this equates to 0.9% and 1% of national GDP in 2100 under 1.5ºC and 2ºC respectively.

Further research could focus on pro-active adaptation, especially ecosystem approaches, to extreme events today.

Small islands

Unlike other IPCC regions where a traditional bathtub approach is taken, for projecting the impacts of sea-level rise, multiple drivers of oceanic and meteorological change are considered. Erosion is more of an immediate issue and is a concern with sea-level rise, but atoll islands are also subject to accretion. Over the century, some coral atolls have sufficiently grown in size over a century (Kench et al. 2015; Duvet 2020). Due to the scale of modelling, impacts for small islands are not commonly published. For example, elevation models are too coarse to determine precise details (Kulp and Strauss, 2019) or model do not consider surface roughness which can reduce flood inundation (Vafeidis et al 2019)

Hazards: Small islands in the Pacific are flooded largely due to compound effects from high tides coinciding with cyclones, distant swells, La Niña conditions combined with human interventions (Canavesio 2019; Ford et al. 2018, Hoeke et al. 2019; Merrifield et al 2014). Tropical cyclones are already impacting small islands and will continue to do so (*high* confidence). With atoll islands around 1m above sea-level, flood frequency is very sensitive to sea-level rise (Vitousek et al. 2019), so with climate change flood frequency is likely to increase. Flooding and future sea-level rise is very locally driven due to topography and bathymetry and can also occur due to drainage and raising groundwaters. Sea-levels are likely to be higher in the Pacific than the global mean (Oppenheimer et al. 2019). There is *very* high confidence that atolls are particularly at risk from rising sea-levels, including the associated effects of ground salinisation that can impact ground water. Groundwater flooding and salinisation may be a more dominant risk than over topping.

Exposure: Risks accrue today through growing populations often near the coast (Mason et al. 2020; Kumar and Taylor 2015; Andrew et al. 2019) and development.

Vulnerability: Small island nations acknowledge that adaptation is essential, widespread and diverse (Klock and Nunn 2019), but challenging to deliver. Coastal hardening which is a relatively common adaptation measure and increasing even if rural islands (Robinson 2017) may decrease risk in the short-term but can amplify long-term risk as atolls cannot accrete naturally or significant population growth may occur behind protected locations. With many built assets on the coast, adaptation requires substantial financial resources (Kumar and Taylor 2015; Mycoo 2014). Seawalls can fail without additional investment, and soft engineering or relocation may be a longer term viable alternative (Nunn et al. 2021; Thomas and Benjamin 2018). Accommodation, such as raising floors is also an option (Magnan et al. 2018) as are community-based measures. For atolls and high islands, land claim and raising (Biribo and Woodroffe 2013; Esteban et al. 2019) can offset risk as it acts as a buffer, but may in itself be exposed. To reduce vulnerability, there is an urgent need for investment strategies as presently adaptation is incremental (*high* confidence).

Small islands are already feeling the impacts of climate change, including loss and damage (Martyr-Koller et al. 2021). Rasmessen et al. 2018 projected islands exposed to sea-level rise based on present population levels of 62 million. This indicated using a bath-tub approach with a 1.5°C rise 0.40 million (0.30 million – 0.56 million representing the 5th and 95th percentiles) people could be exposed. With a 2.0°C rise this increased to 0.42 million (0.30 million – 0.64 million) people and with a 3.0°C rise this increased to 0.43 million (0.32 million – 0.63 million) people.

Due to the number of islands, basic data and modelling is essential to understand precisely what is at risk (*high confidence)* and when, plus how risk will evolve. Greater resources are needed to understand how islands can adapt, including incorporation of loss and damage.

Polar

Polar coasts include those of Greenland and Antarctica and the northern most coast of the Russian Federation. Sea-levels declined around some northern polar costs, such as in semi-enclosed seas (Oppenheimer et al. 2019).

Hazard: Concerns are around the melting of permafrost which could result in local ground water flooding (Larsen et al. AR5 2014). Some projections consider an ice-free Arctic ocean summer under a 2°C scenario (Sanderson et al. 2017), whilst others are more optimistic (Hoegh-Guldberg et al. SR1.5 2018) *(medium* confidence). The latter could cause potential damage to coastal infrastructure which were once ice-free and also coastal settlements and marine transport (Larsen et al. AR5 2014). Land-based ice melt is projected to increase local flooding and potential result in erosion due to greater exposure to waves.

Although a long coast, limited information is known for global risk related to potential land lost, people impacted and economic effects (i.e. exposure) and their vulnerability.

Summary

Globally, uncertainties on the state-of-the-art evolve around (i) local processes on the coast, (ii) elevation and (iii) adaptation (Eyring et al. 2021). These portray the components of risk, such as through an improved understanding of the hazard and who or what is exposed to flooding today. Data in the Searchable Inventory is taken from state-of-the-art global datasets, hence greater understanding of regional to local processes and elevation and possible forms of adaptation are needed to guide the interpretation of this data at sub-regional and sub-national levels.

Local processes on the coast are increasingly important in impact assessments, such as localised subsidence (Nicholls et al. 2021) which can enhance the effects of sea-level rise. Additionally, the inclusion of flood mechanisms and extreme events, such as wave driven flooding, swell waves and El Nino-La Nina events (Hoeke et al 2021; Merrifield et al. 2014) would enable an improved reality of how floods are derived. This is already happening in small island settings due to the scale, as bathtub models are not appropriate at high resolution.

Common issues for further global and sub-global research include the need for improved high-resolution elevation data (Gesch) including a focus on city populations (Neumann et al. 2015) where significant growth is projected leading to large numbers of people at risk from future flooding. The advent of the improved elevation data of Kulp and Strauss (2019) has enabled an improved understanding of who or what is at risk including better communication and education of that risk. As digital elevation models improve in resolution this can lead to more informed impact assessments, globally and at a local level where there is limited or no topographic data available. Hence ongoing investment in elevation datasets is vital.

The ability to analyse greater assets at risk in more detail plus a greater means of adaptation would be advantageous, especially where linked to income and economic prosperity. Present global models broadly focus on hard defences as a means to adapt, and sometimes beach nourishment (Hinkel et al. 2013). Increasingly diverse approaches to adaptation are being applied, such as accommodation and ecosystem-based approaches. Applying these both globally and locally to models would be advantageous as it would increasingly align to real-world examples. Incorporating finance to equate for loss and damage would be advantageous to align with climate adaptation funding alluding to in the Paris Agreement (United Nations 2015) and Glasgow Climate Pact (United Nations 2021). Increasingly there is a need for appropriate data to help with decision making. Where appropriate, data hubs containing accessible climate data would also be an advantage (Jevrejeva et al. 2019).

These gaps apply to all global regions. There is limited research of the impacts of sea-level rise in south and central America, plus a limited but growing research base around African coasts. Hence a greater number of targeted studies would be beneficial here. With mega cities in south, east and south-east Asia, greater research is needed to determine how these cities will cope with sea-level rise in the far future. This is important given the high exposure. In small islands and other coasts that are heavily reliant on tourism as the main income, a greater analysis in adaptation, preparedness and post-disaster recovery with respect to the tourist industry and infrastructure could be considered (e.g as a consequence of hurricanes in the Caribbean Moattly; Sheller). This would be advantageous where tourist income is the main source of economic prosperity and is needed to sustain livelihoods.

2.4 Food security and agriculture

Introduction

The potential impact of climate change on agriculture and food security has been widely discussed in the literature on climate change. There is *high confidence* that climate change will make some areas less suitable for crop production and some areas may become completely unsuitable. Whereas some other areas can increase their agricultural productivity (Fezzi et a 2014). Decreased yields are expected in many areas as conditions pass their optimum temperatures. However, at lower levels of global warming, climate change will likely benefit some crops, as these are projected to prefer the warmer conditions. Whilst some crops may benefit from CO2 fertilisation in terms of increased leaf area and yield, this is accompanied by losses in nutrient and protein content which can offset these changes. Overall, even at low levels of global warming, potential increases in crop yields are unlikely to offset the negative impacts projected for other crops and geographic regions. At higher levels of warming, fewer and fewer positive impacts are projected. Changes to food availability and nutritional content of food will increase the number of people at risk of hunger and malnutrition, with risks generally accruing as temperatures increase and risks generally greater in Africa, and Central and South America. Limiting warming to 1.5°C would avoid significant risks associated with food security and agricultural production (Hoegh-Guldberg et al., 2018). Hasegawa et al. (2021) reviewed the literature on projected impacts of climate change on crop production. They found global crop yield declines of -7.3% for maize; -2.2% for rice and -3.6% for wheat per degree increase in warming. Jägermeyr et al. (2021) used the latest generation of climate scenarios (CMIP6) through AgMIP's GGCMI and found more negative impacts on some major crops, occurring earlier, than previous studies. The study found that average global crop yields for maize are projected to decrease by 24% by the late 21st century, with the declines becoming apparent by 2030. Kummu et al. (2021) found that unhalted growth of greenhouse gas emissions could force nearly one-third of global food crop production beyond its safe climatic space by the end of the century.

Africa

Africa is particularly vulnerable to climate change and is projected to be the region hardest hit by its impacts on food security (*high confidence*). Climate change is expected to reduce agricultural yields in Africa due to shorter growing sessions, increased occurrence of pests and diseases and increased water stress (Niang et al., 2014). Climate change is likely to increase the number of people at risk of hunger in Sub-Saharan Africa, where food security problems are already acute. Janssens et al. (2020) project millions more people will be at risk of hunger in Sub-Saharan Africa with warming of around 3°C. In general, negative impacts on yields are expected with climate change, but the extent of the loss is projected to vary between regions and crops. Across Africa, yields reductions for staple crops such as rice, wheat and maize are expected to be lower at 1.5°C warming than at 2°C (Hoegh-Guldberg et al. 2018), a finding which is consistent with Tyndall projections in the Searchable Inventory. Studies have shown that other crops are also at risk from climate change in Africa. Rippke et al. (2016) found that 30–60% of the common bean growing area and 20–40% of the banana growing areas in Africa will lose viability with global temperature increases of 2.6°C and 4°C respectively.

In Southern Africa, Liu et al. (2019) projected reductions in wheat yield of 0-5% for 1.5°C warming and 5-10% for 2°C warming. This is similar to the trends seen in the Tyndall projections in the Searchable Inventory, which shows greater wheat yield losses with higher levels of warming for southern African countries. By contrast, research conducted by AgMIP (Agricultural Model

Intercomparison and Improvement Project) projected increases in rice and soy yields for southern and eastern regions of Africa (Rosenzweig et al. 2013; Ostberg et al. 2018).

Many studies have projected reductions in crop yields in West Africa. West Africa is projected to see substantial reductions in wheat yield, of around 13% with 1.5°C and 19% with 2°C warming (Schleussner et al. 2016). Sorghum yields were also projected to decline across the region; with average reductions of 2% at 1.5°C and 5% at 2°C warming (Faye et al., 2018). These reductions in crop yields will have significant effects on the local population. For instance, in Burkina Faso, child mortality rates are projected to double for subsistence farmer households due to crop yield loss attributed to climate change with 1.5°C warming (Belesova et al. 2019). Tyndall data in the Searchable Inventory shows projected yield declines of between 4-7% in Burkina Faso with 1.5°C warming, with greater losses projected with further temperature rise.

Asia

Many studies have projected reductions in crop production in South and Southeast Asia. With higher levels of warming, the adverse impacts are expected to increase. There is *medium confidence* that climate change will have overall negative implications for food security across Asia. Rosenzweig et al. (2014) projected reductions in wheat yields of up to 50% in comparison to 1980–2010 baseline in Southeast Asia. Reductions in maize yields are also projected by this study. Janssens et al. (2020) project millions more people will be at risk of hunger in South Asia with warming of around 3°C. A slight increase in the number of people at risk of hunger is projected for Southeast Asia as well.

By contrast, increases in the yields of some staple crops are projected in China. This mixed response is also shown in the Tyndall projections in the Searchable Inventory, which projects reductions in maize and wheat yields but increases in rice and soy yields. By contrast, Jägermeyr et al. (2021) found that sizeable wheat gains are projected by many models for the North China Plains and Central Asia. This is supported by earlier studies that made use of the same models. In their global study of wheat yields, Liu et al. (2019) projected a reduction in yield for India of around 5% with 1.5°C and 2°C warming but increases in wheat yields for China, of around 5% with 1.5°C and 10% with 2°C warming. Ostberg et al. (2018) compared different models and climate scenarios. For China, results projected increases in wheat yield in at least 50% of available combinations of GCM, GGCM, and RCP scenarios with 2.5°C warming. Research into potential changes to crop yields in China demonstrates the importance of whether CO2 fertilisation was included in the modelling. When CO2 fertilisation effects are taken into account, studies focused on China largely project increases in crop yields in the future with warming, whereas those that do not consider CO2 fertilisation often project negative yield changes. Ren et al. (2018) modelled the projected change in 7 crops with warming of around 3.5°C above pre-industrial levels. Results for SSP3 projected around a 15% reduction in yield without CO2 effects, or a 5% increase in yield with CO2 effects included. Similarly, results for SSP5 found around a 10% reduction in yield without CO2 effects, or an 8% increase in yield with CO2 effects included.

Australasia

There are relatively fewer regional and country scale studies of changes to crop production and food security for Australasia. Much of the evidence available for the region focuses on Australia. However, some studies have projected shifts in the climatic suitability for wine grapes across New Zealand (Ausseil et al., 2021). The Searchable Inventory projects reductions in wheat yield in Australia with warming of 1.5°C and above. Wang et al. (2018) also projected reductions in crop yield, particularly across the northeast wheat belt, across much of Australia but did show possible increases in the south of the country. Other recent studies have projected increases in wheat yields in Australia with climate change. For instance, Wang et al. (2019) projected that wheat yields could increase by + 2.6% and + 10.5% in response to climate change by the 2030s with around 1.5°C warming above pre-industrial levels and 2070s with around 2.8°C warming. Similarly, Liu et al. (2019) projected an increase in wheat grain production in Australia with 1.5°C and 2.0°C. However, Ostberg et al. (2018), who compared different models and climate scenarios with 2.5°C warming, found disagreement in the sign of wheat yield change in Australia between different crop models, with some models projecting large reductions in yield (around 50%) and others projecting wheat yields would double in northern Australia with 2.5°C warming. Differences in model set up and assumptions (including the exclusion of CO2 fertilisation in the Tyndall projections) can explain the difference in the sign of wheat yield change between the projections in the Searchable Inventory and these other studies.

Central and South America

Reduced climate suitability and yield for beans, coffee, maize, plantain, and rice are projected for Central and South America (Mbow et al., 2019). There is *high confidence* that overall agricultural production will decrease as a result of climate change. These impacts are projected to worsen with higher levels of warming. Rosenzweig et al. (2014) projected reductions in wheat yields of up to 50% in South America in comparison to 1980–2010 baseline with warming of around 4°C. Smaller reductions in other crops were also projected. Similarly, Jägermeyr et al. (2021) projected spring wheat losses in Mexico and South America with warming of over 4°C, with good agreement between different models. This is consistent with the Tyndall projections in the Searchable Inventory. Soybean losses were also projected in Brazil by both Jägermeyr et al. (2021) and the Searchable Inventory.

There is already evidence that changes in timing and magnitude of precipitation and extreme temperatures are impacting crop yields and agricultural production in Central and South America. This is likely to increase with further warming. Decreasing water availability will be a particular problem for agricultural production.

Europe

Drought and water stress are projected to be particularly influential in driving changes to crop yields in Europe. There is *medium confidence* that some crop yields (such as wheat) may increase in Europe with warming of up to 2°C. However, these gains would be insufficient to offset the other negative effects seen in other crop yields across Europe (*high confidence*). Of the major staple crops, maize is projected to suffer the largest negative mean change in Europe. Jägermeyr et al. (2021) projected reductions in maize yield in current growing areas for the time period 2069-2099 under SSP585 across climate and crop models (corresponding to warming of over 4°C), with the greatest reductions seen in southern Europe. By contrast, the study projected increases in wheat yield across current growing areas in Europe. Liu et al. (2019), in their global study of wheat yields projected a small (around 5%) increase across most of Europe with 1.5°C warming. With 2°C warming, some countries such as Italy and Greece expected to see further increases in wheat yields. However, Ostberg et al. (2018) compared different models and found disagreement in the sign of wheat yield change across Europe with 2.5°C warming.

North America

There is *high confidence* that warming temperatures and projected reductions in freshwater availability are very likely to alter crop production in North America with climate change. Lant et al. (2016) concluded that high risk to the agricultural sector in North America begins just before 2°C warming, but global studies of crop yield change have shown a mixed picture for North

America. Projections in the Searchable Inventory are for reductions in wheat yield in the USA and Canada with warming. By contrast, Liu et al. (2019) projected an increase in wheat production of around 10% for the USA with 1.5°C and 2.0°C warming. For Canada the same study projected an increase in grain production (around 5%) with 1.5°C but then reduction with higher warming levels. Jägermeyr et al. (2021) projected gains for winter wheat in Northern USA and Canada with warming of over 4°C, but losses for spring wheat in Southern USA. Losses were also projected in Soybean in the USA and maize across North America.

Small islands

Small island states are extremely vulnerable to sea level rise, freshwater stress and extreme weather events such as cyclones, which will impact their food security (*high confidence*). Where crops are located close to the coast, sea level rise and storms could lead to a loss of agricultural land. There are few studies of the impacts of climate change on crop production at the national scale for small islands. Crop suitability modelling for economically significant crops in Jamaica found that warming of less than 1.5°C could lead to reductions in areas suitable for production (Rhiney et al., 2018). In terms of food security, many small island states are likely to be more impacted by changes to fisheries than crop production.

Summary

Global food security will become increasingly challenging with projected future climate change, with risks generally building with greater levels of warming. Overall, the impacts on crops grown in the tropics are projected to be more negative than in mid to high latitudes (Mbow et al., 2019). Global analyses have even projected increases in the yield of some staple crops such as wheat in the mid to high latitudes (Rosenzweig et al., 2014). By contrast, the negative effects on food security will be a particular problem in Africa, as well as Central and South America. Modelling studies tend to focus on certain crops, for instance staple crops, such as maize and wheat, or those with a high economic value, such as tea and coffee. Future research should consider a greater range of food crops.

Model projections and state-of-the-art methods still have high uncertainties. For some crops, different crop and climate models disagree on the sign of the change at the global scale (Jägermeyr et al., 2021). Multi-model intercomparisons (such as AgMIP) are increasingly used to evaluate different models and scenarios and these are extremely valuable for quantifying the uncertainties. These studies have shown that rice yields show less variation across models than other crops such as maize and wheat. It is also important to highlight the need for further model comparison studies as new projections and crop models become available. Hasegawa et al. (2021) recently reviewed the literature on climate change effects on crop yields and concluded that robust estimates must draw on various simulation studies. Uncertainties and the full range of results across different models should be clearly presented. Furthermore, the extent to which carbon fertilisation will influence agricultural production remains a key uncertainty in the projections. Few models take into account crop protein content, as well as the effects of changes in phenology, potential long-term changes in soil, and interactions with pests, pathogens and pollinators.

The Tyndall projections in the Searchable Inventory rely on outputs from a single crop model, which does not consider carbon dioxide fertilisation effects, which can have implications for crop yield estimates. Therefore, the results presented are likely to be more negative than other studies (as shown in the regional sections above). However, there is also evidence that the beneficial effects of elevated CO_2 on crop yield have been overestimated and can lead to protein deficiency, thus potentially offsetting increases in crop yield seen with climate change (Medek et al., 2017).

In addition, these estimates assume that the available crop area and the crops grown are constant over time. This assumption is consistent with other modelling projects, including the ISIMIP project and data provided by Climate Analytics. However, this means that the potential to offset declines in yield by shifting agriculture into areas which become more climatically suitable in the future has not been considered. The approach also omits the potential for climate-change induced increases in pests/diseases to further reduce yields. This is consistent with many other studies of the effects of climate change on crop yield.

In addition, the impact of extreme weather events such as extreme heat, droughts and storms on food security with climate change remains uncertain. Extreme climatic events already cause food insecurity and can lead to increases in food prices. The increased number and intensity of extreme events projected to occur with warming is likely to lead to lower food production and increased crop damage. Crops are particularly sensitive to droughts during the developmental stages. Droughts also affect soils which further impacts crop production. As well as impacting crops at the local level, extreme events can disrupt the food supply chain. Extremes are not directly modelled in the projections of crop yield change presented in the Searchable Inventory.

Furthermore, while the impact of climate change on agriculture is widely discussed, there have been few studies that quantify the economic responses to climate-induced crop yield changes with different levels of warming. Relatively few country-level studies of the economic impacts of climate change on agriculture exist (Wang et al., 2021). Additional research into the economic implications is needed.

Despite the uncertainties in the methods and between different crop and climate models, food security metrics all generally show that some regions, such as Africa, Central and South America, will be more vulnerable. Overall, the impact of climate change on crop yield without adaptation is projected to be generally negative, though the magnitude of changes varies greatly within each crop and between regions. The metrics presented in the Searchable Inventory could be combined with other elements of food security, such as food access, food utilisation and food stability, to fully understand the impacts of climate change in this sector. For example, most studies do not consider technological advances.

2.5 Fisheries

Introduction

Fisheries provide food for 7.6 billion of the global population, with fish exports valued at 164 billion US dollars and fisheries production rising year on year (FAO, 2020).

Fisheries state-of-the-art global modelling use a variety of ecosystem models, coupled to Earth System Models (ESMs) from the CMIP ensemble, forced by different RCPs. Dynamic Bioclimate Envelope Models (DBEMs) are a central type of these ecosystem models. DBEMs include marine ecosystem drivers (atmospheric, surface and bottom temperature, surface and bottom oxygen, and net primary productivity) from ESMs (Cheung et al., 2016). DBEMs predict current distributions of fisheries species from known ranges and habitat preferences, and future distributions from changes in habitat suitability. They include movement and dispersal of larvae and adults, population growth, and carrying capacity. The central metric derived from these models is the maximum catch potential (MCP), also called marine fish catch potential (MFCP) in marine specific studies (Cheung et al., 2016). MCP (or MFCP) is a projection of the future fish stock under levels of global warming. Another ecosystem model type, similar to DBEMs, are dynamic size-based food web models (DSFMs). These distinguish fish by size, rather than as individual species. DSFMs include marine ecosystem drivers (hydrodynamics, abiotic environment, temperature, plankton productivity, and biomass per plankton functional type). They represent the food web with 100 pelagic fish groups, log-spaced by weight, which feed according to size-based preference i.e., with large fish feeding on small fish which in turn feed on large plankton. MFCP is also the central metric (Cheung et al., 2019).

Such ecosystem models can be run at global or regional scales, with different definitions used to partition the ocean. Large marine ecosystems (LMEs) are used to partition the coastal ocean into areas with similar topography, current dynamics, productivity, and trophic interactions, and are where around 90% of global fisheries catch is taken. Notably they do not follow countries' national borders. Another way to partition the coastal ocean is by countries exclusive economic zones (EEZs), these extend from the coastline of the country in question, out to 200 nautical miles, where each country has special rights regarding extraction of marine resources (FAO, 2020).

Climate vulnerability assessments (CVAs) are also used to assess the potential impact of climate change on fisheries. CVAs "*provide a framework for evaluating climate impacts over a broad range of species with existing information. These methods combine the exposure of a species to a stressor (climate change and decadal variability) and the sensitivity of species to the stressor. These two components are then combined to estimate an overall vulnerability. Quantitative data are used when available, but qualitative information and expert opinion are used when quantitative data is lacking*" (Hare et al., 2016). Similarly, an FAO study on climate impacts on global inland fisheries used projected temperature and precipitation output of CMIP models at RCP2.6 and RCP8.5 at country levels and projected water stress and population density as stress indicators. The stressors were then scored and combined by country to provide an overview of climate impacts (Harrod et al., 2019).

Africa

The IPCC reports with 'high confidence' that climate change is a 'significant threat' to African marine and freshwater fisheries, with risks accruing with warming (IPCC, AR6, Ch 9). Using African LMEs, risks accrue from a -8% loss in MFCP at 1.5°C to a -44% loss at 3.5°C (Appendix Table A6.1). Using EEZs of African countries from a DBEM and DSFM, average MFCP shows declines under RCP2.6

of -18% (by 2050) to -15% (by 2100), with stronger declines under RCP8.5 of -22% (by 2050) to -43% (by 2100) (Appendix Table A6.2).

Cheung et al. (2016) using DEBM modelling of LMEs, found the reduced MFCP is enhanced in tropical regions, especially at greater levels warming, with MFCPs of -62% and -67% at 3.5°C for the Guinea Current and Somali Coastal Current respectively. This is slightly reduced in Southern Africa with MFCP's of -41% (Benguela Current) and -36% (Agulhas Current) at 3.5°C and further reduced in Northern Africa with an MFCP of -14% (Canary Current) at the same warming level. While at 1.5°C of warming, MFCP across Africa is reduced by -8%, with a range of -1 to -12% (Cheung et al., 2016). Enhanced impacts in tropical regions are in part due to the acute vulnerability of coral reefs to climate change, which are a key habitat for a variety of commercial fish and invertebrate species, particularly at early life stages. The IPCC reports with 'very high confidence' that more than 90% of warm-water coral reefs will be lost at 2.1°C of warming (Hoegh-Guldberg et al., 2018)(IPCC, AR6, Ch 9).

A regional study on the Benguela Current, using an end-to-end ecosystem model, forced with scenarios RCP2.6 and 8.5, found that for over half of the modelled groups biomass reduction increased from >-20% in RCP2.6 to >-30% in RCP 8.5. The largest biomass reduction was for anchovies, increasing from -46% to -53% under the two scenarios (Ortega-Cisneros et al., 2018).

A trait-based CCVA on African inland fisheries of commercially important freshwater fish, found that risks accrue severely with warming; at 2°C warming 36% of species are vulnerable to extinction, this increases to 55-68% with only an additional 0.5°C of warming, and at over 4°C of warming 77-79% of species are vulnerable to extinction. The regions at greatest risk from warming are West African coastal rivers, Rift Valley lakes and the Congo River basin (Nyboer et al., 2019).

Climate-related extreme weather has already had impacts on marine and freshwater fisheries, and these are likely to increase in the future as climate-related extreme weather events increase with climate change (Muringai et al., 2021). Although the report contains no analysis of the risks to the fish stocks themselves.

Asia

Asia contributes 75% of global fisheries production, with China, Indonesia, India, Vietnam and Japan in the top 10 countries globally for fisheries production (FAO, 2020). The IPCC reports 'high agreement' in the literature for 'high vulnerability' of Asian fisheries to climate change (IPCC, AR6, Ch10).

For Asia as a whole, MFCP is projected to decline as temperatures rise from -5% at 1.5°C, to -7% at 2°C and to -35% at 3.5°C (Appendix Table A6.1). The range of responses across ecosystems is large; for several LMEs around Japan MFCP is projected to increase as temperatures rise, by 16% at 1.5°C for the Sea of Japan and Oyashio Current and 31% for the Sea of Okhotsk, increasing up to >30% and >80% respectively by 3.5°C of warming (Cheung et al., 2016). At the other end of the scale at 1.5°C is the Indonesian Sea with declines of -30%, and at 3.5°C the Indonesian Sea and the Gulf of Thailand have MFCP declining by >-90% (Cheung et al., 2016). Using EEZs of Asian countries, Cheung et al. (2019) finds average MFCP shows moderate declines under RCP2.6 of -7% (by 2050) to -6% (by 2100), with stronger declines under RCP8.5 of -14% (by 2050) to -33% (by 2100) (Appendix Table A6.2).

Fernandes et al. (2016) used a regional DBEM, of a physical-biogeochemical model of the Bay of Bengal, using output from a regional climate model and a hydrological model (comprising river-flow and nutrients) and applying different fishing management regimes in Bangladesh to key fished species. The climate model was forced with Special Report on Emissions Scenario (SRES) A1B, a medium-high emissions scenario, now outdated. They find a change in fisheries production of -8%

from 2000s to 2090s, which worsen under 'business as usual' and 'over-fishing' scenarios for two key fished species (Fernandes et al., 2016). Cheung et al. (2016), in their global DBEM, found declines in the Bay of Bengal of -1.5% at 2°C and -38% at 3.5°C.

Barange et al. (2014) employed a dynamic coupled size spectrum model, with high-resolution of shelf seas, also forced with SRES A1B, to 2050, equating to around 2°C of warming. They find moderate declines of MFCP in Asia, varying by region. Notably they find one of the largest increases globally to be in the Kuroshio Current (21.3%), neighbouring the LMEs found by Cheung et al., (2016) to also increase. Although Cheung found declines in the Kuroshio Current LME specifically.

Australasia

For Australasia as a whole, MFCP is projected to decline as temperatures rise from -11% at 1.5°C, to -13% at 2°C and to -28% at 3.5°C (Appendix Table A6.1). Only the Southeast Australian Shelf shows an increase in MFCP with warming, and the effect is moderate, with no effect at 1.5°C, rising to an increase of 6.4% at 3.5°C. All other LMEs in this region are projected to have decreasing MFCP. The most affected area at all levels of warming is the North Australian Shelf, with risks increasing from -24% at 1.5°C, up to -76% at 3.5°C (Cheung et al., 2016). Using EEZs of Australia and New Zealand, average MFCP shows moderate declines under RCP2.6 of -3% (by 2050) to -2% (by 2100), with increased declines under RCP8.5 of -7% (by 2050) to -19% (by 2100) (Appendix Table A6.2).

Climate change is already impacting fisheries in Australia through shifting the range of species poleward, as species move to stay within their thermal tolerance as oceans warm (Gervais et al., 2021). Although Gervais et al. notes that studies are hampered by sparse baseline data on species distributions, and are generally focussed on the highly populated, southerly regions of the country, with a lack of research undertaken in the northerly, tropical regions. Another impact of climate change on Australian fisheries already evident is the loss of key habitat-forming species i.e., the gradual loss of kelp forests in eastern Australia (Vergés et al., 2016) and extreme weather events driving rapid mortality of corals and kelps (from heatwaves), seagrasses (from flooding runoff) and mangroves (from drought) (Babcock et al., 2019). A multi-model approach, with nine regional EcoPath with Ecosim (EwE) models aimed to assess the long-term climate impact of extreme weather events on these key habitat-forming species. A median recovery time for habitat-forming species of 10-15 years (ranging from 4-60 years) was found, which combined with the climate driven increasing frequency of extreme weather events to 1 in 15 years, results in many habitats being unable to sufficiently recover between events, and subsequently reducing fisheries catches by 15-25% (Babcock et al., 2019).

Fulton et al. (2018) uses the Atlantis ecosystem model for the Great Australian Bight, covering two LMEs (Southeast and Southwest Australian Shelves), for a variety of stressors, including climate change, fisheries, protected areas, pollution, and shipping. Fulton et al., find changes in fisheries catch at 2°C (under RCP8.5 in 2050) of declines in demersal fish (-14%), slope fish (-8%) and small forage fish (-11%) and increases in large pelagic fish (16%). For comparison, at 2°C of warming Cheung et al. (2016) find a slight increase in fisheries catch for the Southeast Australian Shelf (1%) and a substantial decrease for the Southwest Australian Shelf (-23%).

Pethybridge et al. (2020) employ 13 marine ecosystem models (of five types) of regions around Australia, forced with the multi-model mean of CMIP5 for RCP8.5 to 2050, finding temperate and demersal regions to be more negatively affected by climate change than tropical and pelagic regions. The demersal/pelagic response is similar to results found by Fulton et al. (2018), while the temperate/tropical response is in opposition to results in Cheung et al. (2016) at 2°C, where the most northerly tropical LME has the strongest negative response (-29%) and the most southerly temperate LME has the most positive response, of a small increase (1%) in catch potential.

In New Zealand, a statistical spatial population model of albacore tuna, found an increase in abundance and a range expansion poleward under RCP8.5 (Cummings et al., 2021). Law et al. (2016) use an ensemble of ESMs to project vertical particle flux under RCP4.5 and RCP8.5 to 2100, this is combined with current fish ranges and diets to generate a 'fish-based' flux. Overall, a decrease in particle flux was found, with subsequent decreases in fish flux for all 38 key species assessed, with biomass changes of between -2.9 to -14.7% for RCP4.5 and between -5.7 to -24.6% for RCP8.5 (Law et al., 2016). This aligns with results from Cheung et al. (2016) which finds declines in the New Zealand Shelf MFCP of -7 to -21% at 1.5°C to 3.5°C of warming.

Central and South America

Central & South America contains the most productive marine ecosystem for fisheries catch, the Humboldt Current System (HCS), where climate is considered the most important driving factor (Bertrand et al., 2019). The IPCC reports 'high confidence' in impacts of climate change hazards in fished marine resources, with 'very high confidence' that the worst impacts will be in the Eastern Tropical Pacific, including the HCS, related to changes in El Niño Southern Oscillation (ENSO) (IPCC, AR6, Ch12).

For Central & South America as whole, MFCP is projected to decline as temperatures rise from -13% at 1.5°C, to -15% at 2°C and to -32% at 3.5°C (Appendix Table A6.1). Six of the seven LMEs have a minimal change in MFCP from 1.5°C to 2°C, with values across the ecosystems ranging between -3% and -17%. The MFCP for four of these ecosystems then reduces at 3.5°C to between -20 and -40% and remains the same for the other two. The other ecosystem, Pacific Central American, stands out as the most affected with risks strongly accruing from -33% at 1.5°C to -98% at 3.5°C (Cheung et al., 2016). Using EEZs of Central & South American countries average MFCP declines under RCP2.6 of -7% by 2050 reducing slightly to -4% by 2100. While under RCP8.5 MFCP declines from -11% by 2050 to -32% by 2100 (Appendix Table A6.2).

A biogeochemical model of the HCS, investigating climate effects on egg and larval dispersal of small pelagic fish (i.e. Anchovy), comparing pre-industrial to 4xCO_2 for a 30-year period, found a significant reduction in fish capacity with increasing CO_2 (Brochier et al., 2013). Global models find more moderate declines in MFCP in the HCS, of -7% to -9% from 1.5°C to 3.5°C (DBEM, Cheung et al., 2016), -3% to -10% from 1.5°C to >3.5°C (DBEM, Cheung et al., 2019) and -4% to -13% from 1.5°C to >3.5°C (DSFM, Cheung et al., 2019). The HCS has previously undergone large changes shifting the ecosystem into different states, these ecosystem shifts are very likely to occur under climate change (Bertrand et al., 2020), but are not currently accounted for in current modelling, especially global scale models. The FAO reports this as a key reason why global models predict a low to moderate impact in this region from climate change (Cheung et al., 2019). Although both types of model in Cheung et al. (2019) predict more substantial declines in Peru's EEZ (northern HCS) at >3.5°S of -55% and -23% (DBEM and DSFM respectively).

The DBEM finds the strongest impacts of climate change occurring in the tropics, in the Pacific Central-American region, of -98% at 3.5°C in Cheung et al. (2016) and -78% at >3.5°C in Cheung et al. (2019), with the DSFM finding more moderate declines of -19% at >3.5C (Cheung et al., 2019).

Europe

The IPCC reports with 'high confidence' that climate change has already negatively impacted marine fisheries in Europe, particularly in the North Sea, Iberian coastal Sea and Celtic-Biscay Shelf (IPCC, AR6, Ch13). Although, with most fish stocks already overfished (Froese et al., 2018), extraction, rather than climate change, is considered the largest impact on fisheries in Europe.

For Europe as a whole, MFCP is projected to decline as temperatures rise from -8% at 1.5°C, to -12% at 2°C and to -19% at 3.5°C (Appendix Table A6.1). One ecosystem is projected to have an opposing trend to the rest, with MFCP in the Black Sea increasing as temperatures increase, from an initial decline of -14% at 1.5°C, up to a 37% increase at 3.5°C. All other ecosystems have negative MFCP at 3.5°C, with three experiencing declines of >-37% (North Sea, Celtic-Biscay Shelf and Mediterranean). Using EEZs of European countries MFCL declines on average by -28% to -25% by 2050, further declining to -31% to -39% by 2100 (RCP2.6 and 8.5 respectively) (Appendix Table A6.2).

The European-wide project CERES (Climate change and European Fisheries and Aquaculture) assessed fisheries using regional-scale models with RCP4.5 and RCP8.5 to 2100, under a range of management scenarios (Peck et al., 2020). For most commercially fished species, abundance was reduced by -35%, between 1.5°C and 4°C, with reductions up to -90% for species in certain regions i.e., herring and plaice in the North Sea, Northeast Atlantic and Bay of Biscay, and mackerel and sardine in the western Mediterranean and Aegean Sea (Peck et al., 2020).

Fernandes et al. (2017) used two coupled regional hydrodynamic-biogeochemical models of UK fisheries under RCP2.6 and RCP8.5 to 2100 and found that MFCP declined by around -60% under RCP8.5, equating to warming >3.5°C. This is higher than the declines found by two global models for the UK under RCP8.5, of -40% (DSFM) and -25% (DBEM) by 2100 (Cheung et al., 2019).

Heatwaves have caused mass mortality events of marine and freshwater species across Europe, and this is likely to worsen under climate change (Frölicher et al., 2018), but such extreme weather events are poorly represented in models.

North America

The IPCC reports with 'high confidence' that climate change will intensify losses in North American fisheries (IPCC, AR6, Ch 14). For North America as a whole, MFCP is projected to decline as temperatures rise from -5% at 1.5°C, to -8% at 2°C and to -22% at 3.5°C (Appendix Table A6.1). LMEs of the Atlantic coast of the U.S. have the largest decline and follow a similar trend, with a small decrease in MFCP from 1.5 to 2°C (range of -7 to -20% decreasing to a range of -10 to -23%), then dropping to -38 to -47% at 3.5°C of global warming. The other LMEs stay within a range of ±2% for 1.5 and 2°C of warming, the Gulf of Alaska has an increase in MFCP at 3.5°C of 10%, while the other LMEs decrease to a range of -11 to -15% (Cheung et al., 2016). Using EEZs of North America, declines average -6% by 2050 for RCP2.6 and RCP8.6, and -5% to -11% by 2100 (RCP2.6 and 8.5 respectively) (Appendix Table A6.2).

Declines in yield and poleward range shifts have been found by several regional studies of North America. Hare et al. (2016) used a CVA of 82 marine species in the Northeast US Shelf, finding that for half of species climate vulnerability is high to very high, and for most species there is a high potential for range distribution shifts with climate change. Rheuban et al. (2017) used a subset of a CMIP5 model, regionally downscaled for the northeast US Shelf under RCP4.5 and RCP8.5. They used bottom temperature combined with the known thermal tolerance of life stages of the American Lobster, and found poleward and offshore range expansion, with range reduction in nearshore southerly regions. Morley et al. (2018) coupled habitat models for 686 marine species to CMIP5 models under RCP2.6 and RCP8.5 for North American Atlantic and Pacific shelves. Range shifts under climate change were mostly poleward following coastlines, but with variation in regions and species. The largest range shifts were in the Californian Current, followed by the Gulf of Alaska, then the northeast US Shelf.

Moore et al. (2021) updated the model from Morley et al. (2018) adding RCP4.5, two new models, and projecting catch levels, assuming the catch changes in direct proportion to the projected change in habitat range. They project catch levels by 2100 for crustaceans will decline by -2.8% to -3.5%, and for fish by -3% to -13.2%, for RCP4.5 and RCP8.5 respectively. Bryndum-Buchholz et al. (2020) using Fish-MIP (involving CMIP5 projections forced with RCP2.6 and 8.5, driving six marine ecosystem models) found declines in biomass of –5 to -40% under RCP8.5 for the northeast US Continental Shelf and Scotian Shelf. Similar to the declines in biomass found by Cheung et al. (2016) of 13-43% in their global DBEM for the same region. Although it should be noted that this DBEM was one of the six models used in Bryndum-Buchholz et al., albeit under slightly different conditions.

Cheung and Frölicher (2020) modelled marine heat waves in the northeast Pacific, using DBEM forced by an ensemble of ESMs using RCP8.5 to 2050, finding that marine heat waves doubled the negative impact of climate change on key fisheries species.

Small islands

Small island countries are often inherently more dependent on fisheries for national income, food security and independence than other countries (Monnereau et al., 2017), with fish protein estimated to contribute 40-90% of the animal protein consumed in Pacific island's (Bell et al., 2009; Hanich et al., 2018).

Bell et al. (2021) modelled the western Pacific Ocean for three tuna species, used a spatial ecosystem and population dynamics model, forced with four ESMs for RCP8.5 to 2050. The combined tuna biomass declined by an average of -13% for the island EEZs, and >-20% for three of the EEZs, while concurrently increasing by an average of 12% in the high seas. Asch et al. (2018) modelled the western Pacific Ocean, including seventeen Pacific Island entities, using DBEM to forecast MFCP to 2100 under RCP8.5. For nine of the island entities MFCP is projected to decline by >-50%. The only increases occur in Wallis and Futuna by 2050, which changes to a decline by 2100. While for Easter Island, in the eastern Pacific, MFCP is projected to increase by 43% by 2100 under RCP8.5 (Cheung et al., 2019).

Townhill et al. (2021) downscaled ESMs under RCP4.5 and RCP8.5 for the South Atlantic, with an ensemble of four species distribution models of five tuna species, to determine changes in habitat suitability in the EEZs of Tristan da Cunha, St Helena, and Ascension Island. Habitat suitability for one species declined in Tristan da Cunha and St Helena, while it increased in the other EEZ. For all other species in every EEZ habitat suitability increased with climate change. Cheung et al. (2019) found increased MFCP for Tristan da Cunha (DBEM 25%, DSFM 1%), and decreased MFCP for Ascension Island (DEBM -26%, DSFM -42%) and St Helena (DBEM -5%, DSFM -43%) by 2100 under RCP8.5.

In their global study, Cheung et al. (2019) projected that by 2100 under RCP8.5, islands in the Indian Ocean may experience a decline in MFCP of -42% on average, while those in the Caribbean are projected to experience a decline of -17% on average. Impacts in tropical small island countries are expected to be more acute due to the vulnerability of coral reefs to climate change, which act as a key habitat for certain life-stages of many commercial fish and invertebrates. The IPCC reports with 'very high confidence' that these tropical corals in the Pacific and Indian Oceans are presently at 'high risk', and with 'high confidence' of 70-90% loss at 1.5°C of warming and 99% loss at >2°C (Hoegh-Guldberg et al., 2018). Global models of climate impacts on coral reefs and those on fisheries are not yet integrated, and so the future impact of declining corals on fisheries species has yet to be quantified with modelling studies.

Polar

Projections differ strongly in the polar regions between global and regional models. Global-scale models often project increases in catch potential, while regional, high-resolution models often project declines in catch due to warming and loss of sea ice (IPCC, AR6, Ch 6).

Global DBEM studies show strong increases in MFCP in polar regions with warming, following the opposite trend to most other global regions. In polar LMEs catch is projected to strongly increase as temperatures rise from 18% at 1.5C, to 41% at 2°C, up to 110% at 3.5°C (Appendix Table A6.1). In polar EEZs catch increases by 42% in 2050 to 71% in 2100 (average of RCP2.6 and 8.5) (Appendix Table A6.2). However, in a global DSFM of polar EEZ's, catch is projected to decline with warming by -2% in 2050 to -8% in 2100 (average of RCP2.6 and 8.5) Appendix Table A6.2).

In the Antarctic LME (sited around the coastline) at 1.5°C and 2°C MFCP is reduced by around -10%, but then increases to 5% at 3.5°C (Cheung et al., 2016). A later global study using the same DBEM reported for small island EEZs in the Southern Ocean, where more of the fishing occurs. For these islands, a similar but more extreme trend was found with catch declining by 2050 by -8 to -1% (RCP2.6 and 8.5) and then increasing by 2100 by 1 to 82% (RCP2.6 and 8.5). The DSFM used in the same study found moderate increases in catch for both RCPs of around 1%, increasing to 1.5% in 2100 (Cheung et al., 2019). A key fisheries species in the Southern Ocean is krill, whose distribution and biomass has shifted poleward and declined with warming. Future projections of krill are still considered uncertain (Atkinson et al., 2019).

The Arctic contains 15 LMEs which exhibit a wide range of responses to climate change. The Faroe Plateau and Newfoundland-Labrador Shelf have declining MCFP for all levels of warming, and the Norwegian Sea and Greenland Sea have minor gains for 1.5 and 2°C which become losses at 3.5°C (Cheung et al., 2016). These four LMES are at lower latitudes in the Atlantic region of the Arctic. At similar latitudes in the Pacific, the Aleutian Islands and East Bering Sea experience substantial increases in MFCP, with the Aleutian Islands rapidly accruing with warming, from increases of 72% at 2°C, up to 164% at 3.5°C. The largest increase is in the Kara Sea, north of Russia, where at only 1.5°C MFCP increases to 89% and continues to increase with warming up to 655% at 3.5°C (Cheung et al., 2016).

Several regional high-resolution models of the eastern Bering Sea have found declines in catch and biomass, opposing trends found in a global DBEM of the same region where catch increases with warming from 27% (1.5°C) to 30% (2°C) to 46% (3.5°C) (Cheung et al., 2016). Szuwalski et al. (2021) found populations declined and contracted poleward for two of three crab species studied. Holsman et al. (2020) used an ensemble of high-resolution downscaled ocean models, coupled to a nutrient-phytoplankton-zooplankton model and a multispecies stock assessment, and found by 2100 under RCP8.5 fisheries stocks declines by -70% for pollock, -41% for cod, and -6% for flounder. By 2100 for RCP4.5, stocks of the same species declined by -47%, -25% and increased by 7% respectively. Reum et al. (2020) used downscaled ESMs under RCP4.5 and 8.5 to force a multispecies size spectrum model of the local foodweb. By 2100 stock biomass is projected to decline by -36%, with fisheries catch declining by -61% (average of RCPs).

Mixed results have been found by regional studies of other areas of the Arctic. Bryndum-Buchholz et al. (2020) used the Fish-MIP model, which involves CMIP5 projections driving six marine ecosystem models, found declines in biomass of -5% to -40% under RCP8.5 in the Labrador-Newfoundland LME region, changing to increases in biomass of 20% to 70% further poleward in the Canadian Eastern Arctic – West Greenland LME. Steiner et al. (2019), using a marine ecosystem multi-model ensemble study of the Western Canadian Arctic, found a decrease in a key fisheries species, Arctic cod, MFCP of -17% by 2100 under RCP8.5, but increases of two-tenfold in MFCP of other fish species. Weatherdon et al. (2016) used a DBEM including 98 exploited marine species along British Columbia (in the Gulf of Alaska LME), forced under RCP2.6 and RCP8.5. Most species declined under both scenarios, with enhanced declines under RCP8.5 compared to RCP2.6, averaging -21% and -15% MFCP respectively. While a global DBEM found a 10% increase in MFCP at 3.5°C in the Gulf of Alaska (Cheung et al., 2016).

Summary

From a global perspective, fisheries are expected to decline with a warming climate ('high confidence' in many regions), with risks accruing as temperatures increase, and risks generally more severe in the tropics (Appendix Tables A6.1 and A6.2). Smaller scale, regional models generally have higher resolution and focus on specific species, in the Polar regions it is notable that these often predict opposing results to global models, with strong increases in catch in global models and strong decreases in catch (with a few exceptions) in regional models. In other areas, regional models predict the same trend as global models, but to varying degrees of strength.

In the majority of regions around the world, exploitation of fisheries resources is the major driver of stock levels rather than climate change (FAO, 2020; Barange et al., 2018), with the FAO stating "*it is important to note that these projections only reflect changes in the capacity of the oceans to produce fish, and do not consider the management decisions that may or may not be taken in response*" (Barange et al., 2018). Modelling the interaction of climate change integrated with changes in fisheries catch, overfishing, marine protected areas etc, is still in early stages and introduces substantial additional complexity.

The increase in extreme weather is considered detrimental to marine fisheries, with studies analysing the impacts of current and historic extreme weather events (Muringai et al., 2021; Sainsbury et al., 2018), but these are yet to be included in most marine fisheries models. For example, marine heatwaves are likely to increase with climate change, threatening fisheries (Smale et al., 2019) and where they have been explicitly modelled in the northeast Pacific, heatwaves were found to double the impact of climate change on fisheries (Cheung and Frölicher 2020). The severe projected impacts of climate change on coral reefs are also yet to be integrated into most marine fisheries models.

Data deficiencies for African freshwater fish, around populations sizes, genetic variability, and life history of species (Nyboer et al., 2019), limit the reliability of models. The low buffering capacity of freshwater ecosystems makes them particularly vulnerable to climate change (Harrod et al., 2019). Modelling of freshwater fisheries globally is far behind that of marine fisheries, in part because of the wide range of freshwater habitats (from lakes, to rivers, to wetlands), and in part because of their small contribution to global fisheries production (12%). The use of modelling for inland fisheries projections is based on model outputs of temperature and hydrological changes due to climate change, with these outputs then used to manually assess the impact on fisheries. Non-climate anthropogenic based stressors are predicted to have a greater impact on inland fisheries than climate change, these stressors include over-exploitation, habitat degradation, pollution, dam building, water extraction among others (Harrod et al., 2019).

North America and the Canadian Arctic have a substantially greater volume of literature, especially with relation to directly modelling fisheries under climate change, compared to most other regions. The regional, high-resolution, multi-system modelling work here needs to be extended globally to improve predictions of climate change impacts on key fisheries species.

2.6 Biodiversity and ecosystem services

Introduction

The observed impacts of climate change on biodiversity were first highlighted in the IPCC Third Assessment Report and a subsequent meta-analysis of the published literature (Root et al. 2003). Since then, hundreds of additional studies have been published such that, by the IPCC Fifth Assessment Report, more than 4000 species had been studied (Parmesan, 2006; Parmesan and Hanley, 2015). These analyses continue to be made and published, and the confidence in the attribution to climate change is even stronger (Scheffers et al., 2016; Wiens, 2016; Cohen et al., 2018; Feeley et al., 2020). There is *very high confidence* and *high agreement* that climate change has impacted, and continues to impact, changes such as range shifts (usually poleward or up in elevation) and the timing of events such as migration, flowering, or breeding. Climate associated local extinctions have been observed in 47% of 976 species examined (Wiens 2016; *very high confidence*). These extinctions were higher in the tropics (55%), than in temperate habitats (39%), higher in freshwater (74%), than in marine (51%) or terrestrial (46%) habitats, and higher in animals (50%) than in plants (39%). Further studies noted that, in many of the areas where local extinctions were observed, changes in extreme weather events had increased at a much higher rate than changes in means (Román-Palacios and Wiens, 2020). Globally, it is much more difficult to identify when a species has become totally extinct, and even more difficult to attribute it with high confidence. Nevertheless, the balance of evidence is that three species/subspecies have become extinct owing, directly or indirectly, to climate change (*medium confidence* (one species), *high confidence* (the other two).

There have been thousands of studies on the potential impacts of climate change on species, ecosystems, and biodiversity, both locally and globally. The largest comprehensive study to date is that by Warren et al. (2018) which drew on the modelling efforts of the Wallace Initiative to project how climate change will constrain the geographic range of over a hundred thousand species globally. The results from this study have underpinned key messages in the IPCC 1.5°C Special Report, and key messages and figures in the forthcoming IPCC Sixth Assessment Report. The Wallace Initiative also underpins many of the entries in the Tyndall data included in the Searchable Inventory and the methods and data are described in appendix A7.

The key findings, globally, from Warren et al. (2018a) are:

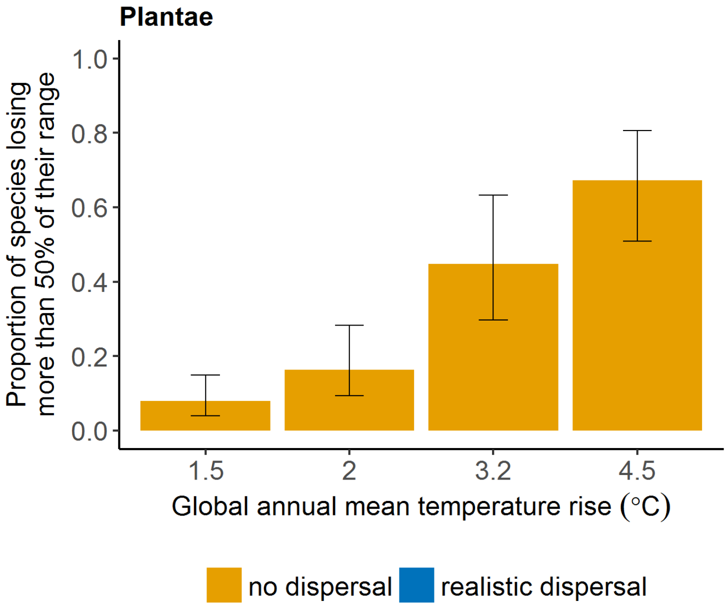


Figure 2: Plants – Proportion of species losing more than 50% of their range

At 3.2°C warming, climatic range losses of >50% are projected in 44% of the terrestrial plants, dropping to 16% at 2°C, and 8% at 1.5°C. Thus, when warming is limited to 1.5°C as compared with 2°C, the numbers of species of plants projected to lose >50% of their climatic range is reduced by ~50%. Thus, limiting global warming to 1.5°C avoids half the risks associated with warming of 2°C for plants.

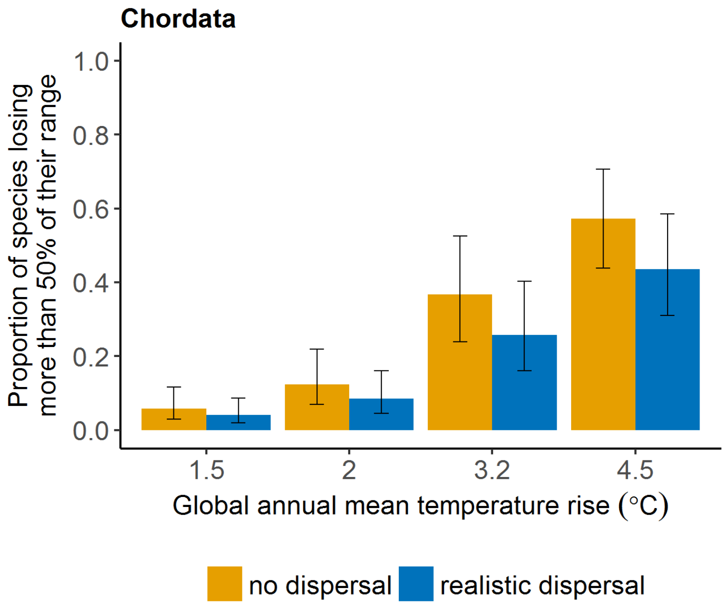


Figure 3: Vertebrates - Proportion of species losing more than 50% of their range

At 3.2°C warming, climatic range losses of >50% are projected in 26% of the terrestrial birds, mammals, reptiles and amphibians, dropping to 8% at 2°C and 4% at 1.5°C. Thus, limiting warming to 1.5°C as compared with 2°C, means the numbers of vertebrates projected to lose >50% of their climatic range are reduced by ~50%. Limiting global warming to 1.5°C avoids half the risks associated with warming of 2°C for vertebrates.

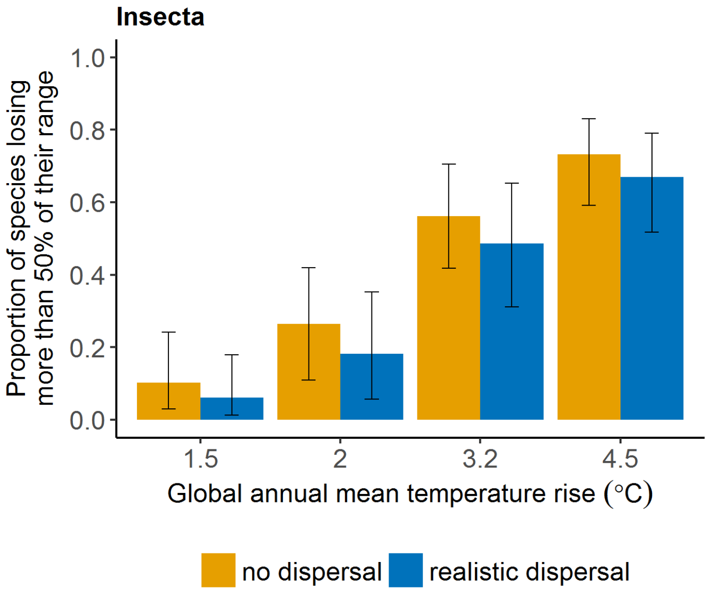


Figure 4: Insects - Proportion of species losing more than 50% of their range

A major advance in this study, compared to previous studies, was the inclusion of large numbers of insects. At 3.2°C warming, climatic range losses of >50% was projected in 49% insects, dropping to 18% at 2°C, and 6% at 1.5°C. Thus, limiting warming to 1.5°C as compared with 2°C, means that the numbers of insects projected to lose >50% of their range are reduced by ~66%. Limiting global warming to 1.5°C avoids two thirds of the risks associated with warming of 2°C for insects. Concern over the impacts of climate change on insects, especially pollinators, has moved from the science policy realm and has been picked up in more mainstream public sources such as *Wired* magazine and the new ABBA song 'Bumblebee'.

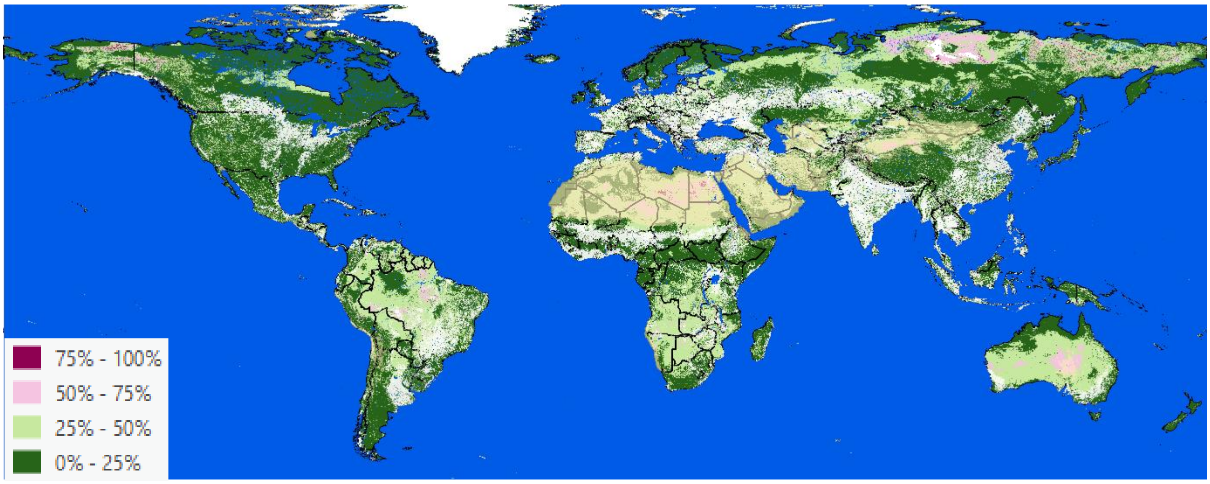
The searchable inventory includes the overall breakdown for projected changes in biodiversity (as a whole as opposed to these individual groups) summarised for countries.

Global Summary: Ecosystems

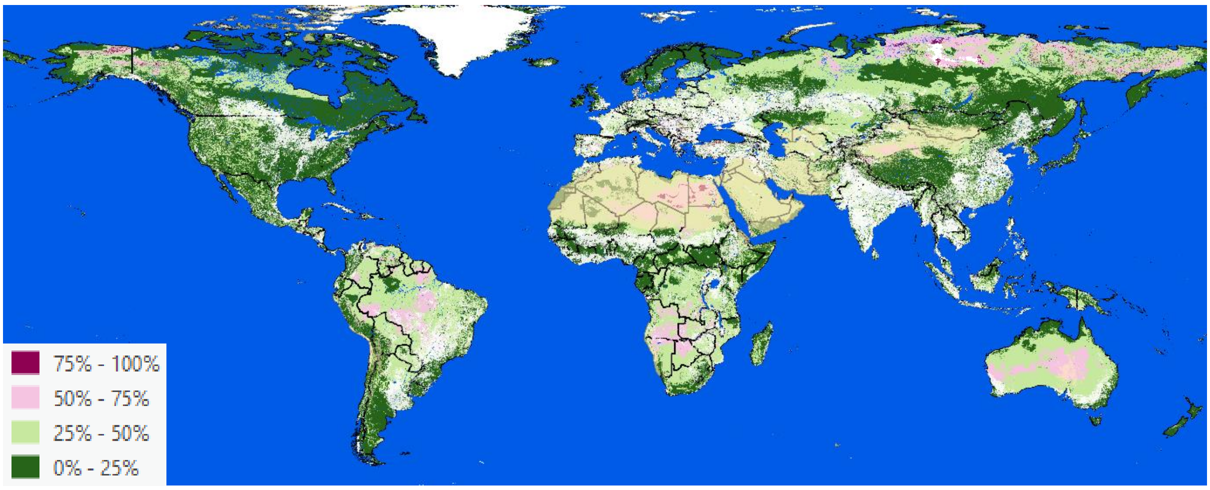
Maps showing biodiversity loss with increasing levels of climate change. The higher the percent of species projected to lose suitable climate in a given area, the greater the risk to ecosystem integrity, functioning and resilience to climate change. Warming levels are based on global levels (GSAT) above pre-industrial temperatures. Colour shading represent proportion of species for which the climate is projected to become unsuitable within a given pixel across their current distributions at a given GSAT warming level, based on the data underpinning Warren et al. (2018; modelled n=119,813 species globally, with no dispersal, averaged over 21 CMIP5 climate models).

Areas shaded in green are above the 50% biodiversity loss threshold, meaning that <50% of species in that area are projected to go locally extinct (I.e., lose their suitable climate). Areas shaded in pink and purple represent significant risk of biodiversity loss (areas where climates become unsuitable, rendering them locally extinct, for >50% and >75% of species, respectively). The maps of species richness remaining have been overlaid with a landcover layer (2015) from the European Space Agency Climate Change Initiative. This landcover layer leaves habitats classified by the ESA as natural as being transparent, cities as black, water as blue, permanent snow/ice as white and bare/rock as dark brown. Areas with a landcover identified as agriculture are 5% transparent, such that potential species richness remaining if the land had not been converted to agricultural shows as pale shading of the legend colours (very pale pink or very pale green). These paler areas represent biodiversity loss due to habitat destruction, but with a potential to be restored, with green shading having potential for restoration to higher species richness than pink and purple shadings.

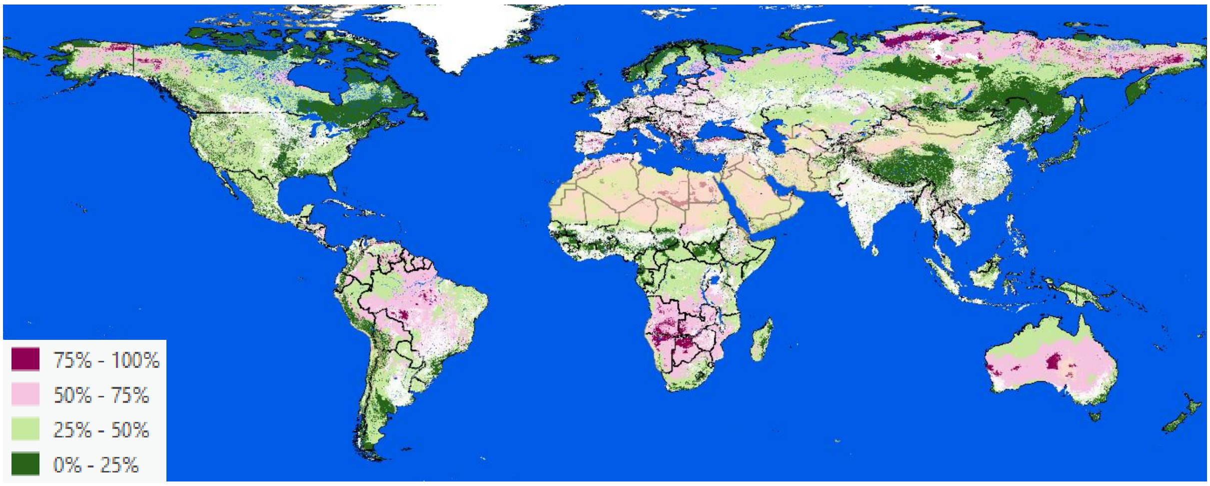
a. 1.5°C



b. 2°C



c. 3°C



d. 4°C

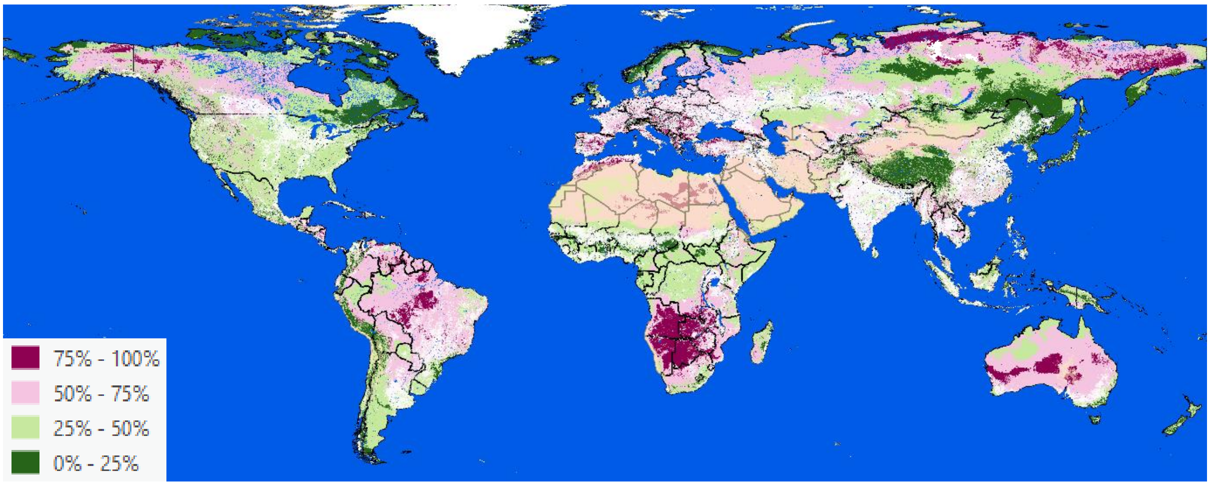


Figure 5: Maps showing biodiversity loss at increasing levels of warming

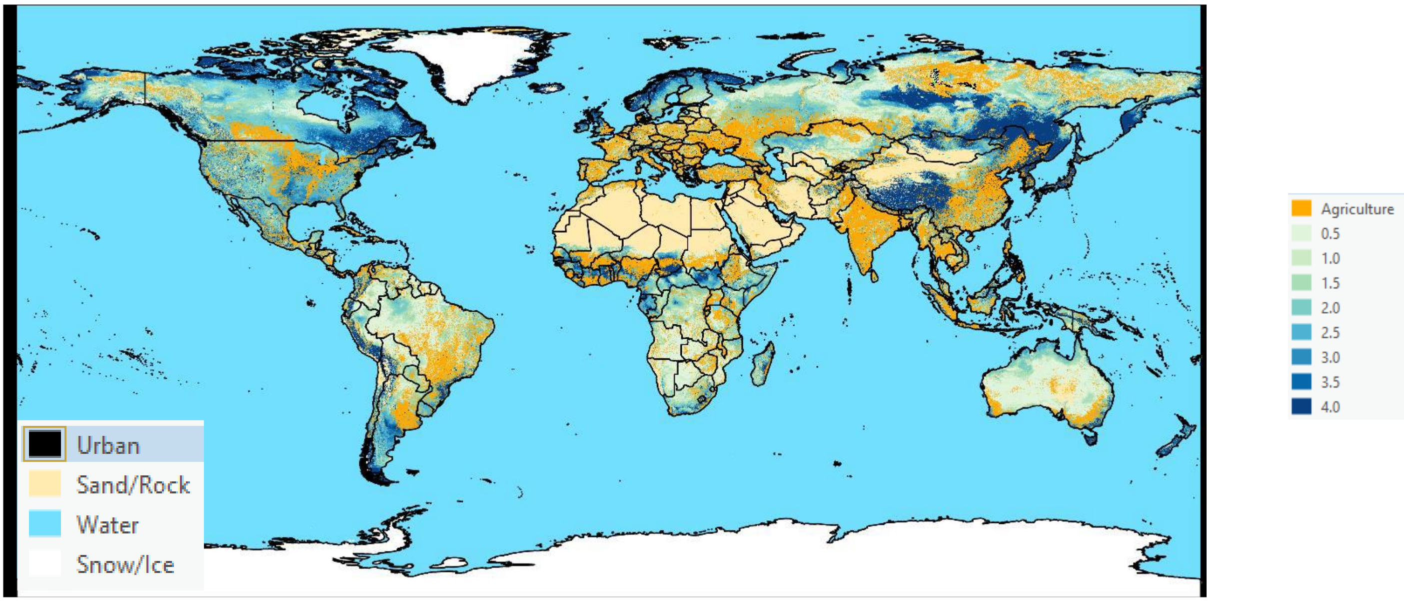


Figure 6: Areas classified as both natural and refugia under different levels of warming

Areas classified as both natural and refugia under different levels of warming are shown in Figure 6. The darker the blue, the higher the temperature at which the area remains a refugia. These areas are projected to be more resilient to higher levels of warming and thus could be considered as ‘better’ areas for new protected areas, at least in terms of climate. Areas in the Maritimes of Canada, the southern cone of South America, the Andes, China and Western and Central Africa show refugia at higher temperatures. Many more areas would be refugia at 2˚C, strengthening the argument that the best adaptation for biodiversity is mitigation.

Global Summary: Species and Extinction Risk

Figure 7 and Figure 8 show the percent of species of different taxonomic groups classified as being under risk of extinction (medium to high confidence). Figure 7 shows the percent of the species group listed projected to be at very high risk of extinction, corresponding to the IUCN Red List criteria for a species classified as "critically endangered" (version 3.1) through losing >80% of its climatically suitable range area. Figure 8 shows the percent of the species group listed projected to be at high risk of extinction, corresponding to the IUCN Red List criteria for a species classified as "endangered" (version 3.1) through losing >50% of its climatically suitable range area. For a) and b), values calculated from the underlying data underpinning (Warren et al., 2018). Values for each temperature are the mean values across 21 CMIP5 models. The grey band represents the high-end of extinction risk from the 10th percentile of the climate models to show the maximum range of values while the low end (90th percentile, 1.5˚C) is not shown as it is too small to appear on the plots. Taxa marked with * represent potential benefits from a kay autonomous adaptation, specifically dispersal at realistic rates (Warren et al., 2018); those with no * have dispersal rates that are essentially not detected in the spatial resolution of the models (20 km). See (Warren et al., 2018) for caveats and more details. Sample size for each group is as follows: Invertebrates (33949), Annelid Worms (155), Butterflies (1684), Moths (6910), Dragonflies (599), Pollinators (1755), Spiders (2212), Beetles (7630), True Bugs (1728), Bees/Ants/Wasps (5914), Flies (4809), Plants (72399), Flowering Plants (52310), Conifers (340), Timber spp (1328), Grasses (3389), Fungi (16187), Vertebrates (12642), Mammals (1769), Carnivores (107), Ungulates (80), Bats (500), Birds

(7968), Passeriformes (4744), Non-passeriformes (3224), Amphibians (1055), Frogs (887), Salamanders (163), Reptiles (1850), Snakes (1741), Turtles (94). Globally, using the above and other data, it is estimated that there is a potential for species extinctions to reach 60% with 5°C GSAT warming (*high confidence*).

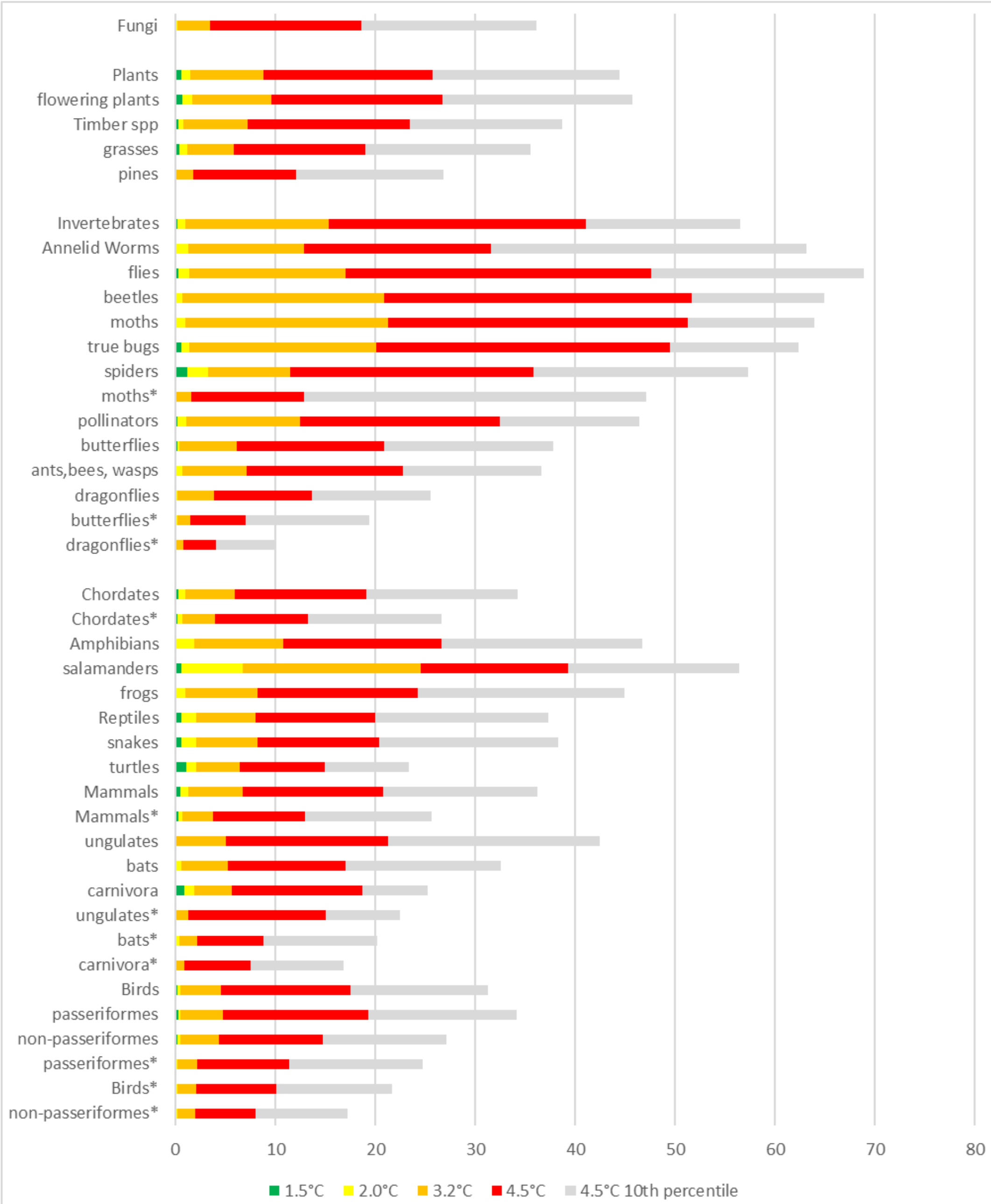


Figure 7: The % of species projected to lose >80% of their climatic range; this would be considered critically endangered or very high extinction risk with a >50% likelihood of extinction in 10-100 years. Even the lowest level of extinction risk from climate change (9% at 1.5°C) is 1000x the background rate. This is in addition to other human causes.

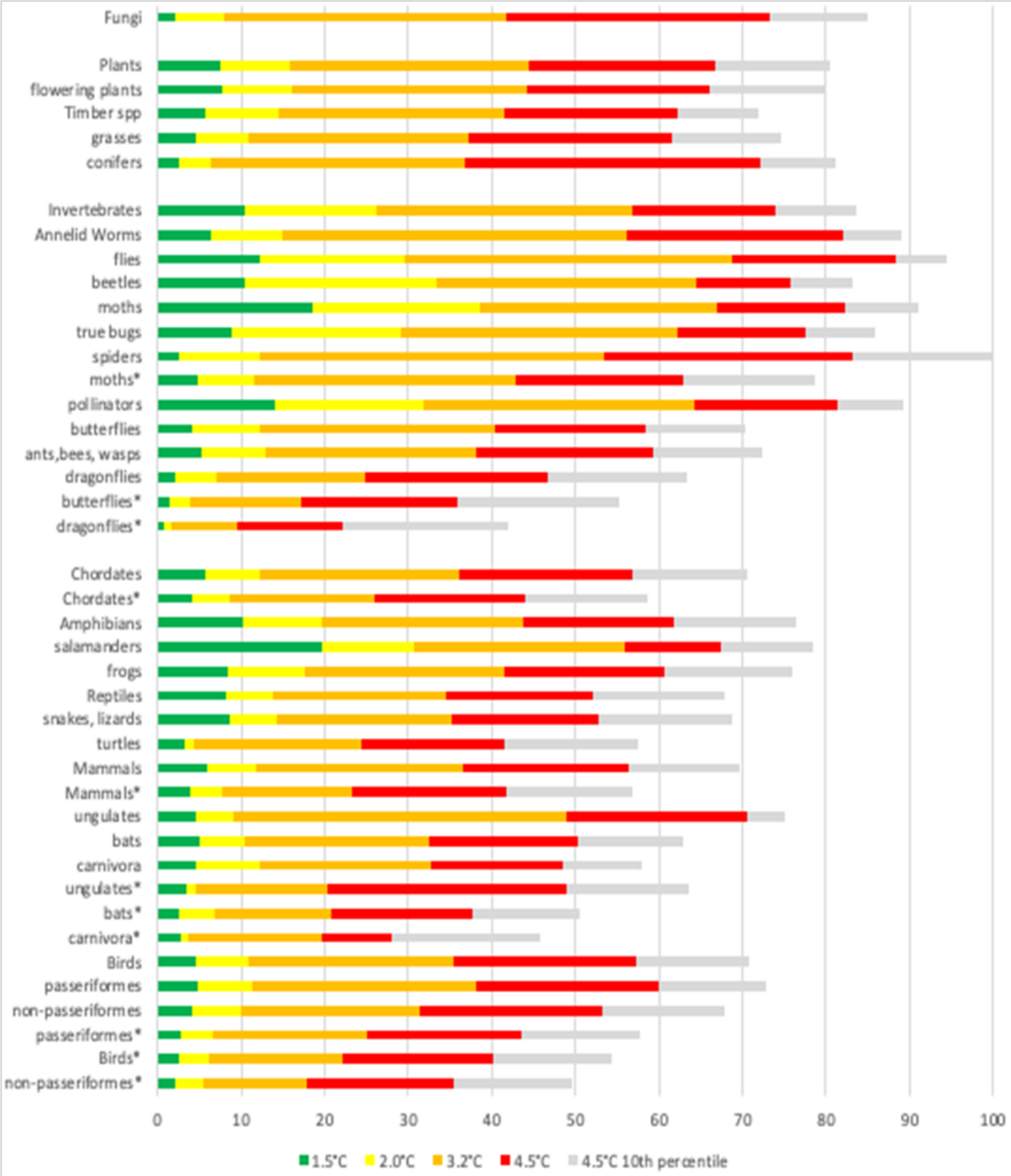


Figure 8: The percent of species of different taxonomic groups classified as being under risk of extinction (medium to high confidence). High extinction risk means >20% likelihood of extinction in 20-100 years. This is based on the number of species projected to lose >50% of their climatic range. This level of range loss would lead to ecosystems with substantially reduced structure and functioning. This would also have significant impacts on the services the ecosystems provide to humans.

Africa

Biodiversity loss as a result of climate change is projected to be widespread across Africa. There is *high confidence* that impacts will worsen with high levels of warming. With warming of greater than 2°C the risk of loss of biodiversity, increases and becomes more widespread, especially in

Central, West and East Africa (Trisos et al., 2020). Endemic species were projected to be particularly impacted (Manes et al., 2021).

Asia

There is *high confidence* that climate change will lead to sizeable changes in the distribution of plant and animal species within Asia. Asia is projected to incur a general northward shift and upward shift of species as a result of continued climate change in those species able to disperse and where there are no barriers. Previous work (and Tyndall projections in the Searchable Inventory) showed that the best refugia in China is likely to be found in the northeast of the country (Price et al. In review) . Important refugia are also projected within the Western Ghats and in the Himalayas. Changes to the species composition or abundance of plant communities are have been projected across the region (Chen et al., 2018; Matsui et al., 2018).

Australasia

There is *high confidence* that climate change will have profound effects on the biodiversity of Australasia, including some irreversible impacts, such as species becoming extinct. Mountainous regions, such as the south-east Australian Alps Bioregion, are particularly vulnerable. However, some native and invasive species may see increases in range as a result of climate change (Rizvanovic et al., 2019; Giejsztowt et al., 2020).

Central and South America

There is *medium confidence* that the biodiversity of Central and South America, particularly within the region's biodiversity hotspots, is likely to be particularly negatively impacted by climate change. Manes et al. (2021) reviewed the literature and found prominent negative impacts for endemic species in Central and South America's biodiversity hotspots. Andean species are likely to be particularly vulnerable due to the high levels of endemicity and their limited ability to adapt by dispersing into new areas as the climate warms (Cuesta et al., 2020). Results from previous work and in the Tyndall projections in the Searchable Inventory showed that much of the Amazon is not projected to contain refugia for biodiversity even with warming as low as 1.5°C.

Europe

Climate change is projected to decrease suitable climate space for many species in Europe and lead to northwards and upslope range shifts. There is *very high confidence* that risks to terrestrial ecosystems in Europe will increase with warming, with southern Europe generally at greater risk than northern Europe. However, species that are adapted to the colder regions of northeast Europe will also be particularly vulnerable as they have limited ability to adapt by colonising northwards. Dyderski et al. (2018) modelled changes to the distribution of major tree species in European regions with warming of around 1.7°C and found that northern distributions of pioneer and coniferous species were most vulnerable.

North America

There is *high confidence* that climate change will increase risks to the biodiversity of North America, with greater risks projected with greater levels of warming. In North America, montane ecosystems, including the Appalachian Mountains biodiversity hotspot, are projected to be particularly vulnerable. Allen (2017) projected over 93% distributional loss for all lichen species investigated in the Appalachian Mountains under a high warming scenario.

Small islands

Island biodiversity is projected to be particularly vulnerable to climate change due to geographic isolation, high endemicity, and typically narrow ranges and small population sizes of many species (Kumar et al., 2020; Manes et al., 2021). There is *high confidence* that increased climate change will significantly affect the biodiversity and ecosystems of small islands. Manes et al. (2021) reviewed previous studies and found that 100% of endemic species from islands examined faced extinction with warming. The biodiversity of small islands will also be affected by sea level rise (Bellard et al. 2014) and this is not considered in most typical climate change/terrestrial species distribution models. Sea level rise is projected to submerge some small islands, increase coastal erosion and lead to saline water intrusion, affecting habitats close to the coast.

Outside of hotspots, there have been few systemic analyses of how climate change may impact the terrestrial biodiversity of islands (here including large islands, such as Papua-New Guinea that have fallen through gaps in IPCC coverage). For IPCC AR6, an analysis was undertaken using data from Warren et al. 2018a and 2018b and these results are shown, island by island in an accompanying table in that chapter. Equivalent data are in the Searchable Inventory.

Polar

High Arctic biodiversity is particularly vulnerable to climate change owing to high exposure to climate related hazard, high sensitivity and limited adaptive capacity. As warming continues, range shifts will become more pronounced. Wauchope et al. (2017) modelled the impact of warming on Arctic shorebirds and found that 66% of species are projected to lose the majority of currently suitable breeding area with RCP4.5 and 83% with RCP8.5 in 2070. Foden et al. (2013) found that the proportion of bird species threatened was highest in the Arctic and Southern Ocean. Unlike in other areas, species adapted to polar regions would not be able to shift their ranges to track a warming climate. Higher temperatures are already causing degradation of permafrost in the Arctic tundra. Further climate change is projected to expand distributions of woody plants in many areas of Arctic and alpine environments, reducing the area of tundra (Mod and Luoto, 2016). There is *high confidence* that the encroachment of woody shrubs will continue with higher levels of warming.

Ecosystem Services and Natural Capital

There is high confidence that degradation of ecosystems leads to loss of ecosystem services and ecosystem resiliency. This is from any impact, including climate change (e.g., observed changes in biomes attributed to climate change already impacting some ecosystems services). There is medium confidence that observed changes in species, with <1°C GSAT warming, have already impacted ecosystem services. However, there is high confidence that continued changes to species and ecosystems will reduce the ability of ecosystems to provide necessary human services. This is the logic underpinning the Natural Capital Climate Risk Register (Price et al in review) and extensively discussed by the UK Natural Capital Coalition and formalized in the UN SEEA Environmental Accounting guidelines (2021). Ecosystem protection affords some protection from further loss to ecosystem services from many impacts, but not from direct climate change impacts. However, ecosystem restoration can increase ecosystem services and work to rebuild the natural capital bank (high confidence). This benefit declines with increasing GSAT, especially at warming levels of 3°C and higher.

Summary

Species rarely go locally extinct owing to changes in the mean. This is also true in the three species that are thought to have gone extinct owing to climate change. Local extinction is largely thought to be tied to changes in one or more extreme events, operating either directly, or indirectly. The mean climate should be seen as a proxy for a future where what is currently extreme, becomes the new mean. Models projecting how species' ranges (or populations) change with projected future climate change are almost all based on changes in mean climates. This, then, is one of the key research gaps needing to be addressed. While there has been some progress along these lines in plants, it is much more difficult to model how animals may respond to extreme events at a global level. Adequately assessing how extreme events may shape a species range requires regular survey data to enable associating species' occurrences at place x with the climate at place x over a period of years. This level of information is only available for some taxa in a few areas and is not adequate for modelling large numbers of species over the globe.

Almost all model projections are likely to be *conservative*, owing to processes that are not included in the models that, overall, tend to underestimate projected impacts. A key factor omitted from many models is the effect of extreme events (such as floods, seasonal droughts, or heatwaves, which can then in turn lead to fire for example), that are generally projected to increase in frequency and intensity as climate changes. This is important because species do not experience the mean climate – they experience a series of changing extreme events around the mean, and as those extremes become more extreme it is the experience of these that are likely to cause local extinction. This is particularly important because climate change increases climate variability disproportionately compared to the mean (that is, if for example, the mean summer climate in a place becomes 2°C warmer locally, the heatwaves are likely to be more than 2°C warmer than previously experienced, and they are likely to happen more often). Whether species can recover or not from extreme events depends on how quickly the climate returns to 'normal' or how often the event in question occurs. In the few cases where extreme events, or adequate time series, have been included in a bioclimatic modelling study, the projected impacts were modelled to occur much earlier than models based on changes in the means. While certain traits may make some individual species more resilient to climate change (and research is just beginning to really tease out what these traits are), the lack of inclusion of extreme events suggests that many species may be more sensitive than once thought. Another key factor missing in many models is the tendency for changes, often increases, in the ranges of pests and diseases as the climate warms. These pests and diseases then impact biodiversity and this is not included in the bioclimatic models. Even mechanistic models, based on physiology, that run at daily or yearly time steps often do not include disturbances such as pests and fire.

What this means, in terms of natural resource and conservation planning, is that the "best" approach needs to combine a no-regrets conservation strategy with the precautionary principle. No-regrets management means that an action is taken that should benefit biodiversity no matter what happens (only possible up to a point, 2°C in many areas). The precautionary principle would guide planners and practitioners to consider the information the climate change and bioclimatic models are providing and to use them to guide their activities, whilst also not blindly trusting the projections. This allows the decision maker to take the information from one or more sources (modelling and other sources) and to then use their expert judgement to make the best decision. A key message is that owing to the uncertainty in model projections, it can be helpful to retain flexibility in the decision-making process, so that the decision can be re-visited (adaptive management) as more data or monitoring information comes to light. This allows decisions to be revised as (a) scientific information improves, perhaps allowing more confident regional projections of precipitation to be made and/or (b) monitoring of the effects that climate change is having in a local area confirms, or opposes, the effects projected by the models. This concept of adaptive, iterative management is well understood in the literature pertaining to adaptation of human systems to climate change. In these situations, it is important to avoid lock-in to a decision that would not be robust for some of the projected climate change outcomes. So, combining these two activities would suggest that, all things being equal, a given conservation action that would normally be considered as successful, performed in an area projected to be a refugia, would be a better decision than performing the same activity in an area projected to be an area of concern. The biodiversity may be the same in both locations; the models are just helping guide long-term actions when resources are limited.

See Sections above for detailed global summaries.

2.7 Health (heat stress and disease)

Introduction

High temperatures and heatwaves are associated with significant impacts on human health. Exposure to higher temperatures can cause heat exhaustion and heat stroke and increase the probability of heat related mortality (Gasparrini et al., 2015). Other consequences can include impacts on mental health, wellbeing and hospital admissions (e.g., Åström et al., 2013). Impacts to human health can also be amplified where humidity is higher (Armstrong et al., 2019). Older people who have a higher prevalence of chronic disease, reduced physiological condition, and greater potential of social isolation are particularly vulnerable to heat stress (Chen et al., 2020), as well as babies and young children, and those with underlying health conditions (Heaviside et al., 2017; WHO, 2018). High temperatures and heatwaves can also affect labour productivity and labour supply (Smith et al., 2016; Kjellstrom et al., 2009; Gosling et al., 2018; Dasgupta et al., 2021). Any changes in productivity will feed through to national income causing a macroeconomic effect (Day et al., 2018).

The IPCC (2021) highlights that with continued global warming all regions are projected to experience further increases in hot climatic impact-drivers, with *high confidence* that extreme thresholds relevant to health will be exceeded more frequently by 2050 with 2°C of global warming. The ageing global population is also projected to drive an increase in *vulnerability* to heat (Chen et al., 2020), while the projected increase in urban populations could increase *exposure*, given the role of the urban heat Island (UHI) effect, particularly on night-time extremes, and future urban development on amplifying extreme temperatures (Tong et al., 2021; Zhao et al., 2018; Heaviside et al., 2017; IPCC (AR6, 2021)).

Overall, climate change is expected to lead to seasonal changes and latitudinal or altitudinal shifts of many vector-borne diseases, including malaria, dengue, Lyme disease, and West Nile fever, with expansions and reductions in different regions. Many projections of climate change impacts on health and diseases make use of species distribution modelling, to understand changes in the climate suitability and geographic range of species that spread vector-borne diseases, such as mosquitoes and ticks. In addition to projecting the climate suitability, studies also consider exposure through changes to the population exposed to diseases.

Africa

The IPCC (2021) report that future warming, even at lower warming levels, will cause a substantial increase in heatwave magnitude and frequency over most of Africa and significantly increase the likelihood of temperature extremes exceeding the record-hot year of 2015 in Africa, which had large impacts on health and mortality (Nangombe et al., 2018).

Andrews et al. (2018) looked at changes in population exposed to excessive heat stress. Changes to workability and survivability reflect the exceedance of predefined Wet Bulb Globe Temperature thresholds (WBGT, which assesses the effects of temperature, humidity, and other environmental factors on humans) alongside population projections to calculate change in exposure from 1986-2005 to 2100 for different warming levels. For the present-day extreme heat exposure (in shade) was seen in Chad and Algeria. At 1.5°C this zone expands to more countries of Africa (Mali and Niger). At 2°C, countries in North and central North Africa are affected, and at 3°C tropical and subtropical Africa (including Ghana) are also affected (based on four CMIP5 global climate models from ISIMIP2b, assuming RCP 6.0 which represents a mid-range climate future).

Ahmadalipour et al., (2018; 2019) used the WBGT to quantify mortality associated with excessive heat stress for people aged over 65 years across the Middle East and North Africa. Central African countries such as Benin, Togo, Central African Republic, Burkina Faso and Guinea, were found to exhibit the highest heat-related mortality. Mortality was found to be at least 50% lower at 2°C compared to a no mitigation scenario. Sylla et al. (2018) use the NOAA's Heat Index, which combines temperature and humidity, and a Human Discomfort Index which provides metrics on the percentage of population exposed, to assess heat stress and discomfort in West Africa. The study reports an increase of up to 36 days during which the entire population feels heat discomfort at 2°C, reduced to 15 days at 1.5°C, in countries including Senegal, Mali, Burkina Faso, Niger, and Chad. Sun et al. (2019) analysed global heat stress alongside population projections (SSP2). Limiting global warming to 1.5 °C instead of 2°C would allow countries in Africa to avoid impacts from heat exposure, for example, ~90% of heat related exposure was avoided in Egypt at 1.5 °C vs. 2°C.

Data from Climate Analytics shows declines in labour productivity compared to a 1986-2006 baseline, increasing in severity in line with warming levels of 1.5, 2.0, 2.5, and 3°C in Africa. Under RCP8.5 Central African Republic, Ivory Coast, South Sudan and Sierra Leone in Mid and West Africa face reductions in labour productivity of 16.8% or more. Similar regional patterns are reported in Roson and Sartori et al (2016), with heat projected to reduce agricultural labour productivity by 17.7% at 2°C and 37% at 4°C in Benin, and by 17.7% at 2°C and 36.9% in Ghana.

de Lima et al. (2021) combine metrics of agricultural labour productivity change and climate induced crop yield changes to assess economic implications for the region through the GTAP economic model at warming levels from 1°C to 5°C. They find a decline in unskilled agricultural earnings of over 20% in sub-Saharan Africa regions at 3°C.

Changes to temperature and precipitation will alter the distribution, intensity of transmission, and seasonality of malaria across Africa. Zermoglio et al. (2019) modelled the changes to malaria exposure across Africa and found an increase in endemic malaria exposure (defined as areas exposed for 10-12 months of the year) in many regions. Results showed an additional 16-18 million people will shift from areas of no exposure to endemic malaria exposure with warming of around 2°C, many in East Africa. In addition, an additional 3-26 million people are projected to be exposed to seasonal malaria (i.e. occurring in 7-9 months of the year) in Southern Africa. Ryan et al. (2020) also projected an increase in malaria in East and southern Africa and the Sahel with around 1.5°C, which becomes more pronounced with higher warming levels.

With higher warming levels, projections suggest reduced endemic exposure in some areas of West Africa, as temperatures exceed thermal thresholds for mosquitoes (Zermoglio et al., 2019). However, these areas will still experience malaria exposure in 1-6 months of the year. In Nigeria, the range of Anopheles mosquitoes is projected to increase by 15% with approximately 2°C, 27% with 2.5°C warming and 32% with 4°C warming (Akpan et al., 2019). The Searchable Inventory also highlights that in parts of Africa a drying climate reduces the exposure to malaria in many areas (Warren et al., In Press).

The distribution of the mosquitoes (*Aedes spp.*) which transmit the Dengue, Chikungunya, yellow fever and Zika viruses is also highly sensitive to temperature and precipitation. Gaythorpe et al (2020) modelled yellow fever transmission and projected an increase in the force of infection across Africa, particularly in East and Central regions, with warming of 1.8°C and above.

In addition to vector-borne diseases, an increase in diarrhoeal disease is projected for central and east Africa with 2.1°C. The transmission of *Schistosoma mansoni* – a waterborne parasite – is also projected to increase by up to 20% over most of eastern Africa with warming of up to 2.5°C above pre-industrial levels (McCreesh et al., 2015).

Asia

Vicedo-Cabrera (2018) project that the countries that would face greatest excess mortality from future global warming of 1.5, 2, 3, and 4 °C above pre-industrial (using three GCMs under RCP8.5) are in South-East Asia, including Vietnam, Thailand and the Philippines. Sun et al., (2019) reported that for a 1981-2000 baseline, globally India and China were at greatest risk from exposure to heat stress, and accounting for population change (SSP2). Under 1.5 °C and 2.0°C warming they remained the countries at greatest risk from exposure to heat stress, and in Asia they were joined by newly affected regions in Indonesia. Limiting global warming to 1.5 °C instead of 2°C would allow countries such as India to avoid many of these impacts, with ~50-80% of heat related exposure avoided across countries in Asia at 1.5°C compared to 2°C. Andrews et al. (2018) found that at 1.5°C more areas of South Asia, including larger parts of India, Bangladesh, Thailand, and Cambodia, are exposed to extreme heat. However, the areas exposed expand much more at 3°C, across Western and South Asia and over much larger areas of India and Pakistan.

Data from Climate Analytics highlights declines in labour productivity compared to a 1986-2006 baseline (constant population), increasing in severity in line with warming levels of 1.5, 2.0, 2.5, and 3°C in Asia. Under RCP8.5 large reductions in labour productivity of 14.8% or more are reported for Bahrain, Singapore, Qatar and UAE. Similar regional trends are reported in Roson and Sartori et al (2016), with heat impacts projected to reduce agricultural labour productivity by 22% at 2°C and 45.3% at 4°C in Singapore, and by 21.7% at 2°C and 44.6% in Brunei.

de Lima et al. (2021) find that changes in agricultural labour productivity and climate induced crop yield result in a decline in unskilled agricultural earnings exceeding 20% in the Southeast Asia region at 3°C, the worst affected region globally.

There is a high likelihood that climate change will alter the geographical range of malaria vectors and change the risk of malaria infections. Projections of the geographic distribution of Anopheles mosquitoes show an increase in China and Taiwan, but a reduction in parts of India and Southeast Asia (Khormi and Kumar, 2016). Malaria incidence in northern China is projected to increase by 69%–182% by 2050 (Song et al., 2016). The WHO (2014) projected additional annual deaths attributable to climate change in 2030 and 2050 compared to 1961-1990 levels and showed a significant malaria increase in South Asia.

Changes to the distribution of the mosquitoes (Aedes spp.) are expected to increase dengue risk. In China, under RCP8.5 conditions, the high-risk area for dengue transmission would expand to include an additional 34 counties (accounting for 20 million people) in 2020s, 114 counties (60 million people) in 2030s – warming of around 1.7C above pre-industrial levels, 208 counties (160 million people) in 2050s – warming of around 2.5C above pre-industrial levels (Fan and Liu, 2019). By contrast, For RCP2.6, the high-risk area would include 146 counties (172 million people) in 2020s (warming of around 1.5C). This is supported by other literature which showed higher numbers of dengue fever cases are projected to occur under RCP 8.5 than RCP2.6 in China (Song et al., 2017).

In Nepal, dengue fever is expected to expand under all RCPs (Acharya et al., 2018). About 80% of the population would live in climatically suitable areas in the 2050s under RCP26. This would increase to over 90% with RCP8.5 in the 2070s.

Changes to waterborne diseases (diarrhoea, leptospirosis and typhoid fever) across Asia with climate change are likely to be linked to extreme weather events such as heavy rain and tropical cyclones.

Australasia

King et al (2017) find that extreme heat events are projected to become significantly and substantially more common in Australia under 2°C warming versus 1.5°C warming. Likewise, the IPCC (2021) highlights that dangerous humid heat thresholds, with the potential to affect health, are projected to be exceeded more frequently over the 21st century in Australia under all RCPs, with Northern Australia particularly vulnerable. Andrews et al (2018) projects that even at 1.5°C warming above pre-industrial levels, parts of Australia are projected to be exposed to extreme heat stress, accounting for population exposure, impacting workability and survivability. However, in Western Australian exposure to extreme heat stress is shown to decrease in spatial extent at higher warming levels due to climate variability in models. Likewise, Sun et al. (2019) analysed global heat stress, also accounting for population exposure (SSP2). Newly affected regions exposed to dangerous or extremely dangerous days for vulnerable groups were shown to appear in Australia at 1.5 °C and increase at 2°C, with Northern Australia particularly vulnerable.

Data from Climate Analytics shows slight declines in labour productivity compared to a 1986-2006 baseline (constant population), in the region. Under RCP8.5 labour productivity in Australia is projected to decline by 3.2%, 4.3% and 7.7% at 1.5°C, 2°C and 3°C global warming respectively. Impacts are minimal in New Zealand, with projected declines in labour productivity of 0.07%, 0.1% and 0.3% at 1.5°C, 2°C and 3°C global warming respectively. de Lima et al. (2021) combine metrics of agricultural labour productivity change and climate induced crop yield changes to assess economic implications for the region at warming levels from 1°C to 5°C. They find a decline in unskilled agricultural earnings of ~2.5% across Australia and New Zealand at 3°C.

Central and South America

Sun et al. (2019) analysed global heat stress accounting for population exposure (SSP2). They found large parts of northern South America would be exposed to dangerous or extremely dangerous days over 40.6°C for vulnerable groups, given increases in temperature and humidity, at 1.5 °C and with increasing frequency at 2°C. Likewise, Andrews et al (2018) projects that with 2°C warming above pre-industrial levels that exposure to extreme heat stress, impacting on workability and survivability, will extend to areas of Central South America, including Brazil, Colombia, Guatemala, Ecuador, Peru and Venezuela. At 3°C warming much larger areas of South America are projected to be affected, particularly Peru and Brazil.

Data from Climate Analytics shows declines in labour productivity compared to a 1986-2006 baseline (constant population), across all countries in the region. Under RCP8.5 labour productivity is projected to decline by over 17% in Venezuela and Brazil, and by over 18% in Guyana and Suriname at 3°C. Similar regional trends are reported in Roson and Sartori et al (2016), with heat impacts projected to reduce agricultural labour productivity by 18.3% at 2°C and 37.5% at 4°C in parts of Central America. de Lima et al. (2021) find that changes in agricultural labour productivity and climate induced crop yield result in a decline in unskilled agricultural earnings of ~4% across Central America and ~7% across South America at 3°C.

Climate change is projected to expand the geographic range of mosquitoes across Central and South America, leading to an overall increase in disease with warmer temperatures. Laporta et al. (2015) modelled changes to the distributions of malaria vector species in South America and found that geographic distribution of the malarial parasite P. falciparum increased under all scenarios analysed. With warming of around 3°C by 2070 the distributions of malaria vectors are projected to increase to 35-46% of the continent. Cabrera et al. (2020) modelled climate suitability for the mosquito Aedes aegypti in Colombia with different levels of warming. With 2°C warming, range expansion is projected, with Andean regions particularly seeing an increase in suitability for the mosquito. However, with the highest warming levels, many areas are no longer suitable for mosquitos and the range contracts within Colombia.

Colon-Gonzales et al. (2018) projected the number of dengue cases per year in Latin America and the Caribbean as 10.7 million with 1.5°C warming, 11.0 million with 2.0°C warming and 11.8 million with 3.7°C warming in the 2050s. For Brazil, this study projected 503.0 million fewer cases in the 2050s with 1.5°C compared to 3.7°C warming. For Colombia, 97.4 million fewer cases were projected in the 2050s with 1.5°C compared to 3.7°C warming. This study underpins the Tyndall data in the Searchable Inventory.

Europe

The IPCC (2021) have projected that for Europe critical thresholds relevant for humans would be exceeded for global warming of 2°C and higher. King and Karoly (2017) report that events of a similar magnitude to the 2003 European Summer, which caused tens of thousands of deaths increase significantly even under lower global warming targets but would be at least 25% less frequent at 1.5°C versus 2 °C global warming level. Vicedo-Cabrera (2018) project that countries in Southern Europe would be exposed to excess mortality from future global warming of 1.5°C and above, becoming more severe as warming exceeds 3 and 4 °C above pre-industrial (using three GCMs under RCP8.5), including Spain and Italy.

However, projections can be viewed as less significant compared to other global regions when considering more extreme heat stress metrics. Sun et al. (2019) analysed global heat stress accounting for population exposure (SSP2), focusing on more extreme conditions over 40.6°C. Using this index exposure for Europe was found to be minimal, with only limited occurrences in small areas of South and South Eastern Europe at 1.5 °C and 2°C. Similarly, while Andrews et al (2018) projects that at 1.5°C and 2°C warming above pre-industrial levels parts of Southern Europe will be exposed to moderate and high (in shade) occupational heat exposure, it is not projected to pass these global thresholds of extreme heat stress.

Data from Climate Analytics shows declines in labour productivity compared to a 1986-2006 baseline (constant population), across all countries in the region. Under RCP8.5 countries in Southern Europe face the largest impacts, with labour productivity projected to decline by 3.3% and 3.4% in Greece and Portugal, and by 4.9% in Spain at 3°C. Gosling et al., (2018) find that limiting warming to 2°C above pre-industrial levels could avoid substantial impacts on labour productivity in countries such as Greece, Italy, Macedonia, Portugal, Spain and Turkey.

Climatic suitability for malaria transmission in Europe is increasing but still remains lower compared to other regions due to economic development of European countries and good access to healthcare. Some regions currently at risk of malaria will see a reduction in risk in the future, while others will see an increase (Liu-Helmersson et al.2019). Overall, Europe has been projected to see an increased invasion of Aedes aegypti mosquitoes under 4.9°C global warming, increasing the exposure to malaria (Liu-Helmersson et al., 2019).

Lyme disease is the most prevalent tick-borne disease in Europe and projections are for an increase with climate change. Evidence indicates that the Lyme disease and Tick-Borne Encephalitis vector Ixodes ricinus is likely to spread further north and into higher elevations that were previously climatically unsuitable (Porretta et al., 2013). Boeckmann and Joyner (2014) found potential habitat expansion of these ticks of 3.8% across Europe with 2°C warming. In addition, an increase in the number of tick-borne encephalitis infections has been projected within central Europe because of the extended length of tick season (Nah et al., 2020).

Increased warming in Europe could also lead to an expansion in the area suitable for West Nile virus transmission, particularly along the current edges of its transmission areas, such as Eastern

Croatia, Northeastern and Northwestern Turkey (Semenza et al., 2016). Further expansion is projected with greater warming. Similarly, models generally project an increase in climatic suitability for chikungunya transmission across large parts of Europe, including for France, Spain, Germany and Italy (Tjaden et al., 2017). However, the study also showed that some areas along the Italian Adriatic coast are projected to experience a decline in suitability.

North America

Under future projections of warming Hsiang et al (2017) report an increase in mortality in southern counties in the USA, offsetting reductions in cold related mortality. By the mid-century, Limaye et al (2018) also projected significant heat related mortality due to cardiovascular stress across Eastern USA (under the IPCC A2 emission scenario), particularly for urbanised counties and elderly populations, estimating 11,562 additional annual deaths in those aged 65+.

Andrews et al (2018) projects that at 1.5°C warming above pre-industrial levels parts of the East and Southeast USA will be exposed to moderate and high (in shade) occupational heat exposure, and above 2°C will be exposed to extreme heat stress (WBGT of 34°C). Sun et al. (2019) analysed global heat stress, accounting for population exposure (SSP2). They found similar spatial trends as Andrews et al (2018), with parts of Southeast USA exposed to dangerous or extremely dangerous days over 40.6°C for vulnerable groups, given increases in temperature and humidity, at 1.5 °C. The frequency increases at 2°C, particularly when considered in combination with the area of land affected and the relative size of the affected population. Integrating this exposure data highlights that the United States is expected to be under threat from severe heat stress by 2100.

Data from Climate Analytics shows declines in labour productivity compared to a 1986-2006 baseline (constant population), across North America. Under RCP8.5 at 3°C the largest impacts regionally on labour productivity are projected for the USA (-5%), whilst Canada is less affected (-0.6%). At the sectoral level, Hsiang et al (2017) report that total hours of labour supply in the USA decline by 0.53% per each degree of global warming for workers in high-intensity work sectors such as construction, manufacturing, and agriculture.

As in Europe, climate change is projected to increase the spread of the most prevalent Lyme disease vector (Ixodes scapularis in North America) and lead to an increase in cases of Lyme disease. In the United States, 2°C warming could increase the number of Lyme disease cases by over 20% (Dumic and Severnini, 2018), due to warmer winter and spring temperatures leading to a longer tick season (Monaghan et al., 2015). Similarly, climate change is projected to expand the geographic range of Chikungunya in North America (Tjaden et al., 2017).

Small islands

The effect of extreme heat is expected to exacerbate health impacts in small Islands, especially for more vulnerable populations with many small island states currently suffering from increased morbidity and mortality due to weather extremes (IPCC, 2014).

Data from Climate Analytics shows declines in labour productivity compared to a 1986-2006 baseline (constant population), across all countries in the Caribbean. Under RCP8.5 at 3°C the largest impacts on labour productivity are projected for Curacao (-15%), Trinidad and Tobago (-14.5%), Cuba (-13.1%) and Barbados (-12.7%). Similar regional trends are reported in Roson and Sartori et al (2016), who project declines in agricultural labour productivity of 18.6% at 2°C and 38.7% at 4°C in Trinidad and Tobago.

There are few studies of the impacts of climate change on disease at the national scale for small islands, but tropical and sub-tropical islands face risks from vector-borne diseases, and these are expected to increase with future climate change. The Caribbean region has a high probability of mosquito distribution, increasing the risk of contracting Zika (Cabrera et al., 2020). Colon-Gonzales et al. (2018) projected 31.3 million fewer dengue cases in Haiti in the 2050s with 1.5°C compared to 3.7°C warming. Teurlai et al. (2015) found that increases in mean temperature could double the dengue burden in New Caledonia with approximately 3°C warming.

The changing climate is likely to alter the risk of water-borne diseases in small island states. These risks are linked to other impacts such as sea level rise and extreme events such as cyclones.

Summary

Despite the use of different methods, and their underlying uncertainties, as well as uncertainties due to different climate models, the general trends of increasing heat and heatwaves and the effects of heat exposure on health, labour supply and productivity are clear. All regions are projected to face increased heat related mortality, particularly equatorial regions (i.e., countries in Central and South America, South and South East Asia and parts of sub-Saharan Africa), as well as Southern Europe, parts of the USA and northern Australia (Vicedo-Cabrera et al., 2018; KJellstrom et al., 2018). Heat-related mortality increases with higher warming levels and could be substantially reduced if warming was limited to 1.5°C or 2°C. However, at current temperatures some countries, including Pakistan and Chad, already face extreme heat stress conditions that affect workability and have implications in terms of reduced labour supply or productivity.

While there is substantial literature on heat-health relationships in many regions, many studies focus on the creation of ERFs and the assessment of historic events, while less specifically consider implications at different global warming levels. Gaps are particularly noticeable for Africa where there is a lack of literature on past and projected mortality and morbidity related effects compared to other continents (Ahmadalipour et al., 2019) and Small Islands. Some global studies developing statistical relationships between climate variables and epidemiologic data on morbidity or mortality exclude Africa due to a lack of available observed data on mortality counts (Gasparrini et al., 2017; Armstrong et al., 2019); and country specific studies are also more limited than seen for other regions such as Europe, USA, China, or Australia (Mora et al., 2017 and Chen et al., 2020). Nangombe et al (2018) highlight limited analyses of impacts at lower 1.5 °C and 2 °C warming levels for Africa.

There is also less consensus on which heat-stress indicators are best suited to specific heat-related impact assessments (Goldie et al., 2018; Schwingshackl et al; 2021), and coverage of the role of adaptation. Where it is included, adaptation is normally captured in a simplistic manner with more research needed to better quantify adaptation (Sanderson et al., 2017). Many studies also assume constant population, but future heat-related mortality is shown to be underestimated when population growth and demographic change is not included (Sanderson et al., 2017; Chen et al., 2020; Rohat et al., 2019). This is particularly important given population growth is projected to be highest in the region's most vulnerable to heat exposure, including parts of Africa and Asia (Andrews et al 2018).

While many studies also focus on the implications of heat-exposure on reductions in labour productivity, the related economic consequences are less frequently modelled. There is also limited integrated analysis of concurrent or compounding impacts, for example, implications of both reduced agricultural labour productivity and supply and changes on crop yields on economies (de Lima et al. 2021).

Vector-borne diseases are generally projected to increase globally because of higher temperatures and changing rainfall patterns. These increases in diseases and effects on human health will disproportionately affect the poorest people. In addition, tick-borne diseases, including Lyme disease, are likely to increase across the northern hemisphere with climate change. Waterborne diseases are also projected to increase. There is an increased risk of transmission of Schistosoma mansoni in eastern Africa.

Extreme events will have important impacts on the vector-borne and water-borne diseases. More research is needed into the potential impacts of extreme weather events on water-borne diseases. Globally, there is limited evidence on projected changes to water-borne diseases and how these will impact human health. In addition, more research is needed on the transmission of food-borne diseases under climate change scenarios.

In general, models projecting the impact of climate change on health related to diseases cannot take factors such as age and socioeconomic status into account. Due to these and other factors that influence the patterns of diseases, there is still significant uncertainty in the model projections (Zermoglio et al., 2019; Giesen et al., 2020).

2.8 Fire

Introduction

Fire is a natural phenomenon in the Earth System that has shaped the landscape of many of Earth's biomes for millions of years (Archibald et al., 2013; Bond & Keeley, 2005; Bowman et al., 2009; He et al., 2019; Pausas et al., 2017; Pausas & Keeley, 2009). Fires burn around 3-5 million km^2 and emit around 8 billion tonnes of CO_2 to the atmosphere on average per year (Chuvieco et al., 2019; Giglio et al., 2018; van der Werf et al., 2017). These fire emissions, and the subsequent sequestration fluxes of around 7 billion tonnes of CO_2 per year resulting from post-fire vegetation recovery, are major fluxes in the carbon cycle (Lasslop et al., 2019; van der Werf et al., 2017; Yue et al., 2016; Yin et al., 2020). Globally, fires reduce the quantity of carbon stored in vegetation by around 10% and are thus a major control on atmospheric CO_2 concentrations and climate (Lasslop et al., 2020a).

The majority of fires do not present immediate risks to society and often contribute to ecosystem health, however the Centre for Research on the Epidemiology of Disasters (2021) estimates that wildfire events that were declared as disasters have directly killed 2,500, injured 8,000 and displaced 175,000 people from their homes globally since 1990. The economic costs of some fires can also be large. Notably, the total economic cost of the California wildfires in 2020 alone were estimated to be US$149 billion or 1.5% of the state's gross domestic product (GDP), including US$28 billion in capital losses, $32 billion in health costs and $89 billion through suppressed economic activity extending beyond California (Wang et al., 2021). Economists estimated that the Australian wildfires of 2019/2020 caused around US$75 billion losses or 6% of the country's GDP (Read & Denniss, 2020).

The cost of suppressing fires is also substantial, even in non-extreme years in some regions. For example, on average around US$500 million is spent annually on suppressing fires in Canada and around US$1-2 billion is spent in the US (Hope et al., 2016; Jolly et al., 2015; Stocks & Martell, 2016; Tymstra et al., 2020; National Interagency Fire Center, 2020). Fire impacts on society extend beyond their direct destructive force, with exposure to smoke contributing to over 300,000 premature deaths per year (Johnston et al., 2012) particularly in the tropics (Balmes, 2020; Reid et al., 2016). It is estimated that US$1.5 billion was spent treating adverse respiratory health issues due to the smoke emitted by 2019/2020 wildfires in Australia (Johnston et al., 2021).

The impact of fires on wildlife and ecosystems can also be profound. As a stark example, the Australian 2019/2020 wildfires impacted over 30% of the available habitat of 70 vertebrate species, including 21 endangered species (Ward et al., 2020). Fire is also a key disturbance mechanism that can prompt change in land cover from forest to non-forest in regions where climate becomes out of phase with the existing vegetation, with various implications for carbon storage, biodiversity and other ecosystem services (Burrell et al., 2020, 2021; He et al., 2019; Hirota et al., 2011; Staver et al., 2011). This may trigger climate-carbon cycle feedbacks that reinforce or accelerate the initial climate perturbations (Harrison et al., 2018; Lasslop et al., 2019, 2020; Pellegrini et al., 2018; Walker et al., 2019; Yin et al., 2020; Zou et al., 2020).

The coexistence and interaction of climatic, bioclimatic and human factors is a critical challenge to studying, understanding and communicating the impacts of climate change on fire activity (Abram et al., 2021; Bistinas et al., 2014; Doerr & Santín, 2016; Forkel et al., 2019b; Kelley et al., 2019). It can be difficult to disentangle the impacts of individual drivers on fire activity because fire is the result of the simultaneous occurrence of three factors: an ample stock of fuel; fire weather conditions that are sufficiently dry to desiccate the fuel; and a human or natural ignition source (Abram et al., 2021; Bistinas et al., 2014; Forkel et al., 2019b; Kelley et al., 2019; Pausas

& Ribeiro, 2013; Teckentrup et al., 2019). This nexus of drivers and constraints on fire leads to debate about the causes of major wildfire events, as well as the contributions of climate change, vegetation responses to climate change, and human activities to trends in wildfire activity.

In the regional sections below, we used the Canadian forest fire weather index (FWI; Van Wagner, 1987), which is among the most commonly applied systems for rating fire danger (Field et al., 2015; Flannigan et al., 2013, 2009; Jolly et al. 2015. We calculated the annual (calendar year) fire weather season length (FWSL) following Jolly et al. (2015) as the number of days per year when the FWI exceeded the midrange value of all daily observations during the period 1979-2019. FWSL is a measure of the annual frequency of fire weather, while FWI95d is a measure of the annual frequency of fire weather extremes with respect to the period of available observations (see Appendix A.9 for further details).

Africa

FWSL is simulated to have already emerged in Algeria, Botswana, Madagascar, Malawi, Mauritania, Morocco, Mozambique, Senegal, South Africa, Tunisia, Zambia, and Zimbabwe. In addition, FWI95d is simulated to have already emerged in Algeria, Botswana, Eswatini, Madagascar, Morocco, Mozambique, Namibia, South Africa, United Republic of Tanzania, Zambia and Zimbabwe. The countries listed here have already experienced an unprecedented shift in fire weather relative to the natural variability simulated for the pre-industrial period.

At 1.5°C of warming, FWSL is projected to emerge in Eswatini, Lesotho, Mali, and Namibia. Also at 1.5°C of warming, FWI95d is projected to emerge in Angola, Burkina Faso, Chad, Kenya, Lesotho, Malawi, Mauritania, Nigeria, and Tunisia. At 2.0°C of warming, FWSL is projected to emerge in Angola, Democratic Republic of the Congo and Guinea. Also at 2.0°C of warming, FWI95d is projected to emerge in Democratic Republic of Congo, Gabon, Mali, Niger, and Sudan. At 3.0°C of warming, FWSL is projected to emerge in Burkina Faso, Gabon, Niger, United Republic of Tanzania. Also at 3.0°C of warming, FWI95d is projected to emerge in Cameroon, Congo, Equatorial Guinea, Guinea, Somalia. No further emergence occurs across the African nations at 4.0°C. The countries listed here are projected to experience unprecedented fire weather under future warming increments relative to the natural variability simulated for the pre-industrial period.

The absolute and relative magnitude of the simulated increases in FWSL and FWI95d experienced by these countries can be accessed via the Searchable Inventory. The absolute increases are also plotted in Figures A9.2 and A9.3.

We are not aware of regional studies focussing on the simulated changes in fire weather in Africa. The lack of prior focus on change in FWSL or FWI_{95d} may relate to the known poor coherence between BA and fire weather across much of this fire-prone continent. Around 85% of BA in Africa occurs in savannah environments, where fire activity shows a stronger dependence on weather conditions during antecedent growing season than on fire weather (van der Werf et al., 2008; Archibald et al., 2009; Chen et al., 2017; Zubkova et al., 2019; Alvarado et al., 2020). A study by Pricope & Binford (2012) of MODIS active fire and burned area datasets in the Kavango-Zambezi Transfrontier Conservation Area (covering parts of Angola, Botswana, Namibia, Zambia and Zimbabwe), revealed increasing trends in fire occurrence and mean fire size, despite variations in land-use or fire management policy, which have a noticeable effect. In addition, human fragmentation of the naturally fire-prone landscape is an increasing restriction to fire spread (Andela et al., 2017; Gregoire et al., 2013).

In regions of Africa that are not fuel-limited, including tropical rainforests and tropical moist forests, changes in BA are expected to show a more direct relationship with changes in fire weather than in the case of the fuel-limited savannahs. Consequently, the emergence of fire weather in equatorial and nations of west and central Africa might be expected to result in more direct consequences for wildfire activity than elsewhere on the continent. Nonetheless, we note that any responses of fire activity to increased fire weather in the region will be mediated by patterns of human ignitions, land clearing and forest degradation (Gregoire et al., 2013). Zhao et al. (2021) recently showed that the distribution of burned area in moist African forests strongly reflects forest edges, which are degraded by disturbance associated with adjacent land uses and exposed to accidental or intentional ignitions. While a recent study by Chuvieco et al. (2021) used statistical methods to determine human factors led to an increase in the interannual variability of burned area in regions of tropical Africa with at least medium burned area occurrence.Asia

Asia

FWSL is simulated to have already emerged in Nepal, Turkey and the Russian Federation. In addition, FWI_{95d} is simulated to have already emerged in China, Iran, Iraq, Nepal, the Russian Federation, Syria and Turkey. The countries listed here have already experienced an unprecedented shift in fire weather relative to the natural variability simulated for the pre-industrial period.

At 1.5°C of warming, FWSL is projected to emerge in Afghanistan, China, Iran, Iraq, and Syria, Also at 1.5°C of warming, FWI_{95d} is projected to emerge in Afghanistan, India, Japan, and Vietnam. At 2.0°C of warming, FWSL is projected to emerge in Japan, Kyrgyzstan, Laos, North Korea, Tajikistan, Thailand, Turkmenistan, and Vietnam. Also at 2.0°C of warming, FWI_{95d} is projected to emerge in Kyrgyzstan, Laos, North Korea, Tajikistan, Thailand, and Yemen. At 3.0°C of warming, FWSL is projected to emerge in Cambodia, India, Indonesia, Kazakhstan, Malaysia, Mongolia, Pakistan, and Uzbekistan. Also at 3.0°C of warming, FWI_{95d} is projected to emerge in Bangladesh, Cambodia, Indonesia, Kazakhstan, Malaysia, Mongolia, Pakistan, Turkmenistan, and Uzbekistan. No further emergence occurs across the Asian nations at 4.0°C. The countries listed here will experience unprecedented fire weather under future warming increments relative to the natural variability simulated for the pre-industrial period.

The absolute and relative magnitude of the simulated increases in FWSL and FWI_{95d} experienced by these countries can be accessed via the Searchable Inventory. The absolute increases are also plotted in A9.4 and A9.5.

A trend for deforestation and peatland drainage in countries such as Indonesia, Malaysia and Papua New Guinea, has led to large-scale fires in equatorial Asia, particularly during drought years (van der Werf et al., 2008). In northeast China, Zhao et al. (2020) observed an increase in number of ground-reported summer fires in 2000-2017 compared to 1966-1999, that they attribute to an increase in summer lightning resulting from climate change. For central Asia, using the modified Nesterov index and the HadGEM2-ES global climate model, Zong et al (2020) project an increase in fire weather of between 63-146% and an increase in burned area of 3-13%, depending on the future emissions scenario, by the period 2017-2099, compared to baseline (1971-2000). Zou et al. (2020) used the Community Earth System Model REgion-Specific ecosystem feedback Fire (CESM RESFire) model to investigate climate – fire – ecosystem interactions. They project future increases in hot, dry weather conditions and the fire combustion factor metric, based on a 10-day average of fire weather parameters (temperature, precipitation, soil moisture), in southeast Asia under modest warming of RCP4.5. Justino et al. (2021) calculated the Potential Fire Danger Index (PFIv2, based on precipitation, temperature, humidity and vegetation type) for the whole Arctic region, finding hotspots in mid-latitude areas of Eurasia and Siberia that were not detected by FWI, which assumes constant pine forest vegetation. Statistically significant positive trends in burned area were reported by Tomshin et al. (2021) for parts of eastern Siberia, coinciding with positive and negative trends in air temperature and precipitation, over the period 2001-2020.

As in the case of other regions, changes in fire weather should not be understood to translate directly to changes in fire activity since the latter is largely dependent on other bioclimatic and, particularly in Eurasia, human factors including deforestation and agriculture (Miles et al., 2006; Huang et al., 2012). A recent study by Chuvieco et al. (2021) used statistical methods to determine human factors led to an increase in the interannual variability of burned area in regions of Central Asia with at least medium burned area occurrence.

Australasia

At 1.5°C of warming, FWI_{95d} is projected to emerge in Australia. At 2.0°C of warming, FWSL is projected to emerge in Australia. Also at 2.0°C of warming, FWI_{95d} is projected to emerge in New Zealand. At 3.0°C of warming, FWSL is projected to emerge in New Zealand. No further emergence occurs across the Australasian nations at 4.0°C. The countries listed here will experience unprecedented fire weather under future warming increments relative to the natural variability simulated for the pre-industrial period.

The absolute and relative magnitude of the simulated increases in FWSL and FWI_{95d} experienced by these countries can be accessed via the Searchable Inventory. The absolute increases are also plotted in A9.6 and A9.7.

Numerous studies have modelled future change in fire weather in the fire-prone country of Australia. Models run by Clarke et al. (2011) projected increases in the annual number of days with extreme fire weather in southeast Australia of 30-200% by 2100, relative to the modern period under a high emissions scenario (SRES A2). Clarke et al. (2016) noted that projections of future fire weather can be highly model-dependent in Australia, specifically due to diverging simulations of future precipitation across models. Sharples et al. (2016) projected the future occurrence of pyroconvective conditions, which are strongly associated with the most extreme bushfires, based on simulations from an ensemble of regional climate models, in southeast Australian forest. On average, the models indicated a 30% increase in the occurrence of extreme C-Haines index values of 30% by 2070 relative to the modern period under SRES A2. Dowdy et al. (2019) modelled the future frequency of extreme FFDI and C-Haines index values using global and regional climate models under RCP8.5, which indicated that increases in extreme FFDI across Australia could be modulated by a reduction in the frequency of pyroconvective extremes in the northeast and a contrasting increase in most other regions. Di Virgilio et al. (2019) modelled the future occurrence of days when both the FFDI and C-Haines indices are very high to severe using regional climate model simulations under SRES A2, identifying significant increases in spring and lesser increases in summer by 2060-2079. Herold et al. (2021) recently showed that 1-in-20-year FFDI values observed in recent decades will return at least twice as frequently by 2060–2079 across much of southeast Australia, with strong agreement across an ensemble of 12 regional climate models under SRES A2. In broad agreement with these previous studies, our analysis suggests that FWSL and FWI_{95d} will increase in southeast Australian forests to 34% and 47%, respectively, above the pre-industrial period at a global MAT increment of 2.0°C, and further to ~50% and ~60-70%, respectively, above the pre-industrial period at 3.0-4.0°C warming.

Here, as in prior regional studies, we found that fire weather is yet to emerge beyond pre-industrial variability in Australia where large pre-industrial variability obscures the signal of anthropogenic climate change despite visible trends in FWSL and FWI_{95d} (Dowdy, 2018; Head et al., 2014; Sharples et al., 2016; van Oldenborgh et al., 2021; Williamson et al., 2016; Yoon et al., 2015). The distinction between anthropogenic and natural signals is particularly challenging to unravel in the case of southeast Australia due to the strong pre-industrial variability imposed by several large-scale climate oscillations (ENSO, the IOD, and SAM) (Abram et al., 2021; Clarke et al., 2013; Dowdy, 2018; Harris & Lucas, 2019; Lewis et al., 2020; van Oldenborgh et al., 2021).

Event attribution studies have also been conducted in Australia. Lewis et al. (2020) suggested that extreme temperatures at the time of the 2018 bushfires in northern Queensland were 4.5 times more likely due to anthropogenic climate change and the rainfall deficit was 1.5 times more likely, enhancing the probability of an event on the scale of the 2018 bushfires. Climate models run by van Oldenborgh et al. (2021) suggested that the FWI values seen during the 2019/2020 bushfires in southeast Australia were at least 30% more likely as a result of anthropogenic climate change.

Central and South America

FWSL is simulated to have already emerged in Argentina, Bolivia, Brazil, Chile and Paraguay. In addition, FWI_{95d} is simulated to have already emerged in Argentina, Bolivia, Brazil, Chile. The countries listed here have already experienced an unprecedented shift in fire weather relative to the natural variability simulated for the pre-industrial period.

At 1.5°C of warming, FWSL is projected to emerge in Colombia, Peru, and Venezuela. Also at 1.5°C of warming, FWI_{95d} is projected to emerge in Colombia, Paraguay, Peru, and Venezuela. At 2.0°C of warming, FWSL is projected to emerge in Guyana. Also at 2.0°C of warming, FWI_{95d} is projected to emerge in Ecuador and Guyana. At 3.0°C of warming, FWSL is projected to emerge in Ecuador, El Salvador, and Suriname. Also at 3.0°C of warming, FWI_{95d} is projected to emerge in El Salvador and Suriname. No further emergence occurs across the Central and South American nations at 4.0°C. The countries listed here will experience unprecedented fire weather under future warming increments relative to the natural variability simulated for the pre-industrial period.

The absolute and relative magnitude of the simulated increases in FWSL and FWI_{95d} experienced by these countries can be accessed via the Searchable Inventory. The absolute increases are also plotted in Figures A9.8 and A9.9.

Various studies have investigated the impact of climate change on future fire weather in South America. Betts et al. (2015) used one ESM (HadGEM2-ES) to project the forest fire danger index (FFDI) under multiple RCP scenarios, finding increases in FFDI across Brazil, Argentina and Chile under all scenarios and greater increases at higher levels of global warming. Fonseca et al. (2019) investigated the projected impacts of climate change and land-use change in the Brazilian Amazon using the CMIP5 ensemble under RCP4.5 and RCP8.5 and either a sustainable or fragmented land-use scenario. Land area with a fire relative probability (FRP) >0.3 (a relevant threshold from the literature) is projected to increase in both mid- (2041-2070) and late-century (2071-2100), with land-use change scenarios accounting for a greater increase than climate scenarios, due to the use of fire for deforestation and pasture management. In October, the month of greatest change, the optimistic scenario (RCP4.5 and sustainable land-use) results in more than a 20% increase in land area with FRP >0.3, while for the pessimistic scenario (RCP8.5 and fragmented land-use) the increase is over 110%. Silva et al. (2016) focussed on Brazilian woody savannas and shrubland, using a regional climate model (RCA4) forced by the EC-Earth ESM to project systematic increases in 21st century fire regime sensitivity under moderate (RCP4.5) warming. The Meteorological Fire Danger Index (MFDI), developed for Brazilian biomes, was projected to increase in number of days in the 'critical' cateogry by 28% (2021-2150) and 32% (2071-2100), due mostly to a 2°C increase in maximum daily temperature. Recent analyses throughout South America by Oliveira-Junior et al. (2021) reveal fire foci and MFDI has traditionally (1980-2015) been greatest in mid-eastern Brazil, and western Bolivia, central Paraguay and northern Argentina. Future projections indicate and 19% and 24% increase above baseline of land area with high MFDI, in southern and eastern Brazil, for RCP2.6 and RCP8.5 respectively. Additional increases are also projected for northern Colombia and Venezuela (RCP2.6) and northern Colombia and Venezuela, southern Peru and Bolivia and more parts of Argentina (RCP8.5). Fire severity likely varies due to changes in large scale atmospheric circulation mode, such as ENSO and the SAM, causing interannual and centennial-scale variability, respectively (Holz et al., 2017; Oliveira-Junior et al., 2021).

As in the case of other regions, changes in fire weather should not be understood to translate directly to changes in fire activity since the latter is largely dependent on other bioclimatic and human factors (Betts et al., 2015; Fonseca et al., 2019). Patterns of deforestation are the dominant driver of fire patterns in Amazonia (Aragão et al., 2018; Silva et al. 2021), while patterns of antecedent vegetation productivity exert a major control on fuel availability and fire occurrence in the Cerrado region of Brazil (Alvarado et al., 2020).

Europe

FWSL is simulated to have already emerged in Bulgaria, Georgia, Greece, Iceland, Romania, Serbia, and Spain. In addition, FWI_{95d} is simulated to have already emerged in Bulgaria, Georgia, Greece, Portugal, Romania, Serbia, and Spain. The countries listed here have already experienced an unprecedented shift in fire weather relative to the natural variability simulated for the pre-industrial period.

At 1.5°C of warming, FWSL is projected to emerge in Bosnia and Herzegovina, Croatia, Finland, France, Italy, Moldova, North Macedonia, Portugal, Slovenia, Sweden, Switzerland, Ukraine. Also at 1.5°C of warming, FWI_{95d} is projected to emerge in Bosnia and Herzegovina, Croatia, Finland, France, Iceland, Italy, Moldova, the Netherlands, North Macedonia, Norway, Slovakia, Slovenia, Sweden, Switzerland, Ukraine. At 2.0°C of warming, FWSL is projected to emerge in Austria, Germany, Hungary, the Netherlands, Norway, Slovakia, and the United Kingdom. Also at 2.0°C of warming, FWI_{95d} is projected to emerge in Austria, Germany, Hungary, and the United Kingdom. At 3.0°C of warming, FWSL is projected to emerge in Belarus, Latvia, and Poland. Also at 3.0°C of warming, FWI_{95d} is projected to emerge in Belarus, Latvia, and Poland. No further emergence occurs across the European nations at 4.0°C. The countries listed here will experience unprecedented fire weather under future warming increments relative to the natural variability simulated for the pre-industrial period.

The absolute and relative magnitude of the simulated increases in FWSL and FWI_{95d} experienced by these countries can be accessed via the Searchable Inventory. The absolute increases are also plotted in Figures A9.10 and A9.11.

Numerous modelling studies have focusses on projecting future change in fire weather frequency in the fire-prone Mediterranean region of Europe. Moriondo et al. (2006) used a single climate model to show increases in mean FWI, FWSL and extreme fire weather frequency (week-long episodes of FWI > 45) lead to an increase in fire probability even in a relatively low emission scenario (SRES B2). Several studies have also projected increase in temperature, precipitation and drought and heatwaves and evaluated their effects on the likelihood of fire occurrence and BA in the Mediterranean (Parente et al., 2018; Turco et al., 2014). Fargeon et al. (2020) used three regional climate models under RCP4.5 and RCP8.5 to project that, by the end of the century, mean summer FWI will increase by + 24-67% and the frequency of 90th percentile FWI will increase by + 19-50% in France with greater rates of change in southern regions. Using an 8-model ensemble of regional climate models under RCP4.5 and RCP8.5, Ruffault et al. (2020) projected that the frequency of fire weather conditions linked to the largest fire types ("heatwave" and "hot drought" fires) in France, Portugal, Greece and Tunisia will increase by 14 and 30% by the end of the century under the RCP4.5 and RCP8.5, respectively. Calheiros et al. (2021) used projections from 11 regional climate models under RCP4.5 and RCP8.5 to reveal significant increase in future fire weather on the Iberian Peninsula that will be temporally pronounced in late spring and early autumn, and spatially pronounced in southern and eastern parts of the region. Our analyses indicate that FWSL has already increased by 20% and FWI_{95d} by 51% since the pre-industrial period, with the majority of models in agreement on the sign and significance of the historical change. The analysis also suggests that FWSL will rise by 47-65% above the pre-industrial average at 1.5-2.0°C warming, and by 97-135% at 3.0-4.0°C warming. FWI_{95d} is projected to rise far more steeply, by 115-162% at 1.5-2.0°C warming and 295-439% at 3.0-4.0°C warming.

Several event attribution studies have also been conducted in parts of Europe. Krikken et al. (2019) found that the FWI values present during the 2018 wildfires in Sweden were around 10% more likely as a result of anthropogenic climate change and that the likelihood of the fire weather conditions seen at that time will double under 2.0ºC of warming above pre-industrial levels. Barbero et al. (2020) used a 17-model ensemble of CMIP5 models to show that fire weather conditions that triggered fires in the 2003 fire season in France would have a <0.2% annual probability of occurrence in the absence of anthropogenic climate change, compared to a probability of ~10% (return interval ~10 years) under today's climate. Based on dual runs of the climate models, Barbero et al. (2020) concluded that anthropogenic climate change was responsible for nearly half of the observed increases in fire weather across the Mediterranean region of France. The detectable impact of climate change on fire weather is consistent with the broader concept of Mediterranean amplification of climate change marked by strong emergent increases in the frequency of hot and dry summers (Fargeon et al., 2020; Turco et al., 2018b).

North America

FWSL is simulated to have already emerged in Canada, Mexico and the United States. In addition, FWI_{95d} is simulated to have already emerged in Canada, Mexico and the United States. The countries listed here have already experienced an unprecedented shift in fire weather relative to the natural variability simulated for the pre-industrial period. Both FWSL and FWI_{95d} have already emerged across all three countries in North America.

The absolute and relative magnitude of the simulated increases in FWSL and FWI_{95d} experienced by these countries can be accessed via the Searchable Inventory. The absolute increases are also plotted in Figures A9.12 and A9.13.

Substantial increases in future fire weather have previously been modelled in North American boreal regions, where mean annual temperatures are increasing at a faster rate than elsewhere in the world (de Groot et al., 2013; Flannigan et al., 2005, 2009, 2013; Kirchmeier-Young et al., 2017, 2019; Wotton et al., 2017; Coogan et al., 2019). De Groot et al. (2013) used several models and CO_2 concentration scenarios to simulate the impacts of climate change on daily severity rating (DSR), a component of the FWI representing the degree to which a fire could be suppressed, in two large boreal study areas in Canada and Russia. All models and climate change scenarios indicated that future fire weather conditions will become more severe in both regions by up to a factor of 4-5 during the peak of the fire season in the late 21st Century relative to the late 20th Century, with the largest increases occurring in western Canada. The annual number of spread days, defined according to operational thresholds that are deemed by practitioners to be supportive of fire spread, will increase by 35–400% by mid-to-late century across Canada, relative to late 20th century conditions (Wang et al., 2015, 2017). Wotton et al. (2017) analysed projections from three climate models, which showed progressive increases in both fuel dryness and the potential intensity of fires that occur in Canadian boreal forests during the 21st Century. The number of days with greatest potential of intense, and often unmanageable, crown fires was simulated to increase due to changes in moisture availability in aboveground biomass. The projections of future fire weather and its interannual variability vary across ecosystems (Kitzberger et al., 2017; Young et al., 2017). Alaskan Arctic tundra and boreal forest edge environments are projected to experience the largest increases in fire weather, where the 30-year fire probability is projected to increase four-fold by 2100 under RCP6.0, based on change in climatic conditions (Young et al., 2017).

Numerous modelling assessments of change in fire weather have also been completed for the western US. Barbero et al. (2015) used an ensemble of climate models to project change in the frequency of fire weather conditions prone to producing large fire events (90th percentile BA) under the RCP8.5 scenario. The models projected an increase in the likelihood of large fires across most historically fire-prone regions of the western US, with the largest increases in the northwest US. Goss et al., (2020) showed ubiquitous, albeit heterogenous, increases in extreme fire weather days (FWI_{95d}) in Autumn (September-November, when the largest wind-driven fires tend to occur) through 2100 in the western US under RCP4.5 and RCP8.5. The models indicated that the magnitude of the trend in Autumn FWI_{95d} is not likely to be spatially uniform, yet increases are essentially ubiquitous across all vegetated areas of California. In some regions, relative increases in extreme FWI frequency are projected to exceed 50% by the late-21st century under RCP4.5 and approach 100% under RCP8.5 by the late-21st century relative to 1950–1979. Abatzoglou et al. (2021) used an 18-model ensemble to project the future likelihood of fire weather conditions linked to spatially synchronous large fire outbreaks across much of the western US under both RCP4.5 and RCP8.5. The models projected that such prolonged spatially synchronous extremes, which have occurred on average in one-in-three years during 1991-2020, will occur in the majority of years during 2050-2100 regardless of the RCP scenario.

A number of event attribution studies have focussed on recent wildfires in North America. The 2015 Alaskan wildfires occurred amidst fire weather conditions that were 34-60% more likely due to anthropogenic effects on temperature and moisture availability, although lightning strikes were the dominant ignition source and the effect of anthropogenic climate change on lightning activity was not established (Partain et al., 2016). Kirchmeier-Young et al. (2017) demonstrated that anthropogenic climate change increased the likelihood of the 2016 Fort McMurray fires in Canada by a factor of 1.5-6 due to increases in FWI. Kirchmeier-Young et al. (2019) later found that anthropogenic climate change increased the probability of extreme fire weather by 2-4 times during record BA in British Columbia during 2017, while 95% of the temperature anomaly at the time of the event was attributed to anthropogenic climate change. Kirchmeier-Young et al., (2019) further used empirical relationships between weather metrics and fire activity in the region to estimate that 86-91% of the BA in British Columbia during 2017 was attributable to anthropogenic climate change.

In addition, a variety of trend attribution studies have focussed on quantifying the contribution of climate change to trends in fire weather. Abatzoglou and Williams (2016) showed that anthropogenic climate change accounted for ~55% of observed increases in fuel dryness from 1979 to 2015 across western US forests. By accounting for strong relationships between BA and fire weather in western US forests, the authors estimated that anthropogenic climate change has doubled the forest fire area.

Summary

Here, we have presented the state-of-the-art evidence for climate-driven increases in fire weather, which result in the increased flammability of vegetation and contribute to an elevated probability of fires. This change in probability is particularly relevant in regions with adequate fuels stocks and ignition sources. We have provided national-level data on simulated change in fire weather season length (FWSL) and extreme fire weather frequency (FWI_{95d}) at policy-relevant temperature increments. These analyses are based on the calculations presented in a recent peer-reviewed assessment of CMIP5 simulations (Abatzoglou et al., 2019). While our analyses represent the state-of-the-art understanding of changes in fire weather at the global scale, we note that CMIP6 model simulations of the requisite daily climate variables have recently become available (Eyring et al., 2016). Hence, there is a clear opportunity to update projections of future fire weather based on projections of core climate variables from the latest and most sophisticated set of climate models involved in CMIP6.

While projections of future fire weather provide valuable insights into future probabilities of fire occurrence via changing vegetation flammability, they nonetheless fail to capture the mediating effects of humans and bioclimatic interactions on future trends in fire activity. This emphasises a need for reliable models of how trends in climate and fire weather translate into trends in BA. Recent benchmarking exercises performed under the remit of FireMIP have indicated that most of the latest generation of fire models are able to reproduce observed spatial and seasonal patterns of BA during the past ~2 decades with greater skill than older models (Hantson et al., 2020) including those involved in CMIP5 (Kloster and Lasslop, 2017). However, the FireMIP models still show a tendency to overestimate BA in savannah-grasslands and underestimate BA in forest regions, and they also struggle to simulate fire season length and interannual variations in BA (Hantson et al., 2020). In addition, there is poor agreement on the historical trends in BA across the FireMIP models, with some indicating large reductions in BA and others indicating increases since 1900. As the FireMIP models are driven by 'offline' prescribed historical changes in climate, CO_2 concentration and population and land use, it also remains unclear how these fire models will perform when coupled to ESMs during CMIP6 (which include complicated 'online' vegetation responses to changes in climate, CO_2 and fire disturbance). An evaluation of the BA simulations from CMIP6 data is eagerly awaited (Lasslop et al., 2020b).

Given the poor agreement on historical BA trends amongst the FireMIP models and the inadequacies of these models in the reproduction of interannual variability, it is perhaps inconceivable that BA projections from the CMIP6 models will provide the degree of clarity required to dramatically increase confidence in their simulated future trajectories of BA under future climate change. Consequently, a need for major step-changes in fire modelling capacity has been highlighted in the literature. Numerous improvements to the model representation of human impacts on fire ignitions and suppression have been suggested. Generally revolving around improved representation of the highly variable relationship between humans and fire on regional and even local scales (Ford et al., 2021; Le Page et al., 2017; Pfieffer et al., 2013; Teixeira et al., 2020). In addition, the representation of sub-grid landscape factors affecting vegetation and fuel continuity and thus fire spread (e.g. terrain, human infrastructure, agricultural mosaics) are viewed as particularly pressing (Wang et al., 2014; Cochrane et al., 2012; Narayanaraj & Wimberly, 2011; Tymstra et al., 2010). These developments in fire modelling are likely to be resolved over the coming decade and should result in major improvements in model capacity to reproduce historical trends in fire. They will bring new capacity to look beyond the impacts of climate change on fire-prone weather and towards a more complete picture of climate change impacts on fire.

2.9 Direct, indirect and induced economic impacts

Introduction

Where appropriate information on types of direct and indirect economic impacts are reflected on within the sector sections above. This section provides a summary of some of the examples of indirect, induced and intangible economic impacts, which can cut across multiple sectors and regions.

Climate change impacts can be described as market or non-market, as well as tangible and intangible, which may or may not be captured by market effects (Figure 9). Tangible and market impacts are fully visible to decision makers as climate impacts translate into higher costs and new investments (e.g., flood protection wall). On the other hand, increased difficulties in sourcing primary resources (e.g., freshwater) will be tangible but market costs are not directly available and decision makers struggle to appreciate the economic extent of such effects.

Intangible effects are less perceivable but not less important. Health costs due to increased mortality or morbidity are intangible but financial costs are accountable for. As noted in section 2.1 severe droughts are associated with health problems from both overheating, and direct and indirect water access issues in both humans and livestock, while water stress and drought have been linked to several human diseases. Similarly, brand value/loyalty and new diseases are intangible but their effects, as we are experiencing, can be quantified and monetized with standard economic tools.

In contrast, intangible and non-market effects are very hard to quantify but could potentially form a substantial component of total economic impacts of climate change. Such effects could include increased anxiety which reduces wellbeing levels, compromised cultural and belief values, reduced trust and social disruption including migration. For example, sections 2.1 highlights that water stress (shortages) and drought has been linked to an increase in violence in some areas, while section 2.7 highlights that the consequences of heat stress can include impacts on mental health and wellbeing.

	Tangible	**Intangible**
Market	Higher cost of production, higher quantity of products	Health impact new diseases, brand value
Non-market	Reduced quantity of resources or number of species	Cultural/belief value Reduced life satisfaction/wellbeing

Figure 9: Differentiation of impacts of climate change

Another crucial categorization is between direct and indirect effects. Direct effects can be attributed primarily to climate change in a cause-effect relationship. In the case of drought direct impacts to business of a reduction in water supply and quality can directly affect productivity. This is particularly the case for sectors that use water as a critical or important part of their production process, such as agriculture or electricity supply. Reduce productivity will result in indirect losses due to changes in the flow of goods and services through sectoral interlinkages and supply chains. As such, droughts can affect economic sectors where water is not a critical or important part of their production process (Jenkins et al., 2021). Likewise, in agricultural economics, a relationship between climate (and weather) and crop yield has been established leading to the direct effect of climate change on tangible market goods (e.g., the price of wheat and maize). Indirect effects can be both market and non-market. Whilst many studies provide important insights into understanding future changes in the growth and quality of major crops - the productive component of food security - how such agricultural impacts would indirectly affect the wider economy and socioeconomic structure, such as poverty levels, of affected countries has, to date, received much less attention (Hertel et al. 2010; 56 Bandara and Cai 2014).

Indirect and induced economic impacts and interlinkages

Importantly, economic estimates of climate change effects still need a shared vision on approaches and key challenges (e.g., intra/inter generation equity, time horizon, risk management and governance of climate change policies). Furthermore, the modelling and evidence on indirect market effects and particularly induced effects (i.e., effects generated by the spending of employees within the supply chain) is still very scarce, particularly where they cut across multiple disciplines and sectors.

For example, drought and water security have direct impacts on economic sectors and society (Arnell 1999). Mortality, morbidity and displacement costs are the most prominent direct social costs but direct and indirect effects on society can also manifest through economic and environment effects. Water scarcity can damage natural habitats and biodiversity and reduce multiple regulating services that provide benefits to society (e.g., water purification or soil water filtration) For example, water is crucial for many recreation activities from boating, fishing, biking, backpacking and wild swimming.

The food supply chain is directly impacted by drought and water security and businesses will face disruption and increased production costs. Indirectly these costs can have unequal effect on users. For example, if the farming sectors face water shortages they might implement new water management strategies which lead to higher production costs. Consumers' final food prices will reflect increased production costs, and in some countries, the effects will be more severe than others with possible displacement effects. The study by Wang et al., (2021) highlighted the potential impact on producers of price changes to primary factors such as land and labour. Such combined factors of impacts on labour combined with changing consumer price effects will be important when considering the impacts on welfare. The study suggests that the impact of rising temperatures on crop yields could reduce overall welfare levels in some of the modelled countries, including India and Ethiopia, even under more stringent climate change goals.

Wang et al., (2021) also highlights how trade can mitigate impacts of decreasing agricultural production at a country level although it may act as less of a buffer for food importing countries if there is a large increase in global food prices. These types of market effects can be hidden in more aggregated multi-region or global analyses (Islam et al. 2016).

As a further example, as highlighted within section 2.3 on coastal flooding, much of the focus of economic studies has been on direct losses and/or avoided losses via adaptation and mitigation. However, there has been less focus on indirect macroeconomic implications, for example how climate change impacts and implementation of adaptation could affect government revenues and expenditures (Parrado et al. 2020). For example, Bosello et al. (2012) model the indirect implications of (direct) sea level rise on GDP, investment, international trade, and welfare for countries in the EU, highlighting the potential for the propagation of effects to landlocked countries as well. Likewise, Schinko et al (2020) account for economy-wide effects of SLR due to cross sectoral linkages and feedback through international trade channels.

Indirect and intangible flooding costs are also less researched (van Ginkel et al 2021) (see section 2.2). Van Ginkel et al (2021) report that flooding is contributing to road and rail network disruptions with significant costs for delayed time for people and cargo, although these costs are rarely monitored. In modelling flooding transport costs for European countries, however, it can also be argued that they overlooked intangible costs described in Babcicky et al (2021), such as psychological effects that impact social wellbeing. Fernandez et al. (2019) is just one of the few examples where tangible and intangible effects of flooding are estimated with wellbeing indicators and econometrics techniques. They collected the life satisfaction index for a period of five years along with flooding experiences, losses, social and economic conditions. For the Philippines they concluded that intangible costs could represent roughly 30% of economic and financial costs.

Limited studies (e.g., Maddison and Bigano, 2003; Albouy et al., 2016; Meier and Rehdaz, 2016) have also attempted to estimate the impact of climate change on the quality of life, or the so called “amenity value of climate”. This notion, in its most general definition, encompasses all the aspects of life affected by climate, including work and free-time activities (e.g., Graff et al, 2018), housing, comfort, consumption and health.

Summary

The above sectoral sections have highlighted many research gaps when related to the estimation of economic impacts related to climate change. For example, it is noted for fluvial flooding that the direct and indirect flood damages are important, but especially the latter still presents as a research gap. The study carried out by (Yin et al. 2021) attempts to quantify economic impacts of future fluvial flooding under climate change and socio-economic development. They discussed the importance of including socio-economic development when estimating direct and indirect flood losses, as well as the role of recovery dynamics, essential to provide a more comprehensive picture of potential losses that will be important for decision makers.

The economic estimates of climate change effects still need a shared vision on approaches and key challenges (e.g. intra/inter generation equity, time horizon, risk management and governance of climate change policies, availability of data on which to base assumptions) and the evidence on non-market and intangible effects is still very scarce. Auffhammer (2018) notes how little has been done on effects of climate change on non-market goods other than mortality. Consequently, key initiatives to help work together on the measurement of the impacts of climate change at the level of detail required for effective decision-making, sector-by-sector and community-by-community, are becoming more evident such as the Climate Impact Lab (https://impactlab.org/), Rhodium group (https://rhg.com/what-we-do/) and the national climate coalition (https://www.theclimatecoalition.org/our-reports).

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Appendix A – Method and Models

A1: Introduction to Methodology

A1.1 Terms and definitions of vulnerability, adaptation, exposure and risk

Risk results from the exposure of vulnerable systems, be they human or natural, to changes in climate-related hazards see Table A1. Vulnerable systems have a propensity or predisposition to be adversely affected as a result of their sensitivity and/or low adaptive capacity. Although the potential for adaptation to reduce risk is not explicitly quantified in this review, some metrics encapsulate the degree to which low a lack adaptive capacity contributes to vulnerability.

Table A1.1: IPCC Definitions

Term	IPCC AR5 (Oppenheimer, Campos, Warren et al. 2014)	IPCC AR6 (in press)
Hazard	The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.	As AR5
Vulnerability	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.	As AR5
Exposure	The presence of people, livelihoods, species or ecosystems, environmental functions, services, and	As AR5

Term	IPCC AR5 (Oppenheimer, Campos, Warren et al. 2014)	IPCC AR6 (in press)
	resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.	
Risk	The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability or likelihood of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. In this report, the term risk is often used to refer to the potential, when the outcome is uncertain, for adverse consequences on lives, livelihoods, health, ecosystems and species, economic, social and cultural assets, services (including environmental services) and infrastructure.	The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and wellbeing, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species. In the context of climate change impacts, risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards. Hazards, exposure and vulnerability may each be subject to uncertainty in terms of magnitude and likelihood of occurrence, and each may change over time and space due to socio-economic changes and human decision-making.
Adaptation	The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may	In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.

Term	IPCC AR5 (Oppenheimer, Campos, Warren et al. 2014)	IPCC AR6 (in press)
	facilitate adjustment to expected climate and its effects.	
Sensitivity		The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).

A1.2 Types of metrics used in this literature review and the Searchable Inventory

As mentioned in the introduction, many of the metrics provided in the Searchable Inventory and discussed in the literature review refer to exposure to climate related hazard, since this is a critical component in risk assessment. Also provided are metrics of climate related hazard itself. These metrics are all collectively referred to as risk-related indicators or risk-related metrics, as they are all elements of risk (where an element refers to the pieces that together combine to form risk as a whole)

Within the Searchable Inventory, the user has the choice of requesting a given metric in the following formats (1) **the absolute value** of the metric given a particular global warming level or (2) the **absolute change of the metric between a past reference period and the particular global warming level** or (3) the **percentage change.** The reference period in (2) or (3) is typically 1961-1990 but may also in some cases be 1986-2015 or other periods.

In the searchable inventory, for some metrics, projected values are independent of the time in which the global warming climate change occurs. For metrics that encapsulate a socioeconomic component, such as population exposure, this necessitates assuming a certain population level. These are taken from a widely available population scenario, Shared Socioeconomic Pathway 2 “Middle of the Road” (SSP2) (see section A1.3 below) which then pins the estimate to a time point.

In addition, the inventory calculates the **percentage avoided change** in the metric that results from limiting global warming climate change to a lower, as opposed to higher, level of average warming, such as 2°C rather than 3°C.

The various formats identified above are not all available for all metrics in the searchable inventory. These different formats are also prevalent in the wider literature. Most literature focuses on the projection of changes in risk-related metrics due to the combination of climate and socioeconomic changes.

An important and perhaps obvious point is that there are a variety of metrics which may be chosen to indicate each particular risk element. For example, for the climate hazard “drought” a wide variety of metrics exist and there is an extensive literature describing the relative merits of the various options. Yet, within the searchable inventory, its scope only allows for a single metric to be presented for drought, which has been carefully selected, on the basis of this literature. Selection of a different metric to indicate the level of climate-related hazard or exposure in a particular sector might result in a different picture about the global distribution of the metric, irrespective of whether absolute or change in metric or its percentage is presented. Within the literature review, some indication of the potential effect of selecting a different metric to measure particular risk components is given, but a full and detailed regional and country breakdown of the possible implications is beyond the scope of this work.

A1.3 General methodological assumptions, spatial scale, and treatment of uncertainties in the regional pattern of climate projection

This section provides information about the assumptions and origin of the metric data in the Searchable Inventory. This is provided so that readers can understand the uncertainties and robustness of the Tyndall data, to help them in the possible application and use of the data. It should be noted that the authors cannot anticipate fully how the data might be used, but in general it is considered helpful to inform readers as much as possible about the underlying assumptions.

To estimate metrics such as changes in climate-related hazards or in exposure to these, it is necessary to consider spatially disaggregated regional climate change scenarios and socioeconomic scenarios, in particular population. This section first describes the origin of these scenarios. The Tyndall data explores well the robustness to uncertainties in regional climate projection, using alternative climate model output to drive extremely detailed, process based models of risk elements. However, the limited scope of the project meant that only one future population scenario could be explored. This means that values of exposure might be larger, or smaller, if different population scenarios were used.

The following sections provide further detail, and a general discussion of potential application of the data, including robustness and confidence.

Socioeconomic scenario

Within the Searchable Inventory, the Tyndall projections are based on regional climate scenarios corresponding to the required levels of globally averaged warming above preindustrial levels. These are combined with one of the Shared Socio-economic Pathways (SSPs, Riahi et al. 2017). The key scenario is SSP2 which describes a 'middle-of-the-road' development for all key drivers, including population, macro-economic and technology assumptions. In particular, the global population rises from 7.2 billion in 2015 to 9.2 billion by 2100 and global GDP from 81.1 trillion US$2005 in 2015 to 537 trillion by 2100. Gridded population data for SSP2 was taken from Jones and O'Neill (2016) archived at: https://www.cgd.ucar.edu/iam/modeling/spatial-population-scenarios.html. We used the 0.125 x 0.125 degree set and aggregated it to the 0.5 x 0.5 degree raster used for the climate projections.

Detailed method for regional climate change projection

Projections were derived by combining monthly observations with projected changes in climate at levels of warming of 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 degrees above pre-industrial levels (1851-

1990) by using data from general circulation models. The target global mean temperature changes were obtained by pattern-scaling the GCM projections using ClimGEN (Osborn et al. 2016).

Specifically, to derive future regional climate change scenarios at 0.5° latitude by 0.5° longitude resolution, capturing uncertainty in regional climate projection, scaled climate change patterns were diagnosed from 22 alternative regional climate change patterns (corresponding to 22 alternative Coupled Model Intercomparison Project (CMIP5) General Circulation Model (GCM) patterns). This was necessary because GCMs have not been run for the precise climate change scenarios used in this study.

To obtain the monthly time-series required by our models, the pattern-scaled changes (anomalies) in mean climate between 1961-1990 and a future 30-year period (2086-2115), was combined with the observed mean climate over a 30-year reference period (1961-1990) so that the observational record provides realistic climate variability (Osborn et al. 2016). Observed climate was taken from the CRU TS3.00 dataset on a 0.5° latitude by 0.5° longitude grid (Harris et al. 2014).

For future precipitation, the observed monthly anomalies were first transformed so that their probability distribution is consistent with the changes in monthly precipitation variability projected by each GCM (see Osborn et al. 2016 for details). Monthly ET was calculated using the Penman–Monteith formula from ClimGen data for minimum, maximum and mean temperature, vapour pressure, cloud cover, and the CRU CL 2.0 wind speed climatology.

This pattern-scaling method for projecting changes in climate assumes that an approximately linear relationship between local changes in climate variables and global-mean surface temperature is valid over the range of climate changes being considered here. The method has been shown to emulate more detailed GCM projections well with errors that are small relative to the climate change signal and relative to the range of projections emerging from alternative GCMs (Osborn et al 2018, Tebaldi and Arblaster 2014). A full review and comparison with other methods may be found in James et al. (2017).

In a minority of metrics, daily time series were required as inputs. In this case, daily anomalies from the WATCH dataset (Weedon et al 2021) were superposed over monthly ClimGEN time series. WATCH is a bias-corrected reanalysis dataset designed for driving impact models and it was selected because it is compatible with the ISI-MIP fast track project (Warszawski et al. 2014).

Potential use of data, robustness and uncertainty issues

Where measures of hazard only are provided, the user should combine them with measures of the spatial distribution of vulnerable human systems or ecosystems in order to take the next step towards an assessment of risk. Where measures of exposure are already provided, the user should combine them with measures of the vulnerability of the exposed system(s) in order to take the next step towards the assessment of risk. Finally, as previously mentioned the user should understand that no additional adaptation is included in the data, and hence any information about the potential to adapt would need to be collected by the user.

In both cases users should understand that the percentage changes in metrics are more robust to uncertainties of many kinds than are the absolute values. The inventory contains information about how the metrics differ when different patterns of regional climate change corresponding to different climate change models are used. This is needed because for example with a 2°C warming, different climate models will project a different pattern of regional temperature and precipitation change, even though the level of global warming is the same. It is important to understand that a 2°C average warming does not mean that the amount of warming in each grid cell is 2°C, only that when averaged over the whole world, including the ocean, the average is

2°C. As mentioned previously, measures of population exposure are based on one middle of the road global population projection only and so if populations increase more or less the exposures would follow suit.

Importantly, the searchable inventory provides metrics that are either totalled, or averaged, over a country. This means that these indicators mask potentially large regional variation about the hazard or exposure within a country. This is particularly the case for large countries such as China or Russia for example, which span a large number of climatic zones some of which will become drier and others wetter as climate changes. On the other hand, projections for very small countries, or islands, containing only a single grid cell, are less robust because they are strongly depending on climate model output for a single grid cell. However, this means that overall, it is often not possible to provide confidence levels for each metric, or indeed each country, since these vary widely between countries and within them.

Where possible, the Tyndall projections in the Tyndall Searchable Inventory are given as ensemble means and ranges across the range of regional climate projections utilised, either 10th to 90th percentile, or sometimes 5th to 95th percentile. The inventory does not contain any quantitative estimates of the uncertainties in output arising from other factors including 1) the difference between using the Tyndall models of impacts and exposure instead of other models; 2) the implications of using alternative metrics. Most of the Tyndall models are state of the art and compare favourably with other approaches. However, a comparison is provided with two other datasets, see below.

Despite these limitations, Appendices A2 to A10 below and the information tab of the Searchable Inventory, summarise the Tyndall Centre's expert judgement as to the robustness of the projections across metrics and regions.

Comparison with the alternative datasets contained in the Searchable Inventory

Data from the Climate Analytics Impact Explorer, some of which are also shown in the Searchable Inventory uses 4 CMIP5 GCMs. Projections from the IPCC WGI Atlas, directly from the CMIP6 General Circulation Model (GCM) model projections are also included, but these in general project only changes in hazard.

The spatial scale of the Tyndall projections is typically the global grid at 0.5° x 0.5° resolution, matching that of the climate change scenarios.

Projections from the IPCC WGI Atlas also cover the global extent but at a slightly coarser 1° x 1° resolution. For inclusion in the Searchable Inventory, the WGI data was disaggregated to the finer resolution using GIS so that the spatial grid matches that of the Tyndall projections and were then aggregated for each country.

The inventory also contains country aggregate metrics produced by Climate Analytics (CA) (http://climate-impact-explorer.climateanalytics.org/) for a wide range of scenarios (economic damage from fluvial floods and tropical cyclones; fraction of population exposed to crop failures, heatwaves and wildfires; land fraction exposed to fluvial floods, crop failures, heatwaves and wildfires; and change in crop yields).A more limited set of projections is available from Climate Analytics at 0.5° x 0.5° resolution, which was considered less useful and not used here.

The projections from CA encompass uncertainty related to the global climate sensitivity to emissions (and how they will play out over time) and the response of local impacts to warming. To do so, CA generated projections for eight policy relevant emission scenarios. Relevant time slices for each warming increment, starting from 1°C and increasing in increments of 0.1°C were generated for a range of scenario-GCM combinations (using 4 CMIP5 GCMs) to identify in which year certain GMT levels are reached. For each specific 0.1°C warming increment identified, projected values were averaged over a 21-year period centred on the identified year. Average values are pooled and median values for each level of warming are computed. The uncertainty range presented is the combination of the uncertainty in the GMT response to a given emission scenario and response of the indicator of interest to a given GMT trajectory. It is important to note that confidence in these results decreases at higher warming levels as these levels are reached in a smaller number of experiments. Results are aggregated to the national level using weighted averages of either population, GDP or area. Unlike the Tyndall data, socio-economic data is assumed to remain constant (population, land-use, management practices, GDP etc.) at 2005 levels. As such the projections reflect the effect of climate change only on the sectoral impacts and damages presented (see http://climate-impact-explorer.climateanalytics.org/methodology/ for further details). To incorporate the data in the Searchable Inventory, country level data from CA for each metric and emission scenario were extracted that corresponded to warming levels of 1.5, 2, 2.5, 3, 3.5 and 4°C, and then averaged across the eight emission scenarios.

The projections from IPCC WGI Interactive Atlas encompass uncertainty similar to the projections from Climate Analytics. Projections are generated using up to 35 CMIP-6 models for a total of 4 policy relevant RCP emission scenarios and up to 4 GMT levels. A specific GMT level is reached when the global near-surface air temperature change averaged over successive 20-year periods first reaches this temperature difference relative to the projections created for the period 1851-1900. In cases where the level is not reached within the simulated time period the GWL is discarded, which leads to lower confidence for higher warming levels as only a few of the RCP scenarios will reach these higher temperatures. Subsequently, mean ensemble values for each level of warming are computed across the range of CMIP-6 models. The interactive atlas does not consider socio-economic data and only presents information for climate variables. The projections thus purely reflect the changes in climatic conditions. For further information on the atlas see IPCC WGI Interactive Atlas.

More generally, the wider literature may use an even wider range of approaches and spatial scales for climate simulations and may employ other approaches to diagnose the pattern of regional climate change, such as dynamical downscaling. A full exploration of the extent to which use of different climate projections might affect the projections within the searchable inventory is beyond the scope of the project.

A1.4 Sector specific assumptions and methods

This appendix contains detailed methodological assumptions underpinning the data presented in the searchable inventory. Some of the key assumptions are tabulated below for readers who require only a brief summary.

Table A1.2: Sector-specific key methodological assumptions in the Searchable Inventory (Tyndall Data)

Sector	Assumption 1	Assumption 2	Assumption 3
Drought	Modelling using this method is sensitive to the choice of input data, including the method	This method may be over-sensitive to increasing	

Sector	Assumption 1	Assumption 2	Assumption 3
	chosen to calculate potential evapotranspiration (PET).	evapotranspiration in areas of high aridity.	
Water security	Water stress is a metric of exposure and how the exposure translates into impact depends on local water management and agricultural practices which are impossible to capture within the chosen modelling framework.	The projections also do not account for any measures of adaptation which might be put in place over time.	
Fluvial flooding	We assumed that future climate variability at the daily timescales is the same as in the present-day observations (changes in the mean climate and in the monthly timescale variability of precipitation are represented).	We did not consider uncertainties due to the hydrological and hydrodynamic models.	Our projection provides the potential risk of flooding, irrespective of non-climatic factors such as land-use changes, river improvements or flood mitigation infrastructure.
Coastal flooding	Modelling takes account of coastal defences in 1995, then impacts assessed with or without future adaptation accounting for socio-economics and sea-level rise. In reality, more adaptation options are available and occur for a wide range of reasons.	That adaptation happens simultaneous or shortly after sea-level rise. In reality this is timed with defence upgrades taking account of nearshore coastal processes.	Scenarios indicate population growth is uniform throughout the country, but coastal population can increase more than the national average, or potentially people may migrate away from the coast.
Agriculture	Modelling is based on a single crop model which does not take into account CO2 fertilisation effects on crop yield. Models that do not	Current crop area and crop type are assumed to remain constant over time.	Modelling does not directly consider the effects of extreme weather events (such as

Sector	Assumption 1	Assumption 2	Assumption 3
	include an estimate of CO2 fertilisation tend to lead to more negative effects than those that consider this process.		flood, drought and heat stress) on crop growth.
Biodiversity	Modelling includes the effects of changes in climate suitability for species based on mean changes in climate. Whilst ability of species to track a changing climate cannot be included in these metrics, the effects would be relatively small	Effects of extreme weather events are not included	Cascading effects of species species interactions are not included
Human health - Dengue and Malaria cases	Modelling does not consider the mass rollout of a vaccine which would significantly reduce risk of infection.	Modelling is based on comprehensive epidemiological datasets, comprising more detail than previous studies. However, other determinants of disease such as socioeconomic development, urbanisation, international flow of people and goods, and deployment of interventions are not accounted for. For example, projected malaria cases must be analysed in the context of a current global contraction due to economic development and disease control efforts.	Results are dependent on the quality and quantity of the epidemiological data recorded, which may vary within and across countries.

Sector	Assumption 1	Assumption 2	Assumption 3
Fire	The fire weather index (FWI) does not account for fuel loads or ignition sources; it is a measure of the of climatic controls on vegetation dryness and thus flammability of the landscape.	FWI is a strong predictor of variability fire activity and fire extent in forests and shrublands, where fuel loads are substantial. Fire weather index is a weaker predictor of fire activity/extent in regions where humans control the fire regime via ignitions/suppression of fires.	Human responses to changing probability of fires, such as enhanced suppression efforts or land management to reduce exposure, are also not represented by the FWI metric.

A.2: Drought and Water Security – State of the art modelling

Drought is one of the key climate-related hazards and when human and natural systems are exposed to it, adverse impacts often occur. The potential for climate change to induce increases in the prevalence of drought, be it through an increased frequency of drought, a tendency towards longer droughts, or an increase in drought severity, is therefore of considerable interest.

There are many different metrics used for modelling drought. The choice of metric depends both on the purpose of the study and underlying data availability. Some drought metrics such as the Standardized Precipitation Index (SPI) are based solely on precipitation, some incorporate a measure of evaporative demand (e.g., Standardized Precipitation-Evapotranspiration Index, SPEI) and some take into account soil moisture (e.g., Palmer Drought Severity Index, PDSI). All of these metrics convert accumulated moisture deficit (or surplus) into a standardised value based on a calibration period. The severity of an event (whether in the historical or future timeseries) is benchmarked against droughts that have been experienced during the calibration period.

In (Price et al., submitted) and in the Searchable Inventory, SPEI (Vicente-Serrano et al., 2010) was used to quantify long-term drought conditions. This approach offers benefits over purely precipitation-based indices because it considers potential evapotranspiration (PET). This is important in climate change related analyses where evaporative losses from the land surface, and thus the area of drying land surface, are expected to increase with rising global temperatures. In addition, SPEI is more straightforward to calculate than PDSI, does not rely on poorly known aspects such as soil characteristics and snow accumulation, and has an explicit timescale over which moisture deficits are accumulated (Vicente-Serrano et al., 2010). However, Cook et al. (2014) found that SPEI has greater sensitivity to future increases in PET than does PDSI in arid regions. This is because soil moisture is an important factor, which is represented in PDSI and not by the SPEI method used here.

Price et al (submitted) looked at six countries (Brazil, China, Egypt, Ethiopia, Ghana and India) using CMIP5 data and the results are in Price et al. (submitted). The analyses, however, were originally calculated at the same resolution, globally, and have been summarized for the Searchable Inventory using the data and methodology below. Drought has been examined, at differing levels and coverages for many countries. There is usually a lag between climate model data being available and it then being used in impact models and analyses. Thus, IPCC Working Group 1 results are more likely to be from the latest models (CMIP6) than the papers analysed for Working Group 2 (where most results were based on CMIP5, some even CMIP3). Most recently, analyses of drought were performed separately for agricultural, meteorological and hydrological drought using CMIP6 model output by the IPCC for the Working Group 1 Interactive Atlas (Gutierrez et al. in press; https://interactive-atlas.ipcc.ch/).

Models

In Price et al (submitted) and the Searchable Inventory, we selected a 12-month timescale (SPEI-12). SPEI-12 represents drought severity by the number of standard deviations by which the water balance is in deficit as compared with the calibration period (e.g. Vicente-Serrano, 2010; Lloyd-Hughes and Saunders, 2002). Categories of drought severity have previously been described by McKee et al (1993) using the simpler but less effective SPI. For example, they defined an SPI < -2 (i.e., more than two standard deviations below normal) as an 'extreme dry' drought' situation. The previous DESNZ study used the 'severe dry' drought' definition, namely when SPI < -1.5 but applied to SPEI (i.e., when the precipitation minus PET accumulated over 12 consecutive months is more than 1.5 standard deviations lower than normal for that month). Drought can occur over different time scales, ranging from a single month to years. Our previous study and data in the

Searchable Inventory used SPEI over a 12-month timescale (SPEI-12). That is, a drought beginning with a magnitude x (in this study, -1.5; approximating 1.5 standard deviations, but potentially including even worst droughts (i.e., <-1.5)) based on the moisture deficit (P-PET) averaged over 12 months. This level of drought has been found to have impacts on both agriculture and groundwater supplies versus using drought lengths of shorter periods. Using SPEI-12 helps avoid potentially misleading seasonally dependent results, particularly in areas with clear wet and dry seasons. SPEI-12 is calculated as a moving average, so an SPEI-12 drought in a given month means that the average conditions in the current plus previous 11 months average to indicate drought conditions of this magnitude. While not every month may have been in drought (indeed, some could have excess moisture), the overall average equates to drought. Thus, when consecutive months of SPEI-12 drought are assessed, the overall length of drought is longer than the number of months indicated, as they are the consecutive months from the time the SPEI-12 drought has begun. Thus, 12 consecutive months of an SPEI-12 severe drought equates to a dry spell that might span 1-2 years when taking into account the time over which the drought developed.

Data Sets Used in the Previous DESNZ study and the Searchable Inventory

For analysis of drought, future time series of meteorological variables (precipitation, mean, minimum and maximum temperature, cloud cover and vapour pressure) are needed. We generated 30-year monthly time series of these variables by combining observed variability from the 30-year reference period (1961-1990) with the pattern-scaled changes in mean climate between reference and future global warming levels. The observed climate came from CRU TS 3.00 (Harris et al., 2014). Using observed variability rather than model-simulated variability avoids problems where model variability is unrealistic but by default prescribes the same variability for the future climate as for the observed climate. The latter limitation is overcome for precipitation (the variable for which changes in variability are the most important to consider in drought) by modifying the default approach to also perturb the observed monthly precipitation variability according to the changes in precipitation variability simulated by the respective GCM. Thus, GCM projected changes in future precipitation variance and distribution skewness are included in the monthly series. Osborn et al. (2016; their figure 3) showed that this approach can emulate GCM projections of the frequency of dry months much better than the default approach in regions where a GCM projects a significant change in precipitation variability.

Potential Evapotranspiration (PET) was calculated using a version of the Penman-Monteith formulation. The climate data and derived drought metrics were all calculated at a spatial resolution of 0.5° latitude and longitude, hence the grid cells used in our spatial analysis are approximately 50x50 km in size in most countries. To calculate the SPEI drought metric, we used monthly P and PET from the data set described above.

Several metrics were derived from the estimated SPEI to provide a more detailed picture of drought conditions based on different SPEI thresholds. First, we determined the probabilities of droughts of a specific category occurring in each grid cell in each month of the 30-year time slice, by dividing the total number of months under drought conditions by the overall number of months (349, because 11 months are lost when forming a 12-month running mean). The results presented in the Searchable Inventory are for SPEI-12 <= -1.5 which is the classification of severe (or worse) droughts. The SPEI-12 threshold of -1.5, or severe drought, is commonly used in drought impact studies. The metric, as it was calculated, included all values less than -1.5 (e.g., extreme drought), but used -1.5 as the starting point. It is also an appropriate threshold for the 30-year calibration period that we use: a value below -1.5 standard deviations will occur 6.7% of the time, i.e. typically, the 24 months with the most negative SPEI-12 values during the calibration period define what is at least a severe drought. A more extreme threshold (e.g. -2, -2.5, etc.) would be less well defined because such strongly negative values occur less frequently during the calibration period. Second, we looked at the total number of months in a drought category per year, the maximum number of consecutive months in a category per year and at the maximum number of consecutive number of months in a category per 30-year period. As noted above, there are a total of 349 monthly SPEI-12 values in each period. By calculating these additional measures, we were able to not only quantify changes in frequency but changes in duration of drought events as well.

A.3: Fluvial Flooding – State of the art modelling

Amongst different types of natural disasters, not only flooding is the most frequent type but also the most socially and economically devastating natural disasters (CRED 2015; Sauer et al. 2021). During the 50-year time period 1970-2019, 44% of all natural disaster events have been flood-related (WMO 2020), followed by storm accounting for 35% which is often connected with floods. At the global scale many regions have seen increased frequencies and intensities of heavy precipitation events (Ranasinghe et al 2021). The observed trend in increasing precipitation, the main driver of floods, have called for an increasing need for strategic global assessments of flood risks in both the present and future conditions (Ward et al. 2013). The modelling tools commonly used to assess changes in fluvial flooding hazards and risks follow a generic framework illustrated in Figure A3.1.

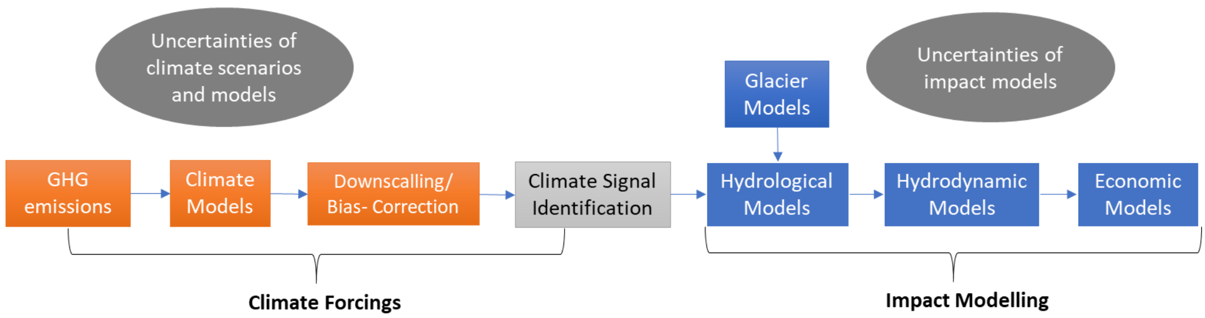


Figure A3.1 A common flood impacts modelling framework

- Climate Forcings

  1. A number of General Circulation Models (GCMs) run in transient experiments through the 21st century, and forced by changing emissions or concentrations of greenhouse gases (GHGs) and anthropogenic aerosols (James et al. 2017).
  2. Downscaling and bias-corrections are often necessary intermediate steps to bridge the spatial gaps and adjust the systematic errors in the GCM's output before they can be used to drive hydrological models which usually run at finer spatial scales compared with GCMs.
  3. The identification of climate change signals is needed to determine what forcing inputs will be used to run through the hydrological models. Many studies of the effects of climate change on flood hazard and exposure use climate scenarios based on projections of future emissions and evaluate impacts and climate risks for specific time periods (see e.g. (Ying et al. 2014; Dankers et al. 2014; Arnell and Gosling 2016; Vetter et al. 2017) and IPCC AR5 reports). This approach makes it difficult to identify the response to a specified degree of global temperature increase (James et al. 2017). There is now an increasing interest in assessing the impacts of climate change at various warming levels instead of future time periods (Arnell et al. 2021).

- Impact Modelling
  1. Hydrological models provide the central node linking the climate forcing with the other impact models. In addition to streamflow, some of them can also simulate soil moisture and groundwater flow.

2. They can be coupled with glacier models accounting for glacier runoff inputs into a river catchment. This is particularly important for mountainous regions.
3. In the case of fluvial flooding hazards, exposures and risks, hydrodynamic models can be used to further simulate flood inundation extent, depth and even velocity which can facilitate risk calculation by using economic models to derive flood footprint including indirect damages (Yin et al. 2021).

Projection flood hazard at different levels of global warming has inherent uncertainties originating from different possible combinations of concentrations of GHGs and anthropogenic aerosols, past observations of climate and of flood hazard, uncertainties in regional climate projection, including those arising from the selection downscaling and bias-correction method, and uncertainties arising from the use of different hydrological models. The uncertainties render it impossible to provide a deterministic projection into the future, resulting in projections always based on an ensemble of modelling outputs. Fluvial flooding hazard projections are usually reported in mean or median values with confidence intervals. The mean value is sensitive to outliers, but the median is more robust when the ensemble size is not large. Because the computational time can be very intensive and using climate forcings from all the climate models is not always possible or desirable, the median values are often used in case of a smaller ensemble size.

Data sets

Precipitation is a crucial component of the water cycle and their intensities and magnitude are directly linked with the severity of fluvial floods (Sauer et al. 2021). The observed precipitation data are either used in the calibration of hydrological modelling or modelling of the baseline period. There has been a rapid development in the global precipitation data sets by various organisations. They include gauge-based, satellite-related, and reanalysis data sets. There is a large degree of variability in the different datasets and it is not a straightforward task to determine which dataset is most suitable. The different datasets also make it difficult to compare results from climate impact studies. Sun et al. (2018) provide a comprehensive review of the data sources and estimation methods of 30 global precipitation data sets and discussed the reliability of different datasets in various regions. NCAR 2020 also provides a summary of 27 global precipitation data sets (NCAR 2020).

Comparison of findings

In this Section, we compare four relevant global studies.

Sauer et al. 2021: They derived river discharge, flooded area and depths at about 25km resolution by using 12 global gridded GHMs participating in ISIMIP2a and coupled with the CaMa-Flood model. They studied absolute trends in **annual maximum daily discharge** and damages in the time period **1971-2010** (see Figure 2). They found the trends in damages are dominated by increasing exposure and modulated by changes in vulnerability. They applied the naturalized experiment referred to as “NOSOC” in the ISIMIP2a protocol, which means no human impacts, such as dams and water abstractions, on river flow were considered.

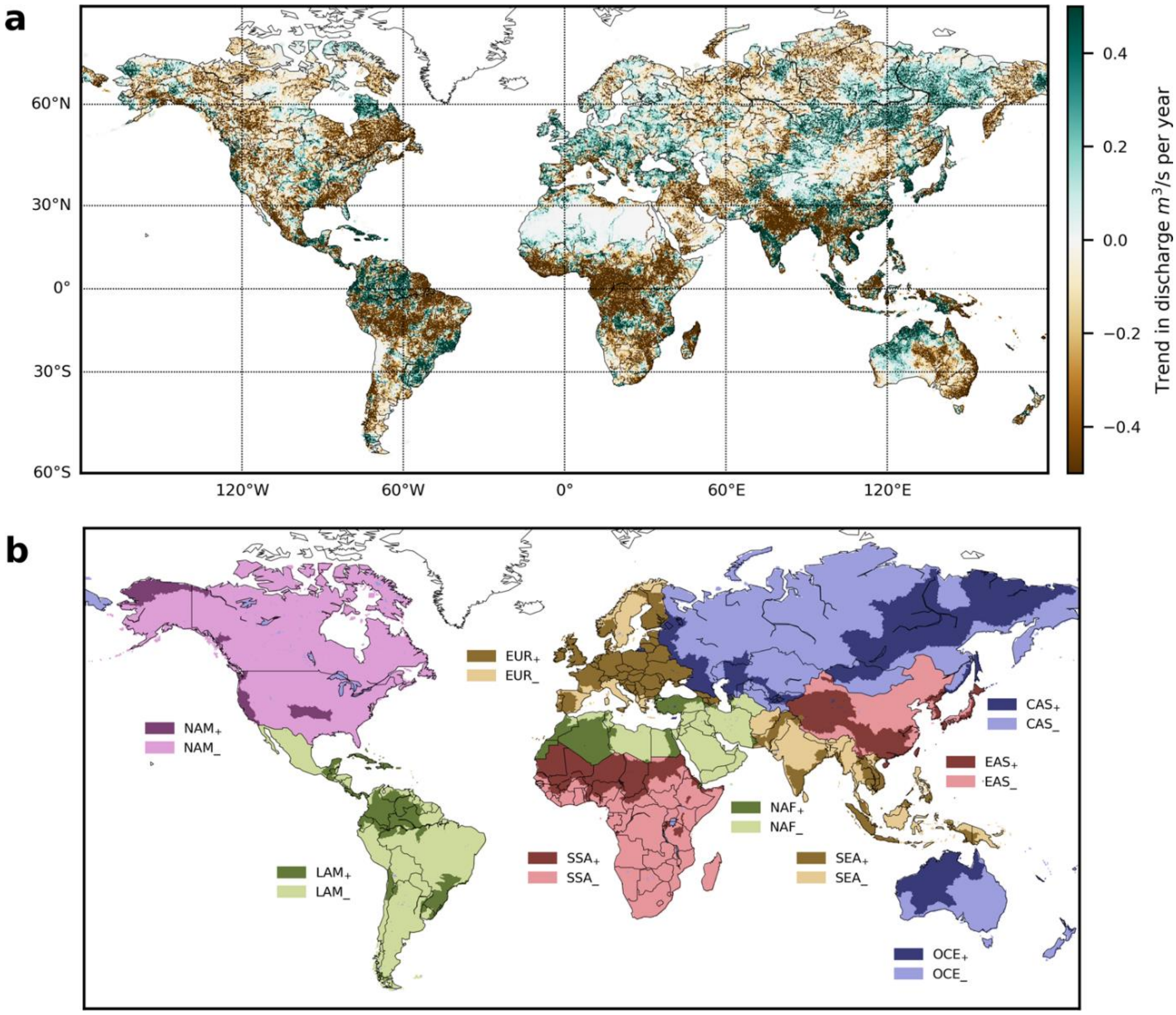


Figure A3.2: Discharge trends and definition of regions. **a** Absolute trends in annual maximum daily discharge in the time period 1971–2010. **b** Map of the nine geographical world regions: North America (NAM), Eastern Asia (EAS), Europe (EUR), Latin America (LAM), Central Asia & Russia (CAS), South & Sub-Saharan Africa (SSA), South & South-East Asia (SEA), North Africa & Middle East (NAF), Oceania (OCE) chosen according to geographical proximity and similarity of socio-economic structure. These regions are then further divided into subregions assembled of river basins with positive (R_+, dark colors) and negative discharge trends (R_-, light colors). (Sauer et al. 2021)

Dottori et al. 2018: They estimated human losses, direct economic damage and subsequent indirect impacts (welfare losses) under 1.5 °C, 2 °C and 3 °C warming and socio-economic scenarios SSP3 and SSP5, assuming no adaptation in the future. The **reference period is 1976-2005** and future period is the 30-year time windows centred on the year that global average temperature is 1.5, 2 and 3 °C above preindustrial temperature. They used the ISIMIP fast-track multi-model hydrological ensemble (50 runoff simulations based on 10 Global Hydrological Models and 5 GCMs) and then used the CaMa-Flood model to produce river discharges at 0.25° resolution. They found on a global scale the relative change in exposed population increase in most parts of the world with ***Asia seeing the largest increase***, and the regional distribution of flooding impacts is uneven, with the ***greatest losses observed also in Asia*** at all analysed warming levels (see Figure 3). They also found the ***impacts are considerably higher under 3 C warming***, but the variability between ensemble members also increases, leading to ***greater uncertainty in flooding impacts at higher warming levels***.

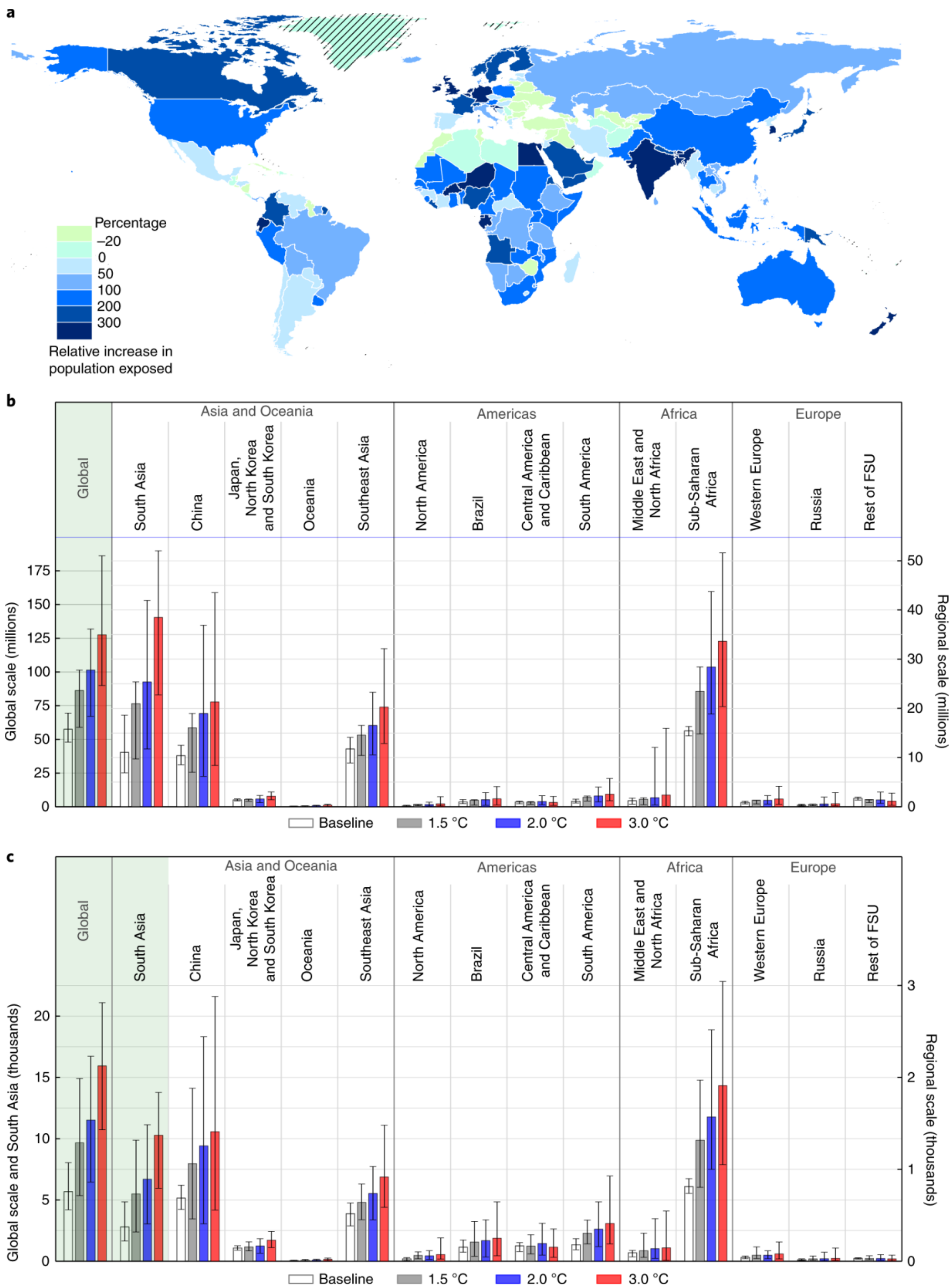


Figure A3.3: **Impacts on the population under the SSP5 scenario. a**, Spatial distribution of the relative increase in the number of people exposed to floods under 3 °C global warming compared to the reference period. Darker blue indicates higher relative increase. Hatching indicates that the confidence level of the average change is less than 90%. **b**,**c**, Number of people exposed (**b**) and killed (**c**) aggregated at the macro-region scale (Supplementary Fig. 1) in the reference period and under different levels of warming. Filled bars reflect the ensemble average, with the error bars indicating the ensemble minimum and maximum. Histograms within the shaded background refer to the left *x* axis scale. FSU, former Soviet Union region. (Dottori et al. 2018)

Alfieri et al. 2017: In this study, 7 GCM outputs were downscalled using the EC-EARTH3-HR v3.1 to a spatial resolution of 0.35°. They were used to drive a global hydrological model, LISFLOOD-RR, at 0.5° resolution. The flood hazard maps at 30 arc-second (~1 km at the equator) were derived from the global streamflow climatology for six selected return periods (T = 10, 20, 50, 100, 200 and 500 years). The Global Human Settlement Layer Global Population Grids [Pesaresi et al., 2013; Freire et al., 2015] for the year 2015 was used as the population data. Figure 5 shows the changes of flood impacts per country at 1.5°C, 2°C, and 4°C. The countries with no hatching are very likely to experience significant changes of flood risk. Changes in flood risk appear unevenly distributed, with the ***largest increases in Asia, U.S., and Europe***. On the other hand, projected changes are statistically not significant in most countries in Africa and Oceania for all considered warming levels. Relative changes in population affected (damage) at 4°C warming are projected to exceed 1000% in 15 (16) countries in Central Europe, South Asia, South America, and Japan (confidence = 90%), as compared to that in 1976–2005. Negative changes in flood risk are found in some countries in Europe and Africa, in agreement with the regional assessment on Europe by (Alfieri et al. 2015b).

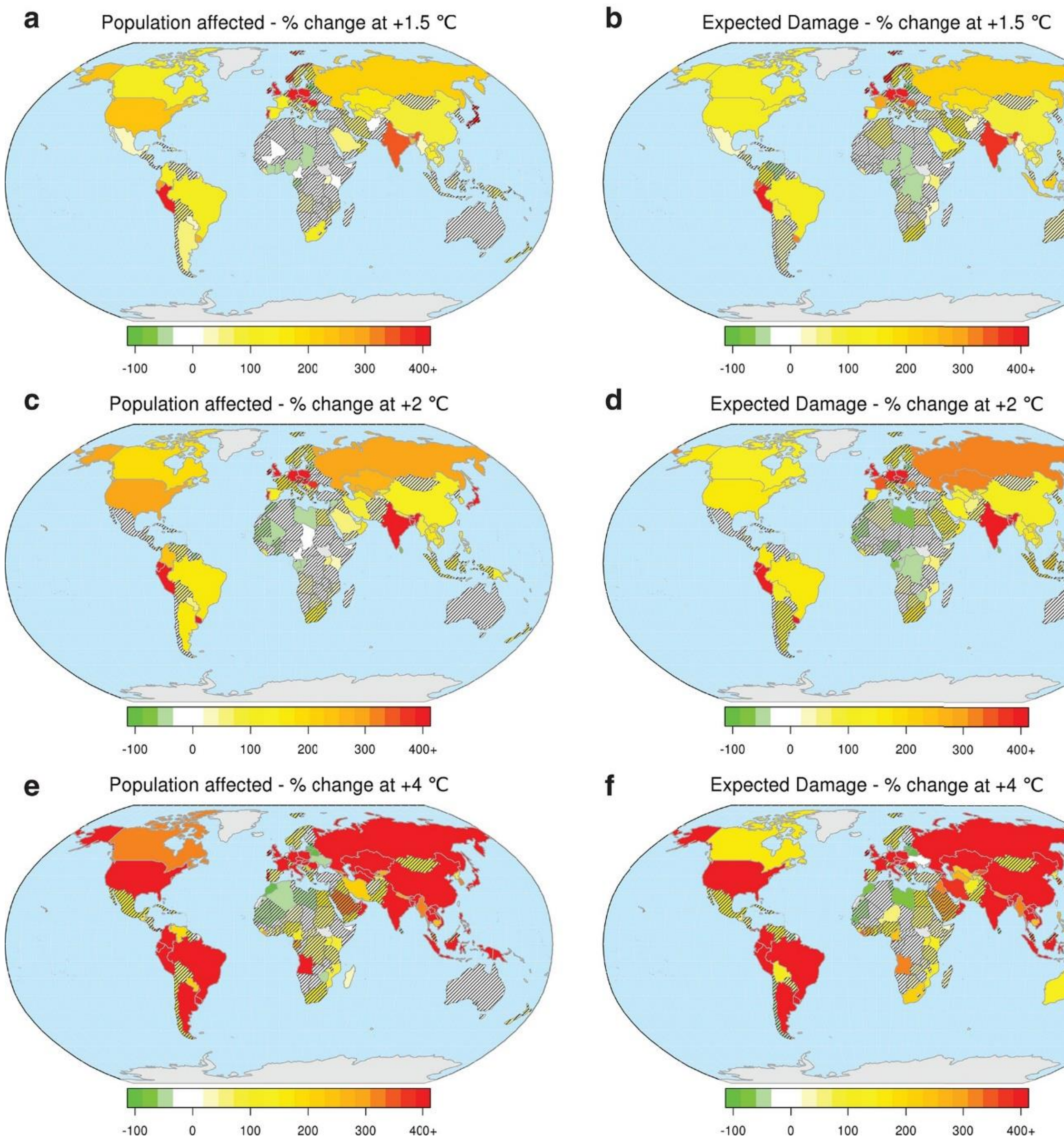


Figure A3.4: Average change in population affected (a,c, e) and expected damage (b, d, f) per country at SWLs. Hatching indicates countries where the confidence level of the average change is less than 90%. (Alfieri et al. 2017)

Hirabayashi et al. 2013: They used the runoff outputs from 11 CMIP5 GCMs and coupled directly with the CaMa-Flood model. The future time period **2071-2100** (21C) and the baseline period is **1971-2000** (20C). The multi-model median return period (years) in 21C for discharge corresponding to the 20C **100-year flood (Q100)** is shown in Figure 5. The return period decreases (increasing flood frequencies and risks) across large areas of South Asia, Southeast Asia, Northeast Eurasia, eastern and low-latitude Africa, and South America. In contrast, flood frequency ***decreases in many regions of northern and eastern Europe, Anatolia, Central Asia, central North America and southern South America***. Globally, flood frequency increases in 42% (23% of the land grid cells showed relatively high consistency >9/11 GCMs) and decreases in 18% of the land grid cells (6% showed relatively high consistency >9/11 GCMs). The ***annual global flood exposure increases by about 4±3 (RCP2.6), 7±5 (RCP4.5), 7±6 (RCP6.0) and 14±10 (RCP8.5) times from 20C to 21C***. This increase in global flood exposure is due mainly to increased exposure in many low-latitude regions, particularly Asia and Africa, where flood frequency is projected to increase in 21C. When a similar calculation was performed with a future medium population growth scenario, the global flood exposure became larger (7-25 times to 20C) than that of the estimation with fixed population. This was particularly true in Asia and Africa, where the population is projected to increase.

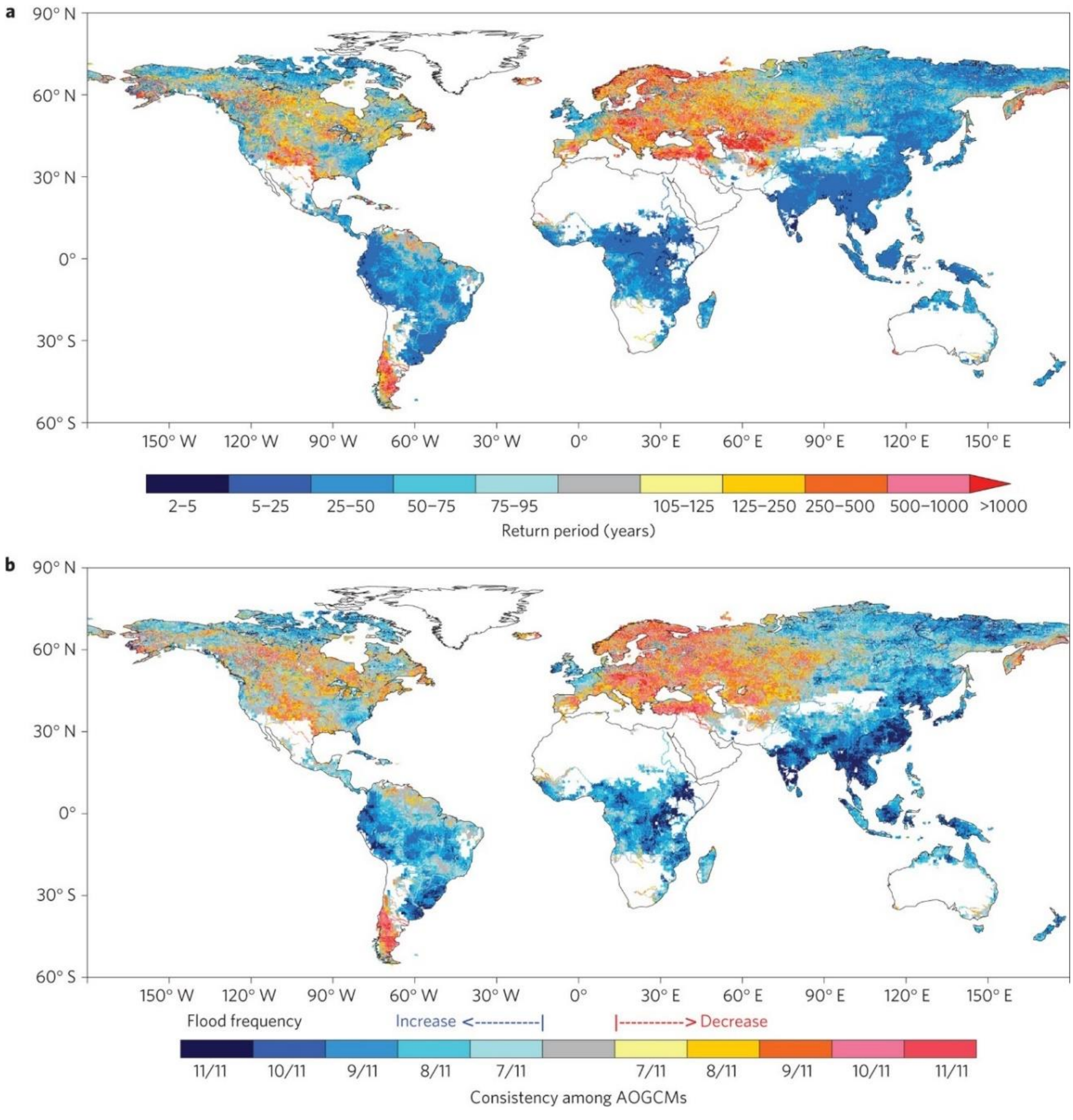


Figure A3.5: **Projected change in flood frequency. a**, Multi-model median return period (years) in 21C for discharge corresponding to the 20C 100-year flood. **b**, Model consistency. Grid cells with mean annual discharge of a retrospective simulation13 for 1979–2010 of <0.01 mm d^{-1} are screened out. The case for the RCP8.5 scenario is shown. (Hirabayashi et al. 2013)

A.4: Coastal Flooding – Additional Tables

One study that did not use the DIVA modelling framework was Haasnoot et al. (2021). They considered the absence of coastal flood protection from flooding (where current protection standards are exceeded). This provides a guide as to who is at risk if there is no additional protection today. This differs from the Tyndall projections in the Searchable Inventory which shows those people at risk with (i.e. an impact) and without protection measures (i.e. exposure). Whilst direction comparison is not possible due to the different definitions to those at risk and regions considered, the trends and relative magnitudes of those at risk may be analysed. This indicates that East Asia and the Pacific, and South Asia have the largest numbers of people at risk, which is analogous to data in the Searchable Inventory.

Table A4.1: People at risk from flooding in millions (where current protection levels are exceeded based on sea-level rise scenarios from Oppenheimer et al. (2019). Extracted from Haasnoot et al. (2021a).

Regions	Year	RCP4.5 (SSP2)		RCP8.5 (SSP5)	
		50th percentile	(17th - 83rd percentile)	50th percentile	(17th - 83rd percentile)
East Asia and Pacific (includes Australasia)	2020	32.4	(32.4 - 33.8)	32.4	(32.4 - 33.8)
	2050	42.4	(39.1 - 45.5)	45.3	(41.7 - 48.9)
	2100	39.3	(34.3 - 56.0)	47.8	(38.8 - 62.0)
South Asia	2020	31.1	(31.1 - 31.5)	31.1	(31.1 - 31.5)
	2050	40.7	(39.3 - 42.2)	40.0	(38.4 - 41.7)
	2100	40.4	(37.7 - 44.4)	38.2	(33.6 - 42.7)
Middle East and North Africa	2020	1.0	(1.0 - 1.3)	1.0	(1.0 - 1.3)
	2050	3.3	(2.8 - 3.6)	3.4	(3.0 - 3.7)
	2100	4.9	(2.4 - 5.6)	5.0	(4.3 - 6.8)
Sub-Saharan Africa	2020	1.8	(1.8 - 1.9)	1.8	(1.8 - 1.9)
	2050	3.7	(3.3 - 4.2)	3.5	(3.1-4.0)
	2100	6.9	(5.7 - 8.4)	6.1	(4.8 - 7.8)
Europe and Central Asia	2020	0.7	(0.7 - 0.7)	0.7	(0.7 - 0.7)
	2050	2.3	(1.0 - 4.0)	3.8	(1.6 - 6.0)
	2100	8.0	(5.9 - 10.6)	19.0	(13.6 - 21.3)
Latin America	2020	0.8	(0.8 - 0.8)	0.8	(0.8 - 0.8)
	2050	1.2	(1.1 - 1.3)	1.2	(1.0 - 1.3)
	2100	1.7	(1.4 - 2.1)	1.8	(1.5 - 2.3)
North America	2020	0.3	(0.3 - 0.3)	0.3	(0.3 - 0.3)
	2050	0.6	(0.5 - 0.7)	0.8	(0.7 - 1.0)
	2100	1.3	(1.0 - 1.7)	3.3	(2.5 - 4.3)

Table A4.2: People at risk from flooding in Africa assuming additional adaptation occurs as socio-economic and climatic conditions change in 2050 and 2100. Average annual number of people flooded (Millions/year). Uncertainty represents high to low (Arnell et al 2019).

Shared socioeconomic pathway	Year	Climate change scenario		
		RCP2.6	RCP4.5	RCP8.5
	2010	0.12	0.12	0.12
SSP1	2050	0.33 (0.31 - 0.34)	0.33 (0.31 - 0.34)	0.34 (0.33 - 0.36)
	2100	0.37 (0.34 - 0.41)	0.39 (0.37 - 0.45)	0.47 (0.41 - 0.52)
SSP2	2050	0.38 (0.37 - 0.41)	0.38 (0.37 - 0.41)	0.40 (0.38 - 0.44)
	2100	0.54 (0.48 - 0.61)	0.59 (0.54 - 0.66)	0.68 (0.61 - 0.80)
SSP3	2050	0.48 (0.44 - 0.51)	0.48 (0.44 - 0.51)	0.51 (0.47 - 0.54)
	2100	0.91 (0.82 - 1.04)	0.99 (0.89 - 1.13)	1.18 (1.04 - 1.37)
SSP4	2050	0.46 (0.44 - 0.50)	0.47 (0.44 - 0.50)	0.50 (0.46 - 0.53)
	2100	0.88 (0.79 - 1)	0.95 (0.86 - 1.10)	1.14 (1.00 - 1.32)
SSP5	2050	0.31 (0.29 - 0.33)	0.31 (0.29 - 0.33)	0.33 (0.30 - 0.34)
	2100	0.34 (0.30 - 0.38)	0.36 (0.34 - 0.40)	0.42 (0.38 - 0.49)

Table A4.3: People at risk from flooding in Asia assuming additional adaptation occurs as socio-economic and climatic conditions change in 2050 and 2100. Average annual number of people flooded (Millions/year). Uncertainty represents high to low (Arnell et al 2019).

Shared socioeconomic pathway	Year	Climate change scenario		
		RCP2.6	RCP4.5	RCP8.5
	2010	1.38	1.38	1.95
SSP1	2050	1.76 (1.67 - 1.86)	1.77 (1.68 - 1.86)	2.26 (2.16 - 2.37)
	2100	1.34 (1.26 - 1.48)	1.44 (1.32 - 1.59)	1.89 (1.72 - 2.15)
SSP2	2050	2.03 (1.93 - 2.16)	2.05 (1.94 - 2.17)	2.59 (2.46 - 2.73)
	2100	1.94 (1.80 - 2.15)	2.07 (1.92 - 2.30)	2.67 (2.44 - 3.04)
SSP3	2050	2.42 (2.32 - 2.55)	2.43 (2.33 - 2.56)	3.04 (2.90 - 3.21)
	2100	3.50 (3.26 - 3.86)	3.74 (3.47 - 4.16)	4.75 (4.34 -5.45)
SSP4	2050	1.99 (1.90 - 2.10)	2.00 (1.90 - 2.10)	2.49 (2.38 - 2.62)
	2100	1.87 (1.76 - 2.07)	1.99 (1.86 - 2.24)	2.50 (2.27 - 2.86)
SSP5	2050	1.67 (1.58 - 1.76)	1.67 (1.59 -1.77)	2.13 (2.04 - 2.25)
	2100	1.24 (1.15 - 1.38)	1.34 (1.23 - 1.47)	1.74 (1.60 - 1.97)

Table A4.4: People at risk from flooding in Australasia assuming additional adaptation occurs as socio-economic and climatic conditions change in 2050 and 2100. Average annual number of people flooded (Millions/year). Uncertainty represents high to low (Arnell et al 2019).

Shared socioeconomic pathway	Year	Climate change scenario		
		RCP2.6	RCP4.5	RCP8.5
	2010	0.01	0.01	0.01
SSP1	2050	0.04 (0.03 - 0.04)	0.04 (0.03 - 0.04)	0.04 (0.04 - 0.04)
	2100	0.05 (0.05 - 0.07)	0.06 (0.05 - 0.08)	0.08 (0.07 - 0.10)
SSP2	2050	0.04 (0.03 - 0.04)	0.04 (0.03 - 0.04)	0.04 (0.04 - 0.04)
	2100	0.06 (0.05 - 0.07)	0.07 (0.06 - 0.08)	0.09 (0.07 - 0.11)
SSP3	2050	0.03 (0.03 - 0.03)	0.03 (0.03 - 0.03)	0.03 (0.03 - 0.04)
	2100	0.04 (0.04 - 0.05)	0.05 (0.04 - 0.06)	0.06 (0.05 - 0.07)
SSP4	2050	0.04 (0.03 - 0.04)	0.04 (0.03 - 0.04)	0.04 (0.03 - 0.04)
	2100	0.05 (0.04 - 0.06)	0.06 (0.05 - 0.07)	0.09 (0.07 - 0.04)
SSP5	2050	0.04 (0.04 - 0.05)	0.04 (0.04 - 0.05)	0.04 (0.05 - 0.05)
	2100	0.08 (0.07 - 0.10)	0.09 (0.08 - 0.12)	0.12 (0.10 - 0.16)

Table A4.5: People at risk from flooding in Central and South America assuming additional adaptation occurs as socio-economic and climatic conditions change in 2050 and 2100. Average annual number of people flooded (Millions/year). Uncertainty represents high to low (Arnell et al 2019).

Shared socioeconomic pathway	Year	Climate change scenario		
		RCP2.6	RCP4.5	RCP8.5
	2010	0.12	0.12	0.12
SSP1	2050	0.34 (0.31 - 0.37)	0.34 (0.31 - 0.37)	0.40 (0.38 - 0.45)
	2100	0.39 (0.34 - 0.44)	0.41 (0.38 - 0.48)	0.44 (0.40 - 0.54)
SSP2	2050	0.36 (0.34 - 0.38)	0.36 (0.34 - 0.38)	0.45 (0.42 - 0.51)
	2100	0.48 (0.42 - 0.53)	0.51 (0.46 - 0.57)	0.62 (0.56 - 0.75)
SSP3	2050	0.37 (0.35 - 0.42)	0.38 (0.36 - 0. 42)	0.54 (0.48 - 0.58)
	2100	0.58 (0.52 - 0.63)	0.61 (0.58 - 0.68)	1.02 (0.92 - 1.23)
SSP4	2050	0.33 (0.31 - 0.36)	0.33 (0.31 - 0.36)	0.42 (0.38 - 0.46)
	2100	0.36 (0.30 - 0.38)	0.38 (0.35 - 0.43)	0.46 (0.42 - 0.56)
SSP5	2050	0.34 (0.33 - 0.37)	0.34 (0.33 - 0.38)	0.38 (0.35 - 0.44)
	2100	0.47 (0.42 - 0.53)	0.51 (0.47 - 0.58)	0.42 (0.38 - 0.50)

Table A4.6: People at risk from flooding in Europe assuming additional adaptation occurs as socio-economic and climatic conditions change in 2050 and 2100. Average annual number of people flooded (Millions/year). Uncertainty represents high to low (Arnell et al 2019).

Shared socioeconomic pathway	Year	Climate change scenario		
		RCP2.6	RCP4.5	RCP8.5
	2010	0.08	0.08	0.08
SSP1	2050	0.21 (0.19 - 0.24)	0.21 (0.19 - 0.24)	0.21 (0.09 - 0.23)
	2100	0.27 (0.22 - 0.31)	0.30 (0.26 - 0.34)	0.35 (0.33 - 0.41)
SSP2	2050	0.21 (0.19 - 0.23)	0.21 (0.19 - 0.23)	0.23 (0.21 - 0.26)
	2100	0.30 (0.25 - 0.35)	0.33 (0.29 - 0.37)	0.39 (0.35 - 0.46)
SSP3	2050	0.19 (0.17 - 0.21)	0.19 (0.17 - 0.21)	0.21 (0.19 - 0.23)
	2100	0.26 (0.22 - 0.31)	0.29 (0.25 - 0.32)	0.33 (0.31 - 0.39)
SSP4	2050	0.19 (0.18 - 0.21)	0.19 (0.18 - 0.21)	0.21 (0.19 - 0.23)
	2100	0.22 (0.18 - 0.26)	0.24 (0.21 - 0.27)	0.28 (0.26 - 0.32)
SSP5	2050	0.23 (0.21 - 0.26)	0.23 (0.21 - 0.26)	0.23 (0.23 - 0.28)
	2100	0.37 (0.31 - 0.44)	0.41 (0.35 - 0.47)	0.48 (0.45 - 0.56)

Table A4.7: People at risk from flooding in North America assuming additional adaptation occurs as socio-economic and climatic conditions change in 2050 and 2100. Average annual number of people flooded (Millions/year). Uncertainty represents high to low (Arnell et al 2019).

Shared socioeconomic pathway	Year	Climate change scenario		
		RCP2.6	RCP4.5	RCP8.5
	2010	0.04	0.04	0.06
SSP1	2050	0.13 (0.12 - 0.15)	0.13 (0.12 - 0.15)	0.16 (0.15 - 0.17)
	2100	0.16 (0.14 - 0.18)	0.18 (0.15 - 0.20)	0.31 (0.27 - 0.34)
SSP2	2050	0.13 (0.11 - 0.14)	0.13 (0.11 - 0.15)	0.15 (0.15 - 0.17)
	2100	0.19 (0.17 - 0.22)	0.21 (0.18 - 0.23)	0.30 (0.27 - 0.34)
SSP3	2050	0.12 (0.11 - 0.13)	0.12 (0.11 - 0.13)	0.12 (0.12 - 0.14)
	2100	0.19 (0.17 - 0.23)	0.21 (0.18 - 0.23)	0.16 (0.15 - 0.18)
SSP4	2050	0.19 (0.17 - 0.23)	0.21 (0.18 - 0.23)	0.16 (0.15 - 0.18)
	2100	0.14 (0.12 - 0.16)	0.15 (0.14 - 0.17)	0.24 (0.21 - 0.27)
SSP5	2050	0.14 (0.12 - 0.16)	0.14 (0.12 - 0.16)	0.18 (0.18 - 0.20)
	2100	0.22 (0.18 - 0.25)	0.23 (0.20 - 0.25)	0.48 (0.43 - 0.53)

A.5: Food security and Agriculture - State of the Art Modelling

Food security is a complex issue and made up of several factors, including food availability, food access, food utilisation and food stability (van Meijl et al. 2020). Many modelling studies into the impacts of climate change on food security have focused on changes to food supplies, such as changes to crop yield and the number of people at risk of hunger. The potential impacts of climate change on crop yields have been widely studied using a variety of methodologies, including through the use of statistical models and process-based crop models. Projections of crop yield changes increasingly draw on a combination of modelling approaches and make use of model intercomparisons (such as AgMIP) and ensemble modelling. Recent studies have also focused on the quality of crops – such as the nutrient density – and the impact on the population, such as reporting changes to the population at risk of hunger or the impact on food prices. Janssens et al. (2020) project that the impacts of climate change will lead to an additional 20 to 73 million people at risk of hunger globally with 3°C warming, many in South Asia and Sub-Saharan Africa. State-of-the-art modelling also often considers additional dimensions of food security, such as political and socio-economic factors.

In the Tyndall data in the Searchable Inventory, impacts of climate change on crop yields are modelled using the statistical crop yield model, ClimaCrop, underpinned by 23 GCMs. ClimaCrop is based on Schlenker and Lobell, (2010) and assumes that the natural logarithm of crop yield is a function of growing season temperature, precipitation and time (Warren et al., 2017). National annual yields were obtained from the FAO (2016) for the years 1961–2012 and matched with CRU TS 3.22 climate data (Harris et al. 2014) for the same period. To quantify the impacts of climate change on crop yields, we limited the crop growing area to locations currently suitable for crop growth, given in Monfreda et al. (2008), keeping both the area and the crops grown constant over time. This model does not take into account carbon dioxide (CO_2) fertilisation effects. Elevated CO_2 in the atmosphere can have a positive effect on photosynthesis and water retention, which can lead to an increase in crop yields. However, this increase is often associated with lower nutritional content of the crops grown. The inclusion (or not) of CO_2 fertilisation is an extremely important factor in modelling the projected impacts of climate change on crop yields. Several studies, such as those conducted through the ISIMIP and AgMIP project (e.g. Ostberg et al., 2018), have shown that when it is included, the sign of yield change is reversed in many regions, including Europe and Asia.

The Searchable Inventory includes metrics on the impact of climate change on four major crops, namely percent yield loss of maize, rice, soy and wheat. Climate Analytics (2021) also includes information on changes to these major crop yields. In addition, they also include total soil moisture content as a metric of agriculture (see Section on Drought and Water Security for further discussion on this metric) and food security and include metrics of the potential impact of extreme events on agriculture. These are the fraction of the population annually exposed to crop failures and the land fraction exposed to crop failures.

A.6: Fisheries – Additional tables

Table A6.1: Projected change in marine fisheries catch potential (%) at levels of warming, relative to pre-industrial level based on outputs from a DBEM. Showing the mean, minimum and maximum of the LMEs within each region (no min, max for Small Islands as only one LME falls into this region). Extracted from Cheung et al. (2016).

Region	Mean (min, max)		
	1.5°C	2.0°C	3.5°C
Africa	-8 (-12, -1)	-12 (-18, -2)	-44 (-67, -14)
Asia	-5 (-30, 31)	-7 (-40, 42)	-32 (-105, 83)
Australasia	-11 (-24, 0)	-13 (-29, 1)	-28 (-76, 6)
Central & South America	-13 (-33, -3)	-15 (-42, -4)	-32 (-98, -4)
Europe	-8 (-19, 4)	-12 (-22, 7)	-19 (-41, 37)
North America	-5 (-20, 1)	-8 (-23, 0)	-22 (-47, 10)
Small Islands	-7	-10	-24
Polar	20 (-15, 89)	45 (-14, 165)	127 (-37, 655)

Table A6.2: FAO projected changes in marine fisheries catch potential (%) by 2050 and 2100 relative to 2000 under RCP2.6 and RCP8.5 based on outputs from a DBEM and a DSFM. Showing the average change per region for country EEZs. Extracted from Cheung et al. (2019).

Region	Year	DBEM		DSFM	
		RCP2.6	RCP8.5	RCP2.6	RCP8.5
Africa	2050	-17.35	-25.54	-18.35	-19.42
	2100	-16.74	-52.01	-13.67	-33.61
Asia	2050	-7.57	-17.64	-6.18	-10.93
	2100	-8.69	-44.93	-3.81	-20.43
Australasia	2050	-4.60	-6.41	-2.29	-8.37
	2100	-3.86	-15.34	0.40	-22.41
Central & South America	2050	-5.10	-8.26	-8.23	-12.87
	2100	-2.73	-44.36	-5.52	-19.18
Europe	2050	-20.14	-23.67	-35.71	-26.66
	2100	-20.52	-40.61	-40.85	-38.29
North America	2050	-2.73	-5.66	-8.34	-5.82
	2100	-4.75	-9.33	-5.05	-12.08
Small Islands	2050	2.87	-7.34	-11.84	-17.02
	2100	5.19	-23.78	-10.00	-28.88
Polar	2050	35.18	49.23	-0.87	-3.97
	2100	45.77	95.93	-2.88	-12.36

A7: Biodiversity and Ecosystem Services – State-of-the-art-modelling

The results presented in the papers and in the Searchable Inventory all draw from the models prepared for the Wallace Initiative. The decision to use this particular database was based on the span of taxa examined and the coherent use of climate model data (21 CMIP5). While there have been other extensive studies (Foden, 2013; Hannah, 2020) they have either not used climate model data (Foden et al (2013) used expert judgement to assess climate exposure risk relative to species' traits) or only a few taxa (Hannah et al. 2020, plants). Warren et al. (2013, 2018) used a consistent set of climate data and modelling methodology across the greatest range of species' taxa. Furthermore, the Wallace Initiative project was designed to sample the broadest range of species to estimate large-scale population changes under a consistent set of climate data A meta-analysis of different climate change impact studies on species (through 2013) found that the differing techniques yielded similar results (Urban 2015).

The methodology used in this project follows that used in Warren et al. 2018 (a,b), Price et al. (submitted b), and Saunders et al (in press). Extensive discussion on the methods, caveats and limitations can be found in Warren et al. 2013, especially the Supplementary Material. Briefly, the global scale Wallace Initiative (WI) database was created using an established species distribution modelling tool, MaxENT (Phillips et al. 2006), to estimate potential changes to the ranges of more than 135,000 species associated with levels of global warming between 1.5 and 6°C (relative to pre-industrial levels), using 21 alternative CMIP5 regional climate change projections for each level of warming to incorporate uncertainty in regional climate projection. As in Warren et al (2018 a,b) calculations were carried out at a 20x20 km scale. The MaxENT analysis works by developing a statistical relationship between current species distributions and current climate, and assuming this relationship holds into the future. To develop these models, species distribution data for many species is required and this was sourced via the Global Biodiversity Information Facility (GBIF; GBIF 2015, Yesson et al. 2007). Species richness remaining in 2100 is calculated based on climates resulting from constraining warming to the lower levels of 1.5° and 2°, compared to higher warming levels of 3° and 4°C in each grid cell. This is then used to quantify the geographical extent of areas we term climate refugia, defined as areas retaining at least 75% of the species currently modelled present under the changed climate (Warren et al. 2018b). This proportion of species must be retained in at least one-half of the regional climate model projections in order to qualify as a refugium, in order to account for uncertainty in regional climate projections. Well-functioning ecosystems depend on the retention of the species that they contain, whereas species loss contributes to loss of ecosystem functioning (Gaston & Fuller 2008). Degradation of ecosystem functioning can then impact ecosystem services and Natural Capital (Price et al., submitted a) and consequently the economic and social systems. Hence, these climate refugia indicate locations where the current ecological community is projected to best be able to be preserved under future climate change. We also look separately at species richness loss (the percentage of species projected to lose 50% of their range) as an indicator of ecosystems that are thought to have lost much of their functioning.

The analyses presented in the Searchable Inventory do not explore the potential for species to move to new geographical locations (adaptation by movement) under climate change. Many mammals, birds, and some insect taxa have a considerable ability to disperse. However, plants, reptiles, amphibians, and most invertebrates much less so (Warren et al 2018a). The degree to which this dispersal results in the successful shifting of individual species' ranges will be affected by their dependency on plants and insects which may have been unable to track their shifting climate envelope and therefore this is excluded from the Searchable Inventory. Furthermore, the recently developed downscaled species data (Price et al. submitted a) used in the Searchable Inventory are unable to take into account dispersal. Dispersal is frequently modelled as an important adaptation for the persistence of individual species and overall global extinction risk. However, at the level of the community, potential changes in competition for limited resources, and/or changes to predator-prey, pollinator and seed dispersal interactions, may counter individual species level benefits.

However, many of the traits that are typically associated with adaptative capacity (e.g., where they live in a canopy; Foden et al. 2013) are actually captured in the Wallace Initiative (and other species distribution) models. Species distribution models start with species occurrence data. Species occurrence data was collected where the species 'occurs' based on its traits – so, the traits considered to provide adaptive capacity in other models in fact do not as they are already 'in the models'. This has implications beyond the biodiversity models. In many models of coffee and chocolate there is an assumption that growing them under shade will convey an adaptation buffer of a few degrees C. However, as the models already include data from the species occurring under shade, it is 'in the model'. Observations of yield changes show declines in shaded areas are on the same order as unshaded.

As well as quantifying the theoretical areal extent of refugia for plants and vertebrates in a pristine environment (i.e., climate only), we also quantify the areal extent of refugia in areas whose land cover has been defined as natural in 2015 using data from the European Space Agency Climate Change Initiative Land Cover Database (ESA CCI; 300m resolution). In this study, natural was defined as cells with >50% natural vegetation. While some agricultural landscapes, and even urban areas may be important for some species, they generally contain lower levels of biodiversity than 'natural' areas.

The aggregated data underpinning Warren et al. 2018 a,b etc. (refugia, species richness remaining and species loss) were subsequently interpolated, on a cell-by-cell base, between warming levels, to generate layers of potential climatic range loss in 0.5°C warming steps from 1°C to 6°C, with 1°C, 1.5°C, 2°C, 2.5°C, 3°C, 3.5°C and 4°C presented here. In order to develop a single metric for 'biodiversity' (as opposed to separate metrics for plants, fungi and animals) it was necessary to work solely with the interpolated data for species richness remaining. This metric was computationally intense and so could only be provided for the 50th percentile.

The climate data used in the Wallace Initiative begin with global temperature time-series corresponding to the Representative Concentration Pathways of 2.6, 4.5, 6 and 8.5 that are then used to scale 21 alternative patterns of regional climate change derived from the CMIP5 model inter-comparison project. Projected climates were produced matching four different levels of warming in the 2080s (i.e., average of the thirty-year period 2071-2100), using the RCP global temperature time series, as follows: RCP8.5 in the 2020s as a proxy for a 1.5°C world; RCP 2.6 in the 2080s for a 2°C world; RCP 6.0 in the 2080s for the higher end of the INDC range (here 3.2°C) and RCP 8.5 in the 2080s for 4.5°C warming. The regional climate change patterns were obtained from the IPCC Data Distribution Centre (www.ipcc-data.org) and were scaled according to the amount of warming provided by the time series and combined with observational climate data (CRU TS 3.0 and WorldClim database for 20 km (10 arc minutes, version 1.4) in order to create 21 alternative projected climate futures (one corresponding to each General Circulation Model) to produce 21 patterns of future regional climate at a fine spatial resolution of 10 arc minutes (Osborn et al. 2016) for each SWL.

Elevational downscaling considers the physical parameter of adiabatic lapse rate. The modelled data, be they 50km or 20km (or even 1 km), are an average of all of the temperatures (and underlying elevations) within a given 'cell' or 'pixel'. In other words, if there is a weather station measuring data at 1000m then local areas higher than this will be cooler and areas lower than this will be warmer. This relationship is modified by local vapour pressure (how much water the atmosphere can hold) but would remain approximately the same with warming. This would especially be expected to hold in reference to the average and the surrounding points (as changes in vapour pressure would likely apply over the area if an entire 'cell'. To elevationally downscale the summary biodiversity data (species richness remaining, refugia) a curve was fit through each taxon to determine how much change there was per increment of temperature (warming or cooling). These curves were then applied to the difference between the 20km annual average temperature and the equivalent 1km annual average temperature WorldClim 1.4 1km (30 arc seconds) data. As some areas were warmer the impacts would increase, and the impacts would decrease in cooler (higher areas). The best way of thinking about this is the difference is a difference in the ability of a species to persist at a scale of 1km owing to differences in temperature. The smaller (finer) the spatial scale, the more information is required to accurately calculate something like micro-refugia (Suggitt et al. 2017). The finer the resolution of the elevation data, the more accurate the data on species occurrences needs to be. Furthermore, depending on the taxa, a species' home range may be large (i.e., hundreds – thousands of meters) so would then potentially span many different cells during a day. For these reasons, limiting the buffering surface to ~1km x 1km and annual temperature is the most scientifically robust approach.

Species Distribution Modelling in the Wallace Initiative

The Wallace Initiative is based on the concept of species climatic-niches and can therefore be applied systematically across the globe. Firstly, the observed climate data is post-processed to provide eight bioclimatic variables (Warren et al 2013). Next, MaxENT is used to identify a statistical relationship between the present-day bioclimatic variables (in 1961-1990) and the distribution of a single species. Secondly, the projected climates are applied to these statistical models to derive potential future climate space for each species in each future scenario. Complete information is available in Warren et al (2018a) and Warren et al (2013). However, some key measures taken to increase rigour and statistical robustness of the findings are: (i) species are assigned to one of fourteen biogeographic realms for the clipping process (to minimize commission errors in applying MaxENT); (ii) species with fewer than 10 data points (occupied grid cells in our analysis) are excluded in order to limit the analysis to those with sufficient data to allow robust statistical analyses; (iii) resampling tests were carried out to identify whether general trends were robust to the inclusion or exclusion of individual species; (iv) rigorous statistical tests were carried out to justify the use of the chosen bioclimatic variables. These steps are all necessary as the questions being asked of these data are not necessarily how any ONE species may be projected to change in relationship with the climate (which we have done) but rather, by treating the species and models as a sample of the overall population whole. Thus, the results are used to infer how biodiversity as a whole may respond to warming, and the best areas to conserve in a warming world.

A8: Health (heat stress and disease) – State-of-the-art-modelling

Methods to assess heat related impacts on human health often utilise information on ambient conditions, such as temperature and humidity (i.e., the *hazard*), or a combination of these such as the wet-bulb globe temperature (WBGT), which assesses the effects of temperature, humidity, and other environmental factors on humans (Andrews et al., 2018). Many heat stress indicators (HSIs) have been developed. No one HSI is considered preferential, as different HSIs can be more applicable to certain regions or impacts such as mortality or productivity changes. Schwingshackl et al., (2021) compared outputs using eight prominent HSIs finding that while the increasing trend in all HSIs was consistent, there was large variance between indicators.

Other approaches use statistical methods to estimate associations between climate variables and epidemiologic data on morbidity or mortality to create exposure-response functions (ERFs) to define regional heat thresholds above which baseline daily mortality or morbidity will increase (Chen et al., 2020; Gasparrini et al., 2015; 2017; Hajat et al., 2014). Changes to labour productivity can also be estimated through ERFs reflecting relationships between workplace health and safety guidelines or economic survey data and WBGT (Kjellstrom et al., 2009; Gosling et al., 2018; Dasgupta et al., 2021). Data from Climate Analytics (2021) on labour productivity related to heat stress is included in the searchable inventory. The metric indicates the percentage decrease in indoor and outdoor labour productivity due to hot and humid conditions.

As with HSIs uncertainty in results can be significant due to the use of different ERFs, for example, linked to the availability and quality of underlying epidemiologic data and whether future population and/or demographic scenarios are considered. The Climate Analytics method is based on Gosling et al., (2018) who use five different ERFs to account for some of this uncertainty. However, the ERFs themselves are derived from field studies focusing on the impact of heat stress on labour specific to a work environment or location with uncertainty around the application of such ERFs globally noted. Population is also assumed to remain constant and so future changes in exposure are not accounted for.

The Searchable Inventory includes two metrics of the impact of climate change on changes in human exposure to vector-borne disease and human health: the number of malaria and dengue cases. Cases are quantified as changes in exposure, using the SSP2 population scenario, relative to an observed baseline climate of 1961-1990 where there is a 66% probability of holding global-mean temperature increase below 1.5°C and 2.0°C, assuming no adaptation. (Warren et al., In Press). Cases were estimated based on clinical and laboratory confirmed reports and fitting a climate-driven empirical model of dengue and malaria incidence, that accounts for long-term and seasonal trends and the spatial and temporal variations in observed dengue data (Colón-González et al. (2018)). Results presented in the Searchable Inventory were found to be in agreement with earlier studies (Warren et al., In Press). However, model uncertainties can reflect the use of different climate scenarios as well as the exclusion of adaptation, e.g., the mass roll-out of vaccines; other determinants of disease, such as socio-economic development and international movement of people; and the underlying quality and quantity of epidemiological data that can differ within and across countries (Colón-González et al. (2018)).

A.9: Fire - State-of-the-art-modelling

Here we describe the methods applied to quantify future changes in FWSL and FWI_{95d} presented in this report and in the Searchable Inventory.

We used the Canadian forest fire weather index (FWI; Van Wagner, 1987), which is among the most commonly applied systems for rating fire danger (Field et al., 2015; Flannigan et al., 2013, 2009; Jolly et al. 2015), to evaluate trends in fire weather during the period 1979-2019. FWI is unitless and a function of four meteorological input variables (temperature, relative humidity, wind speed and 24-hourly accumulated precipitation). These variables are used to produce three fuel moisture codes that integrate the effect of meteorological conditions on fuel moisture across different time horizons (fine fuel moisture code, duff moisture code and drought code). Two indices of fire behaviour (initial spread index and build-up index) are calculated as a function of the fuel moisture codes, and the FWI is calculated as a function of the initial spread index and build-up index. FWI provides an overall metric of the potential for fire to ignite and spread across the landscape. See Jolly et al. (2015) for a more complete description of the Canadian FWI and its calculation, and for a comparison with other fire weather or danger rating systems.

We calculated the annual (calendar year) fire weather season length (FWSL) following Jolly et al. (2015) as the number of days per year when the FWI exceeded the midrange value of all daily observations during the period 1979-2019. In addition, we calculated the annual number of days on which fire weather exceeds the 95th percentile value of all daily observations during the period 1979-2019 (FWI_{95d}). FWSL is a measure of the annual frequency of fire weather, while FWI_{95d} is a measure of the annual frequency of fire weather extremes with respect to the period of available observations. FWSL and FWI_{95d} were calculated separately for each ESM using model-specific FWI midrange values and 95th percentile thresholds (1990-2019). The models were forced with historical forcing during 1850-2005 and with forcing from representative concentration pathway (RCP) 8.5 during 2006-2100. RCP8.5 represents a scenario of rapid ongoing increase in CO_2 concentrations (Meinshausen et al., 2011; Riahi et al., 2011; van Vuuren et al., 2011) and we use it here for sensitivity analysis to temperature thresholds, not as a most-likely future scenario.

We evaluated the change in mean FWSL and FWI_{95d} between the pre-industrial baseline period (1860-1910) and the modern period (1990-2019) for each model and for the multi-model mean. We also calculated changes in FWSL and FWI_{95d} between the 1860-1910 baseline (hereafter pre-industrial) and four global MAT increments of 1.5°C, 2.0°C, 3.0°C and 4.0°C for each model and for the multi-model mean. The time period for the 1.5°C, 2.0°C, 3.0°C and 4.0°C increments was specifically defined as the 30-year period centred around the year in which each temperature threshold is breached in each model. For the gridded analyses shown in Figure A9.1, the approaches applied above were applied at a gridded resolution of 2.5°. For the national summaries shown in Figures A9.2-A9.13, mean values were taken from the constituent 2.5° grid cells within each country.

We also applied a signal-to-noise criterion, as described by Abatzoglou et al. (2019), to test for the emergence of FWSL and FWI_{95d} beyond the pre-industrial variability of the baseline period in the (i) modern period and (ii) the periods of each MAT increment (1.5°C, 2.0°C, 3.0°C and 4.0°C). We treated changes in FWSL and FWI_{95d} as emergent in cases where the majority of models agree on the sign and significance of change, according to the signal-to-noise criterion.

Climatic Controls on Fire

The ability to assess how weather conditions influence the probability of fire has been in recent decades, with attention mostly focusing on how changes in multiple weather and climate variables combined to affect fire probability. Indices of 'fire weather' or 'fire danger' have been devised and applied to observations from meteorological stations and reanalysis datasets, with each index seeking to 'rate' the combined effects of multiple weather variables on the flammability of the landscape (Jolly et al., 2015). Fire weather conceptually refers to the contemporaneous influence of temperature, precipitation, humidity and wind on vegetation dryness (Bedia et al., 2015; Field et al., 2015; Flannigan et al., 2009, 2016; Jolly et al., 2015). Fire weather or fire danger rating systems predominantly rely on inputs of meteorological variables and occasionally soil moisture to represent the contemporaneous and interacting influences of weather on vegetation flammability (Abatzoglou et al., 2018; Abatzoglou & Kolden, 2013; Bedia et al., 2015; de Groot et al., 2013; Field et al., 2015; Flannigan et al., 2005).

Numerous indices of fire weather have been formulated and prominent examples include the Canadian Fire Weather Index (FWI) (Van Wagner, 1987), Australian McArthur Forest Fire Danger Index (FFDI; Noble et al., 1980), US National Fire-Danger Rating System (FDRS; Bradshaw et al., 1984), Swedish Angstrom Index (Chandler et al., 1983) and Nesterov Index (used in parts of Europe and Russia; Nesterov, 1949). These indices have origins in operational fire management and were typically developed by national agencies to assess daily fire probability and inform resource requirements. The Canadian FWI and its sub-components, such as its drought code or fuel moisture codes, have been employed particularly widely to study the influence of weather conditions on vegetation flammability and fire probability in many regions of the world (Abatzoglou et al., 2018; Bedia et al., 2015; Field et al., 2015; Flannigan et al., 2005, 2009, 2016).

Since fire weather indices chiefly account for the contemporaneous meteorological controls on fire probability, they give greatest insight into the likelihood of fire in regions where fire is limited by fuel dryness (Abatzoglou et al., 2018; Bedia et al., 2015), as opposed to those regions where fire is limited by fuel availability (Archibald et al., 2009; Boer et al., 2016; Kelley et al., 2019). Numerous studies have evaluated the co-variability of BA and FWI at global and regional scales. At the global scale, Bedia et al. (2015) showed that the relationship between BA and FWI varies regionally, and is strongest in biomass-rich environments where fuel moisture, rather than fuel availability, is the dominant limitation to fire. Specifically, BA is most sensitive to FWI in ecosystems with low-to-moderate mean annual FWI. On the other hand, BA is relatively insensitive to variability in fire weather in xeric grasslands and shrublands because these are fuel-productivity limited systems (Bedia et al., 2015). Abatzoglou et al. (2018) similarly identified the strongest relationships between BA and FWI in boreal forests and North American temperate forests with ample fuels.

Observed and Projected Trends in Fire Weather

Increases in fire weather represent an increase in the likelihood of fire if fuels and ignition sources are available, with drier, hotter, windier, and less humid conditions priming vegetation to burn. Shifts towards a warmer and more drought-prone climate can act as a key driver of increase in the likelihood of fire, at least up to the point where the system becomes productivity-limited. The Intergovernmental Panel on Climate Change (IPCC) has identified several climate trends that could promote the increasing frequency or extremity of fire weather (Settele et al., 2014, Jia et al., 2019; Fischer et al., 2021): global increases in mean annual surface air temperature (MAT); global increases in the frequency and intensity of heatwaves, and; regional increases in the frequency and intensity of droughts. Consequently, the potential for climate change to influence fire activity by increasing the frequency and severity of fire weather has been investigated using observations and climate models (Abatzoglou et al., 2019; Bedia et al., 2015; Burton et al., 2018; Flannigan et al., 2005; Jain et al., 2017; Jolly et al., 2015).

Box 1: Derivative statistics based on the fire weather index that are indicative of changing fire probability.

Fire weather season length (FWSL): the annual number of days on which the fire weather index value exceeds the midpoint range value of all days in a reference period (herein, 1979-2019). FWSL quantifies the frequency with which fire weather conditions exceed a local threshold below which fires are not likely to occur.

Frequency of 95th percentile fire weather index (FWI_{95d}): the annual number of days on which the fire weather index value exceeds the 95th percentile value of all days in a reference period (herein, 1979-2019). FWI_{95d} quantifies the frequency with which fire weather conditions exceed a local threshold above which the majority of major fires occur.

Temperature of emergence: the temperature at which a signal forced by anthropogenic climate change exceeds the natural climate variability simulated in the absence of anthropogenic forcing. The attribution is performed using a control simulation from a climate model, which indicates the *noise* representing natural climate variability, and a second simulation including anthropogenic forcing, which indicates the temperature change *signal* that occurs relative to the control run. A signal-to-noise criterion (typically a threshold value set at 1 standard deviation above the 30-year mean in the control simulation) is then used to distinguish if the anthropogenic climate change signal has emerged beyond the noise of natural climate variability.

Observed trends in fire weather. Fire weather seasons have extended and extreme fire weather conditions have become more common at the global scale in recent decades, enhancing the flammability of vegetation and pre-conditioning many landscapes to burn more frequently. Jolly et al. (2015) showed that fire weather season length (FWSL; see box 1) increased across 25% of the Earth's vegetated surface during 1979-2013, leading to a 19% increase in global mean FWSL. The trends were shown to hold across different meteorological datasets and metrics of fire weather, with the trends in FWSL in the range of 5-7% decade^{-1} (Jolly et al., 2015). At these continental scales, increases in FWSL have been proportionally greatest in Europe, central and boreal Asia, southern hemisphere South America and temperate North America. In addition, increases in the frequency of extreme fire weather (95th percentile fire weather index values, FWI_{95d}; see box 1) have been most pronounced in southern hemisphere South America, central Asia and across Africa. Trends in extreme fire weather have notably outpaced trends in FWSL in South America and Africa, whereas trends in FWSL have been more pronounced in Europe and boreal Asia than trends in FWI_{95d}. Jain et al. (2021) have recently diagnosed the primary meteorological drivers of increasing FWI_{95d} for continents and ecoregions, finding that either humidity or temperature trends were dominant in most regions while changes in wind speed or daily precipitation have been the dominant driver in very few regions.

Many studies have also been reported on observational trends in fire weather on national or regional scales, in part to evaluate and validate the projections from climate models. Although the comparison of the modelled trends in fire weather with observational trends falls outside the scope of this report, we direct the reader to the following studies which report on observed trends in FWSL or extreme fire weather and compare observed and modelled trends. Conterminous United States: Abatzoglou & Kolden (2013), Abatzoglou & Williams (2016), Williams et al. (2019), Holden et al. (2018) and Goss et al. (2020). Canada and Alaska: Amiro et al. (2004), Girardin et al. (2004, 2009), Jain et al. (2017), Johnston et al. (2020), Wang et al. (2015), Kirchmeier-Young et al. (2017, 2019), Wang et al. (2015), Duffy et al. (2005) and Barrett et al. (2016). Russia and wider Eurasia: Girardin et al. (2009), Groisman et al. (2007) and Justino et al. (2021). Europe: Bedia et al. (2012), Pinto et al. (2020), Venäläinen et al. (2014), Fréjaville & Curt (2015), Krikken et al. (2019) and Giannaros et al. (2021). Australia: Clarke et al. (2013), Williamson et al., (2016), Sharples et al. (2016), Dowdy & Pepler (2018), Dowdy et al. (2019), Di Virgilio et al. (2019), Harris & Lucas (2019), Abram et al. (2021), Canadell et al. (2021), Richardson et al. (2021), and van Oldenborgh et al. (2021). Studies outside of these regions have been sparse.

Simulated trends in fire weather. For historical and future centuries, state-of the-art climate models which contribute to the coupled model intercomparison project (CMIP) also provide the output variables required to assess climate change impacts on fire weather (Abatzoglou et al., 2019; Eyring et al., 2016; Meehl et al., 2009; Taylor et al., 2012). These climate models are driven by historical observations of atmospheric composition including CO_2 concentration. For the future period, the climate models are driven by a variety of Special Report on Emissions Scenarios (SRES) or representative concentration pathways (RCPs), which prescribe the effect of plausible emission scenarios on atmospheric composition (Meinshausen et al., 2011), or by shared socioeconomic pathways (SSPs) which represent plausible emissions trajectories that influence atmospheric composition within the models (Riahi et al., 2017).

A series of global modelling efforts have been undertaken to understand how simulated changes in climate variables will combine to affect fire weather under continued anthropogenic climate forcing. Flannigan et al. (2013) used three climate models and three emission scenarios to evaluate how cumulative severity rating (CSR), a component of the FWI, will change in the mid-century (2041–2050) and late century (2091–2100) relative to the 1971–2000 baseline. They observed significant increases in CSR that are initially most pronounced in high northern latitudes but encompass most of the Earth by the end of the century. Bowman et al. (2017) calculated the future frequency of extreme (93rd percentile) fire weather based on 23 CMIP5 climate models running representative concentration pathway (RCP) 8.5, finding increases on the order of 20-50% by the mid-21st century in many regions that are historically prone to disastrous fires (e.g. the western US and southeast Australia) and larger increases in the Mediterranean and the subtropical Southern Hemisphere.

Abatzoglou et al. (2019) used a 17-model ensemble of CMIP5 climate models to assess past and future trends in FWSL and FWI_{95d}, while also applying the temperature of emergence framework (see box 1) to distinguish the temperature at which fire weather differs significantly from the natural climate variability of the pre-industrial period. Son et al. (2021) recently highlighted that fire weather increases markedly between the 1.5°C and 2.0°C increments of global MAT in many regions, most notably in the Mediterranean, Amazonia and African savannahs. Their results highlight the potential benefits to mitigating fire probability of meeting the 1.5°C ambitious target of the Paris Agreement rather than the 2.0°C commitment.

In section 5, we present a national analysis of trends in FWSL and FWI_{95d} and their emergence beyond pre-industrial variability, based on outputs from Abatzoglou et al. (2019). We also compare the simulated regional change in FWSL and FWI_{95d} with changes in fire weather metrics seen in region-specific studies.

Complicating Factors

While fire weather exerts an important control on the flammability of landscapes, we remind the reader that it is one of a nexus of controls on fire and that changes in fire weather do not alone determine the outcomes for fire activity. Here, we briefly discuss the complicating bioclimatic and human factors that modulate the response of fire activity to changes in fire weather.

Interactions between Climate, Vegetation and Fire

A key concept that has emerged in recent decades is that the world's ecoregions can be arranged along a climatic gradient of productivity-dryness that determines the key limitations on fire (Archibald et al., 2009; Parisien & Moritz, 2009; Pausas & Keeley, 2009; Pausas & Ribeiro, 2013;

Kelley et al., 2019). This is because, in the presence of ample ignition sources, fires depend on both weather conditions conducive to fuel dryness and sufficient vegetation stocks available to burn. For example, fire occurs most frequently in regions with intermediate moisture availability, where dry conditions are sufficiently frequent to intermittently dry the available vegetation but not consistently dry enough to limit fuel production. Hence, fire frequency is determined by a delicate balance between vegetation productivity (fuel production) and the frequency of dry conditions (fuel moisture; the latter influenced by fire weather).

Operating on decadal to centennial timescales, climate change is shifting the global climate zones of temperature and precipitation and affecting both fire weather frequency and the productivity and biogeography of vegetation (Keenan et al., 2014; Piao et al., 2020; Sitch et al., 2015). Hence, the impact of climate change on fire activity is complicated because increases in fire weather can be either compounded or countered by changes in vegetation productivity.

Human Impacts on Patterns of Fire

Contemporary human fire ignition patterns must be understood, at least in part, as the product of regional history. The practices of fire use by Indigenous civilizations continue to influence human uses of fire in the modern period, although they have been variably modified or superseded by colonial attitudes towards fire management. There is substantial evidence that Indigenous and traditional burning of landscapes was widespread on every continent except Antarctica, and particularly in subtropical, Mediterranean, and temperate semi-arid biomes, prior to the onset of colonialism (Trauernicht et al., 2015). Indigenous peoples used landscape and cultural fire intentionally for a wide range of purposes. Highly localized, small-scale fire use facilitated communication and increased abundance of culturally important plants and the production of food, fiber, and medicines, while broader landscape application of fire supported hunting, crop cultivation, land clearing, maintenance of travel routes, and reduced probability of wildfires around communities (Kimmerer & Lake, 2001). Meta-analyses of Indigenous fire use make clear that many groups globally viewed and understood complex ecosystems holistically, and used fire in myriad ways to achieve sustainability and resilience (Trauernicht et al. 2015).

Over the past 500 years, European colonialism in North and South America, Australia, and southern Africa brought vast changes to traditional land practices, including a dramatic reduction in, or outright banning of, Indigenous fire practices across colonial states, widespread grazing, and the spread of intensive agriculture that fragmented natural landscapes (Klein Goldewijk et al., 2011; Marlon et al., 2008). The loss of regular application of fire in many ecosystems that evolved with it has had wide-ranging consequences for contemporary societies, and these consequences have been compounded by land use practices and anthropogenic climate change. Concurrent to the reduction of Indigenous and traditional fire use, the forces of globalization introduced fire to facilitate deforestation and agriculture in regions where landscape fire was rare prior to colonization, such as in Amazonia and other tropical rainforests (Bowman et al., 2011).

Arguably, the role of humans is the greatest source of complexity in our understanding and model representation of modern fire patterns (Ford et al., 2021). Human relationships with fire are as long as human history itself, and they are also regionally complex due to the diverse regional histories of controlling and using fire to cook, heat, hunt and manage land (Bowman et al. 2011). Humans ignite landscape fires intentionally for the purpose of land use change (chiefly deforestation) and land management, as well as through arson and unwanted ignitions such as escape of controlled fires and accidents. Elsewhere, humans reduce fire activity through active fire suppression or preemptive fuel management, and also indirectly by excluding fires from managed areas, urbanisation, and by modifying the density and connectivity of landscape fuels through land use (Andela et al., 2017; Arora & Melton, 2018; Bowman et al., 2017; Lasslop &

Kloster, 2017). These complexities are poorly represented in global fire models (Ford et al., 2021) and it is increasingly appreciated that more must be done to improve the specificity of human-fire relationships in models used for prediction of future fire activity (Bowman et al., 2009; Doerr & Santín, 2016; Ford et al., 2021; Glikson, 2013; Kelley et al., 2019; Lasslop & Kloster, 2017; Pechony & Shindell, 2009; Forkel et al., 2017).

Status of Global Fire Modelling

The growing availability of Earth observation data and understanding of the multiple controls on fire have enabled the development of empirical fire models and improvements to the process-based representation of fire in dynamic global vegetation models (DGVMs) and Earth System models (ESMs). These models have already been used for global-scale simulation of historical trends in fire activity (Arora & Melton, 2018; Kloster & Lasslop, 2017; Knorr et al., 2016; Teckentrup et al., 2019), and in few cases for future periods (Kloster and Lasslop, 2017; Knorr et al., 2016).

Empirical models trained on observational data have been used in a standalone fashion to predict fire activity under predicted changes in climate (Archibald et al., 2009; Balshi et al., 2009; Krawchuk et al., 2009; Moritz et al., 2012; Pechony & Shindell, 2010; Turco et al., 2014; Turco et al., 2018b). Empirical fire models often outperform process-based fire models in reproducing observed patterns and dynamics of fire activity because they have been trained against observational data, although their reliability is unclear when extrapolating outside the range of the training data. However, empirical models omit transient vegetation responses to changes in CO_2 and climate, such that they have limited potential to represent important interactions and feedbacks to climate change in their simulations of future fire activity (Hantson et al., 2016; Harrison et al., 2018; Lasslop et al., 2019; Rabin et al., 2017; Williams & Abatzoglou, 2016).

In process-based fire models, both the ignition and spread of fires is modelled mechanistically as well as the emission of carbon through fuel combustion (Hantson et al., 2016). Lenihan et al. (1998) introduced a model (MCFIRE) that simulates the ignition of fire as a function of drought conditions tied to fine fuel moisture and also the spread of fire from the point of ignition (Lenihan & Bachelet, 2015; Rogers et al., 2011). Venevsky et al. (2002) also introduced a model (RegFIRM) that simulates fire count as a function of the Nesterov fire weather index and fire spread as a function of wind and fuel bed conditions, which has since been adapted to better represent ignition sources (Arora & Boer, 2005; Arora & Melton, 2018; Melton & Arora, 2016) and suppression (Li et al., 2013). Thonicke et al. (2010) built on RegFIRM in their development of the SPITFIRE model, which has been further developed to include lightning and human ignitions in a variety of ways (Kelley et al., 2014; Le Page et al., 2014, 2015; Pfeiffer et al., 2013; Prentice et al., 2011). In additional model developments, emphasis has been placed on better representing fire processes associated with land use change (Kloster et al., 2010; Li et al., 2013). Diverse process-based models are now in existence with many sharing or inheriting elements from earlier models (Hantson et al., 2016). Overall, the process-based models provide a range of representations of the physical processes of fire ignition, spread and other fire dynamics with parameter values that lie within the current (wide) boundaries of process understanding.

Both empirical and process-based models have been employed within a range of DGVMs (Hantson et al., 2016, 2020; Lasslop et al., 2019; Teckentrup et al., 2019), which are the terrestrial component of the ESMs used for future climate simulation. However, ESMs that include fire processes have been found to reproduce satellite observations of BA poorly. Indeed, Kloster and Lasslop (2017) concluded that “fire occurrence is poorly represented in ESMs that participated in CMIP5 and that there is no consensus on how fire occurrence changed over the past and might change in the future”. Given the poor performance of the CMIP5 models, the IPCC relied chiefly on statistical predictions in its recent assessment reports and highlighted the considerable uncertainty in future trends in fire activity (Settele et al., 2014; Jia et al., 2019).

The results of the CMIP5 fire modelling effort exposed a critical need to improve the representation of fire in DGVMs and triggered major efforts, embodied by the Fire Model Intercomparison Project (FireMIP), to improve the process representation and parameterisation of fire models and advance their capability to represent observed patterns of fire in the Earth system (Hantson et al., 2016; Rabin et al., 2017). FireMIP has driven progress in modelling by cross-comparing the methods that are currently employed within models (Hantson et al., 2016), designing an experimental framework to evaluate and compare model representation of key processes (Rabin et al., 2017), and most recently employing that framework, comparing model estimates of BA, identifying key parameters that are the root causes of spread across the model ensemble (Lasslop et al., 2019; Li et al., 2019; Teckentrup et al., 2019) and benchmarking model performance against observations (Forkel et al., 2019a; Hantson et al., 2020). The FireMIP has already helped to encourage developments in fire-enabled DGVMs (Burton et al., 2019; Lasslop et al., 2020a), as well as new research into future changes under various emission scenarios (Burton et al., 2021a).

Scope of this Report

As discussed above, the simulations of burned area from fire models coupled to CMIP5 ESMs are not deemed reliable. Under CMIP6 (Lasslop et al., 2020b), some of the latest fire models developed as part of FireMIP have been coupled to ESMs and used for future projection of fire activity. However, evaluation of the simulations of fire activity from the CMIP6 simulations is not yet complete (Lasslop et al., 2020b). The current limitations to fire modelling capability preclude a reliable analysis of future change in burned area under future climate change (see section 6 “Research Gaps”).

The most recent peer reviewed evidence of climate change impacts on fire probability available stems from the CMIP5 climate model simulations as post-processed by Abatzoglou et al. (2019). In this report and in the Searchable Inventory, we use the FWI simulations presented by Abatzoglou et al. (2019) to evaluate historical and future trends in FWSL and FWI_{95d} during 1861-2100 on a national basis.

While these simulations provide important insights into the impact of climate change on fire probability, we caution against their use as direct metrics of fire probability without ample consideration of other factors that influence fire occurrence. We emphasise this point via three examples as follows.

First, fire weather is known to be a secondary control on burned area in regions with significant fuel limitations. A prime example of this is in the African savannahs, where patterns of fire are principally influenced by fuel availability as determined by vegetation growth in the prior growing season (Alvarado et al., 2020; Archibald et al., 2009). In savannahs, weather conditions lead to the desiccation and turnover of herbaceous vegetation in virtually every dry season, such that the quantity of vegetation produced during the prior wet seasons exerts a greater control on fire than contemporaneous fire weather conditions in the dry season (Alvarado et al., 2020; Archibald et al., 2009; Chen et al., 2017; van der Werf et al., 2008; Zubkova et al., 2019). Zubkova et al. (2019) have shown that reductions in precipitation during the growing season have led to a reduction in fuel availability in African savannahs, partly explaining the reduction in BA in these area in recent decades. Andela et al. (2017) also highlighted that the observed decline in BA in African savannahs relate in part to the expansion of high-capital agriculture, which fragments the naturally fire-prone landscape and constrains fire spread. Indeed, various studies employing statistical or machine learning models have shown that both hydrological and human factors contribute to spatial and temporal variability in BA in most parts of African savannah biome, and that there are few sub-regions where either of these factors are the exclusive driver of variability in fire activity (Andela & van der Werf, 2014; Alvarado et al., 2020; Archibald et al., 2010; van der Werf et al., 2008; Forkel et al., 2017). In any case, contemporaneous fire weather conditions are not viewed as the dominant control on fire activity in African savannahs under the current bioclimatic conditions that these regions experience.

Second, ignition sources must be available if fire is to occur during periods of fire weather. A prime example of this is in tropical rainforests, where patterns of fire are principally controlled by human activities, including deforestation and forest degradation (Aragão et al., 2018; Silva et al. 2021; Nikovonas et al., 2020; Zhao et al., 2021). Human activities are ultimately constrained to periods of fire weather because, at most times of the year, tropical forests are too moist to burn extensively. Hence, deforestation fires are generally ignited at the climatological driest point of the year (maximum fire weather) in order to maximize the removal of biomass (Aragão et al., 2018; Nepstad et al., 2014; Field et al., 2016; Le Page et al., 2010). Nonetheless, without human ignitions sources, fires are very unlikely to occur in tropical forests during years with typical climate as natural ignitions by lightning are not known to be a common phenomenon (Field et al., 2009). In Amazonia, BA trends have changed in sign several times since the 1990s in response to changes in policy and its implementation (Nepstad et al., 2014; Tyukavina et al., 2017; Aragão et al., 2018; Silva et al. 2021; Libonati et al., 2021). These patterns do not mirror trends in fire weather, which emphasises that the dominant control of fire in Amazonia are ignitions and not the availability of suitably dry conditions. Note that while most fires in tropical forests are associated with deforestation, wildfires can occur during protracted droughts (and associated fire weather) when forests become atypically vulnerable to fire, especially at degraded forest edges (Aragão et al., 2018; Nikovonas et al., 2020; Zhao et al., 2021). Extreme fire seasons have occurred during major drought years in tropical forests, highlighting that variability in fire weather can lead to variability around predominantly deforestation-driven trends (Aragão et al., 2018; Lewis et al., 2011; Morton et al., 2013; Nepstad et al., 2008).

Third, humans have developed effective methods of preventing or lessening the impact of unwanted wildfires during periods of fire weather. The prime example of this is the use of controlled or prescribed burning to remove excess fuel loads during safe weather conditions, with the view to prevent fire spread and minimise fire intensity during later periods of extreme fire weather (Burrows & McCaw, 2013; Clarke et al., 2019; Doerr & Santín, 2016; Fernandes et al., 2013; Fernandes & Botelho, 2003; Price et al., 2015). This method is practiced widely in the US, Canada, Australia and some parts of the Mediterranean. Controlled burning is considered effective in reducing the exposure of assets/infrastructure to damage and, to various degrees, to reduce fire frequency and intensity (Bradstock et al., 2012; Hiers et al., 2020; Moritz et al., 2014; Price et al., 2015). Note that the effectiveness of controlled burning could be diminished by lengthening FWSL in some regions (Price et al., 2015; Tolhurst & McCarthy, 2016). For example, extended wildfire seasons in the western US and southeast Australia have resulted in a perceived reduction in the number of days suitable for controlled burning amongst operational services (Prichard et al., 2017; Ximenes et al., 2017). Applications of regional climate models in Australia have also pointed towards a more constrained burn window in southeast Australia in future climates (Di Virgilio et al., 2020; Clarke et al., 2019). Other work has suggested that suppression capacity could be exceeded more regularly in future due to climate change in parts of Canada (Wotton et al., 2017).

These examples highlight that fire weather alone is not an overall indicator of fire risk, however it is an indicator of the changing probability imposed by a changing climate on the flammability of the landscape in regions with productive vegetation and ample ignition sources. It is critical to keep in mind the limitations of fire weather as a predictor of burned area in locations that do not fit these criteria.

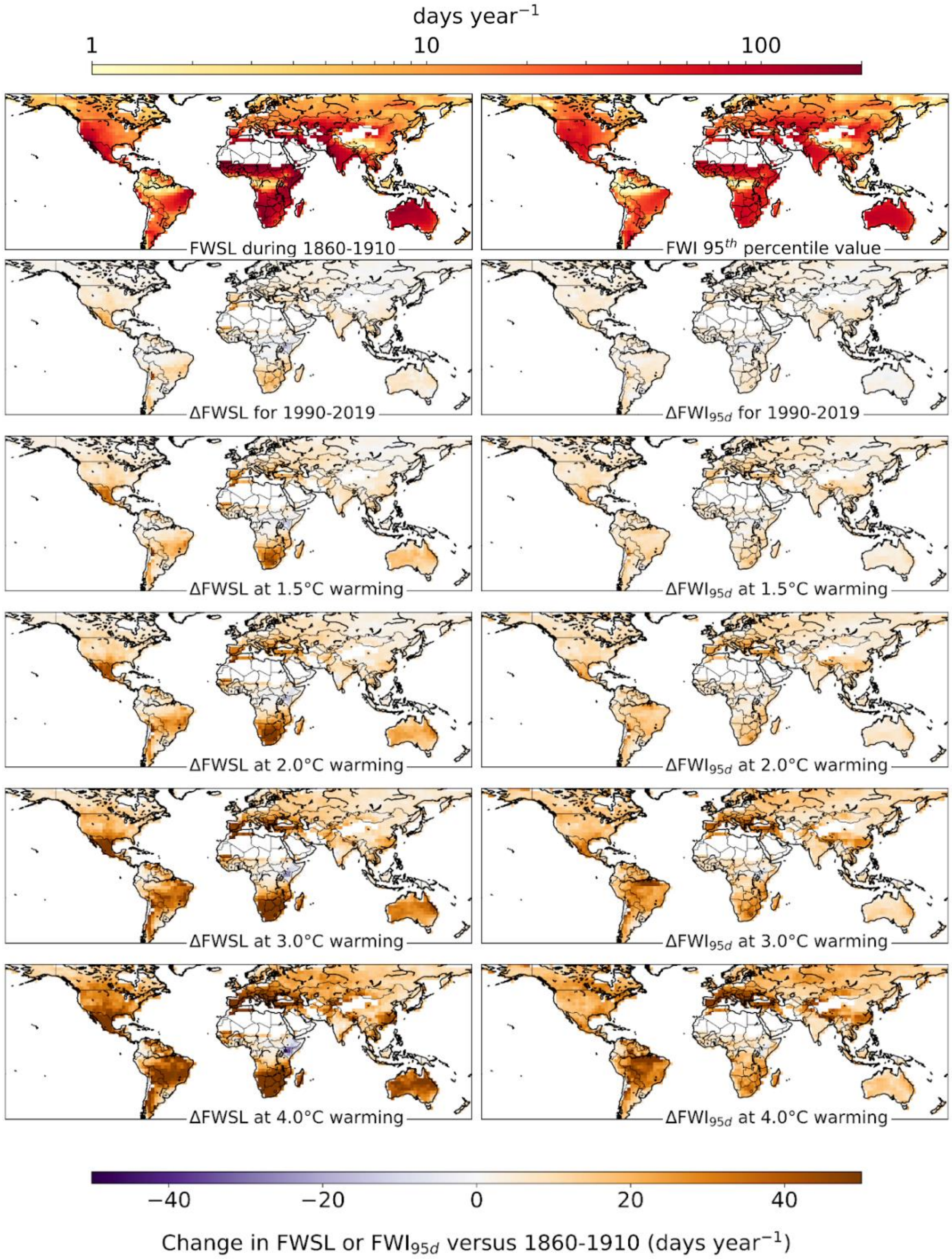


Figure A9.1: Global patterns and trends in fire weather based on multi-model statistics from 17 CMIP5 models (10 models for +4.0°C), gridded at 2.5° resolution. Multi-model mean estimates of (top row) mean and (other rows) change in (left panels) fire weather season length (FWSL) and (right panels) days exceeding the 95th percentile fire weather index (FWI95d). Changes in FWSL and FWI95d are expressed relative to the baseline period (1861–1910) and shown for the modern period (1990-2019) and for each of four global MAT increments as indicated.

Regional results

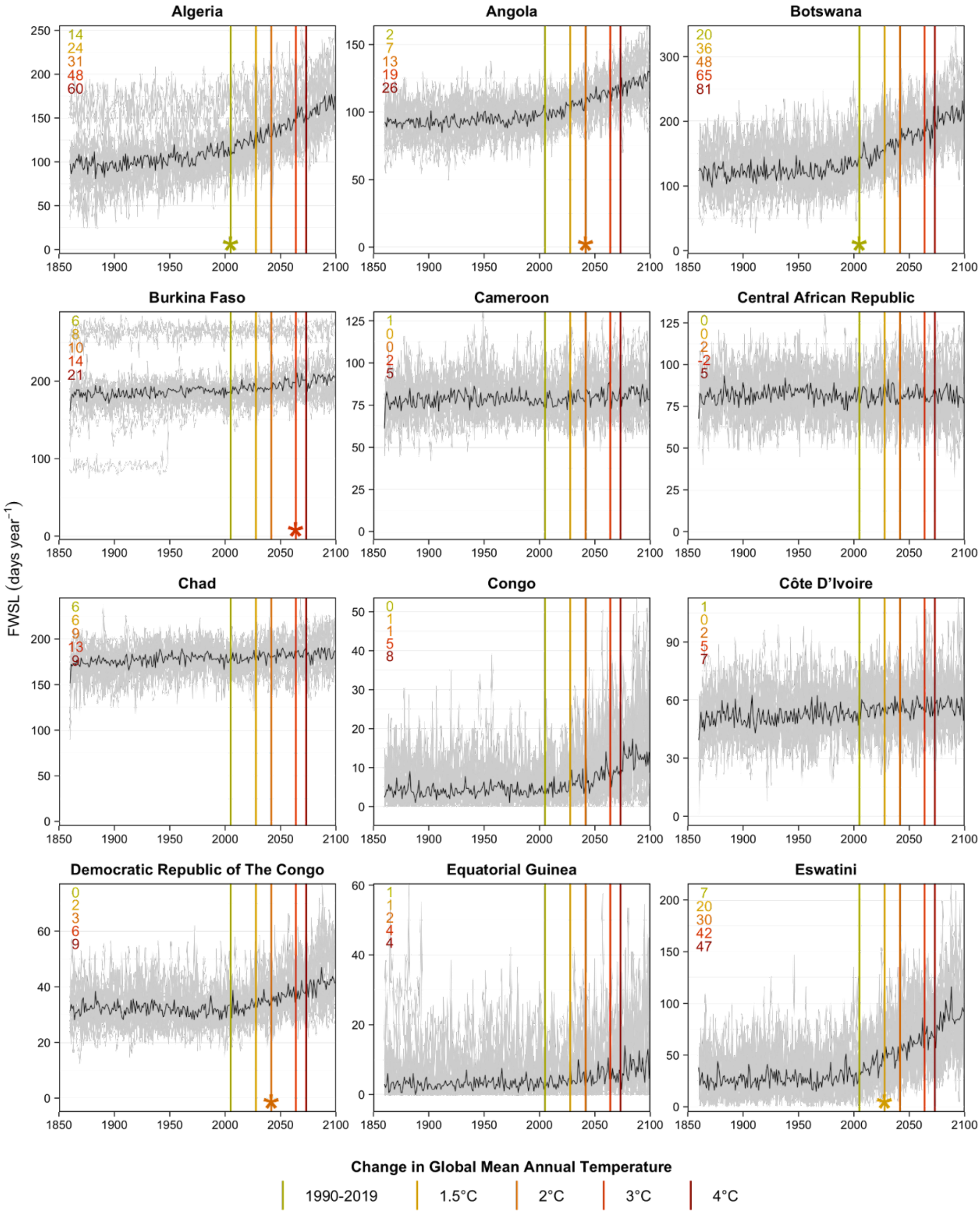


Figure A9.2: Simulated changes in fire weather season length (FWSL; days year-1) for countries in Africa. Simulations are based on Climate Model Intercomparison Project (CMIP5) models running RCP8.5. Each panel represents one country as indicated. Grey lines plot simulated FWSL from individual models. The black line marks the multi-model median value of FWSL. Coloured vertical lines plot the central year of the modern period (1990-2019), or the central year of each period in which increases of 1.5-4.0°C in global mean annual temperature (MAT) are reached relative to the 1860-1910 baseline (as the period at which these temperate increments are reached varies across the models, the year shown represents the multi-model average timing). Inset numbers with matching colour indicate the change in FWSL (days year-1) relative to the pre-industrial period for each temperature increment. Asterisks mark the temperature increment (if any) at which FWSL emerges above its pre-industrial variability according to a strict signal-to-noise criterion, signifying a distinct change in FWSL outside the range of natural variability.

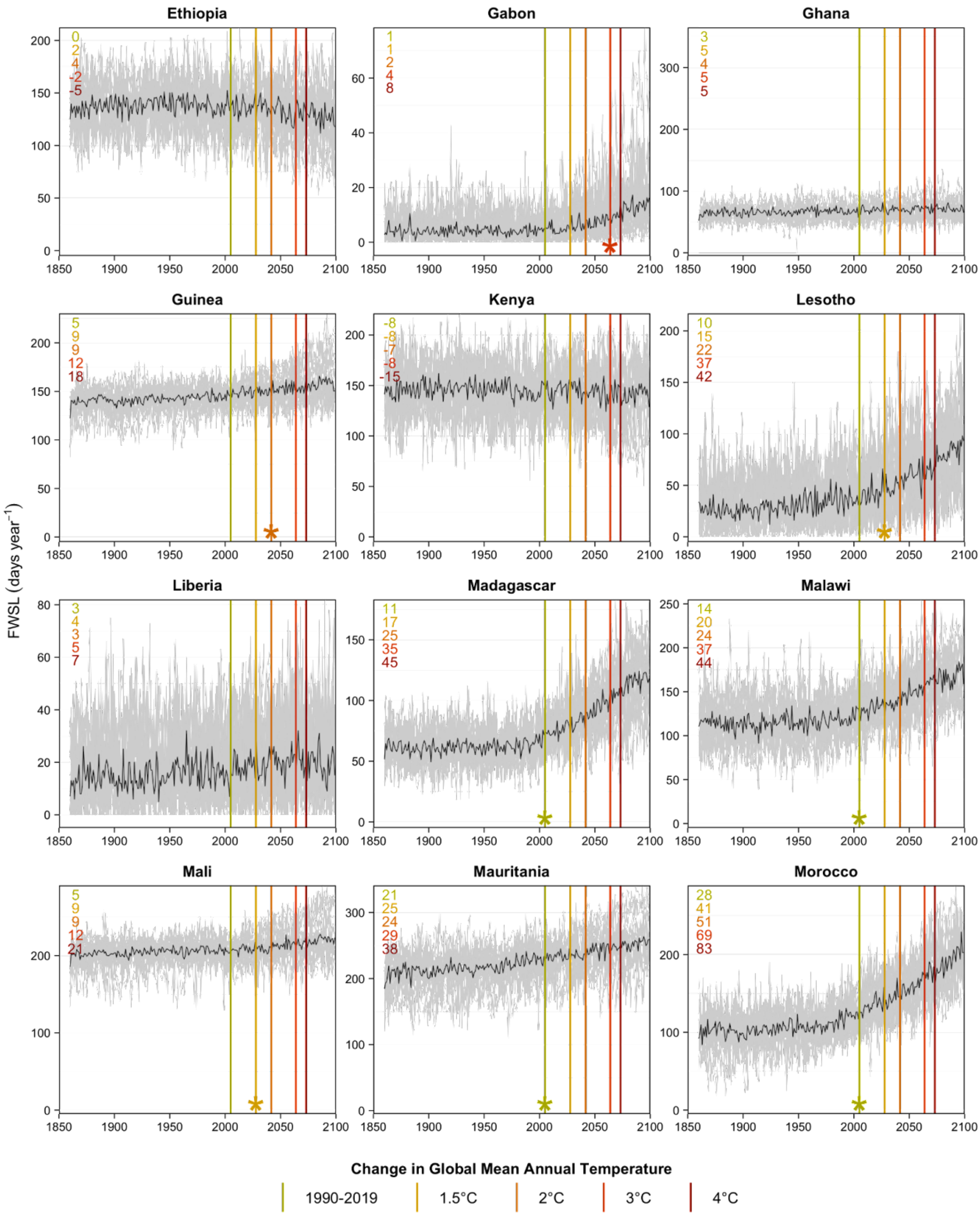
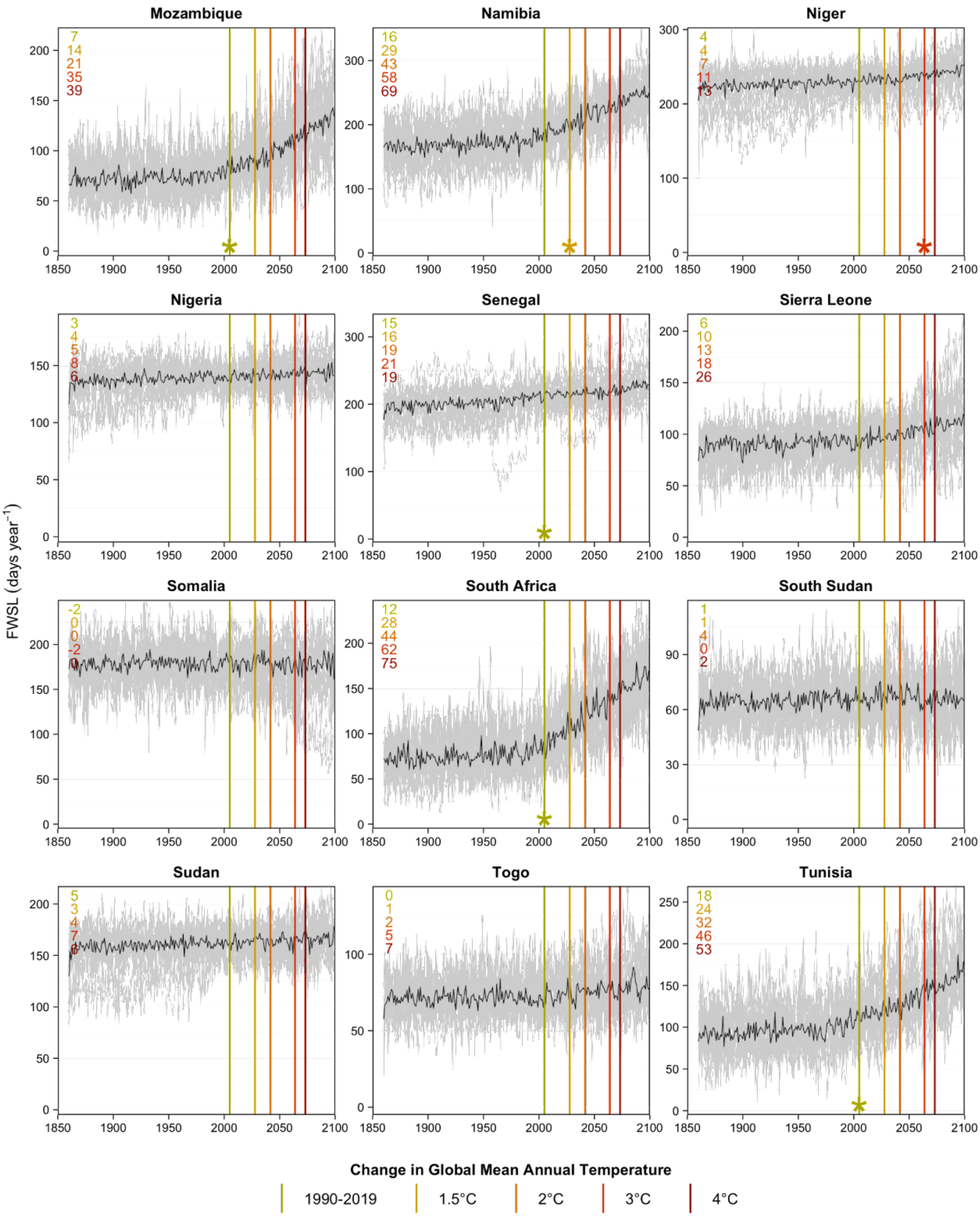


Figure A9.2 (cont.)



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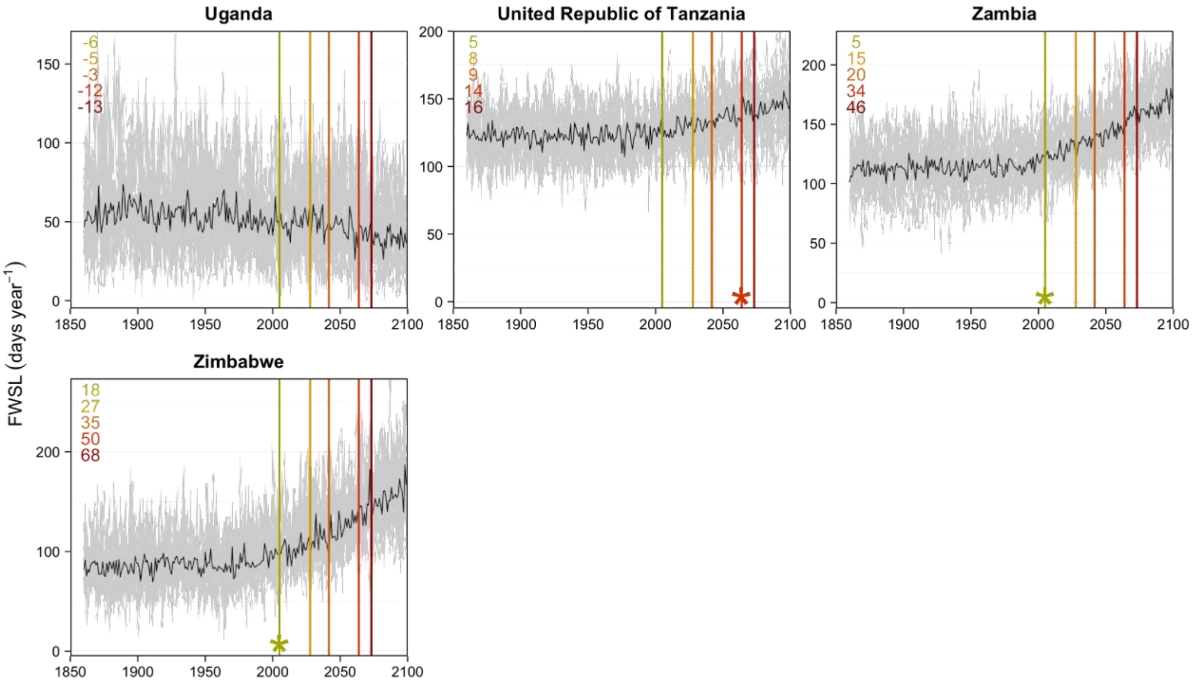

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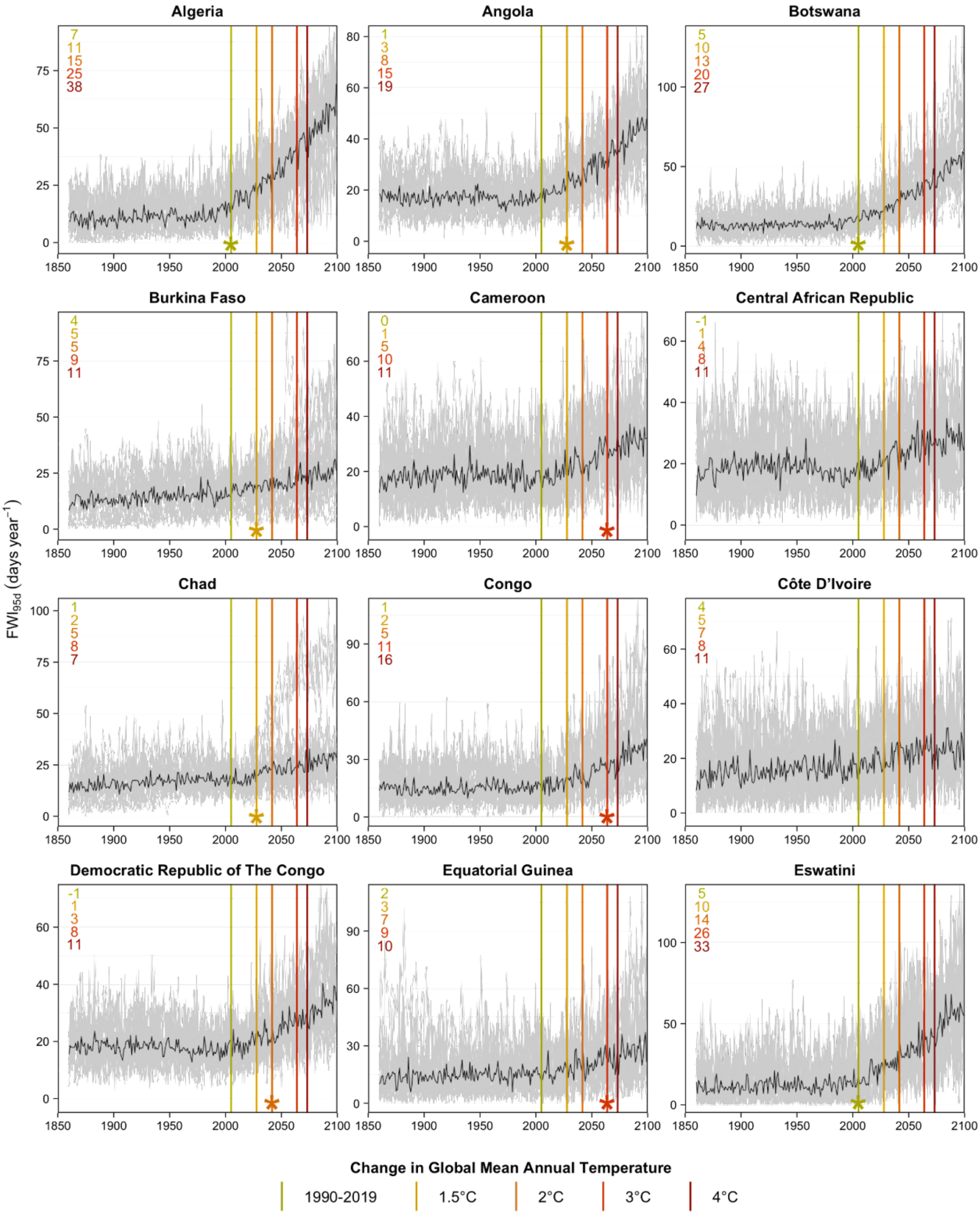
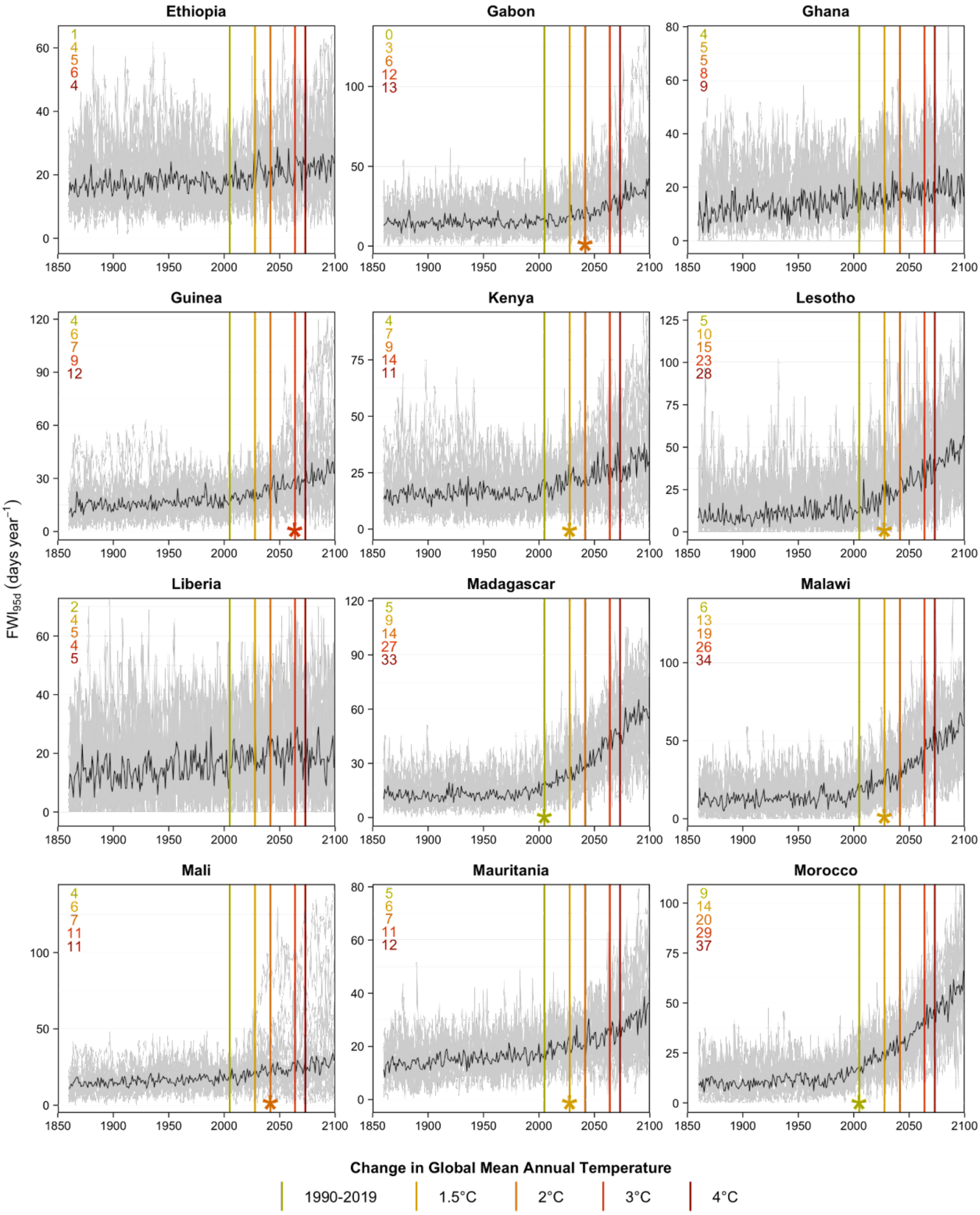


Figure A9.3: Simulated changes in the frequency of 95th percentile fire weather (FWI95d; days year-1) for countries in Africa. Simulations are based on Climate Model Intercomparison Project (CMIP5) models running RCP8.5. Each panel represents one country as indicated. Grey lines plot simulated FWI95d from individual models. The black line marks the multi-model median value of FWI95d. Coloured vertical lines plot the central year of the modern period (1990-2019), or the central year of each period in which increases of 1.5-4.0°C in global mean annual temperature (MAT) are reached relative to the 1860-1910 baseline (as the period at which these temperate increments are reached varies across the models, the year shown represents the multi-model average timing). Inset numbers with matching colour indicate the change in FWI95d (days year-1) relative to the pre-industrial period for each temperature increment. Asterisks mark the temperature increment (if any) at which FWI95d emerges above its pre-industrial variability according to a strict signal-to-noise criterion, signifying a distinct change in FWI95d outside the range of natural variability.



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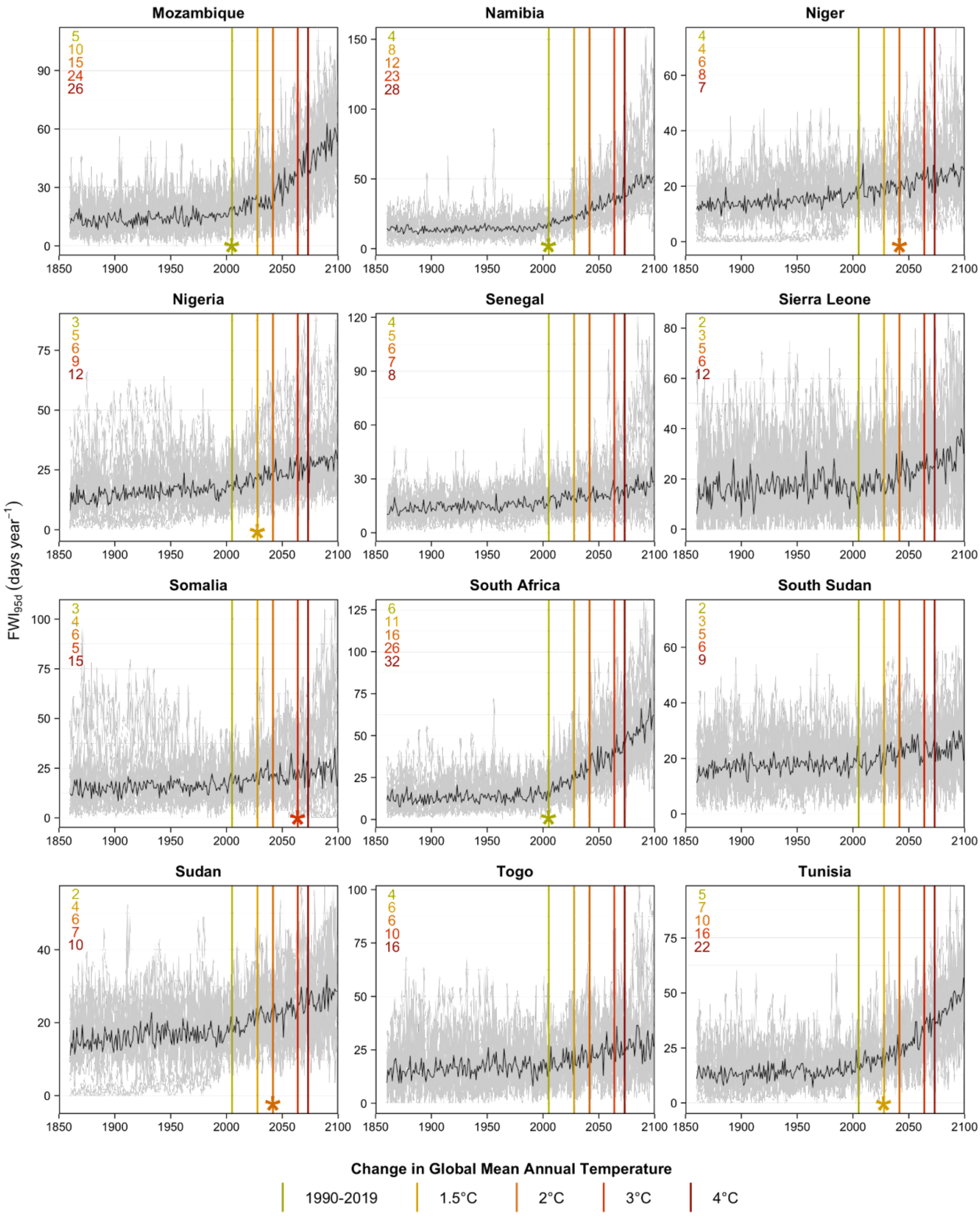

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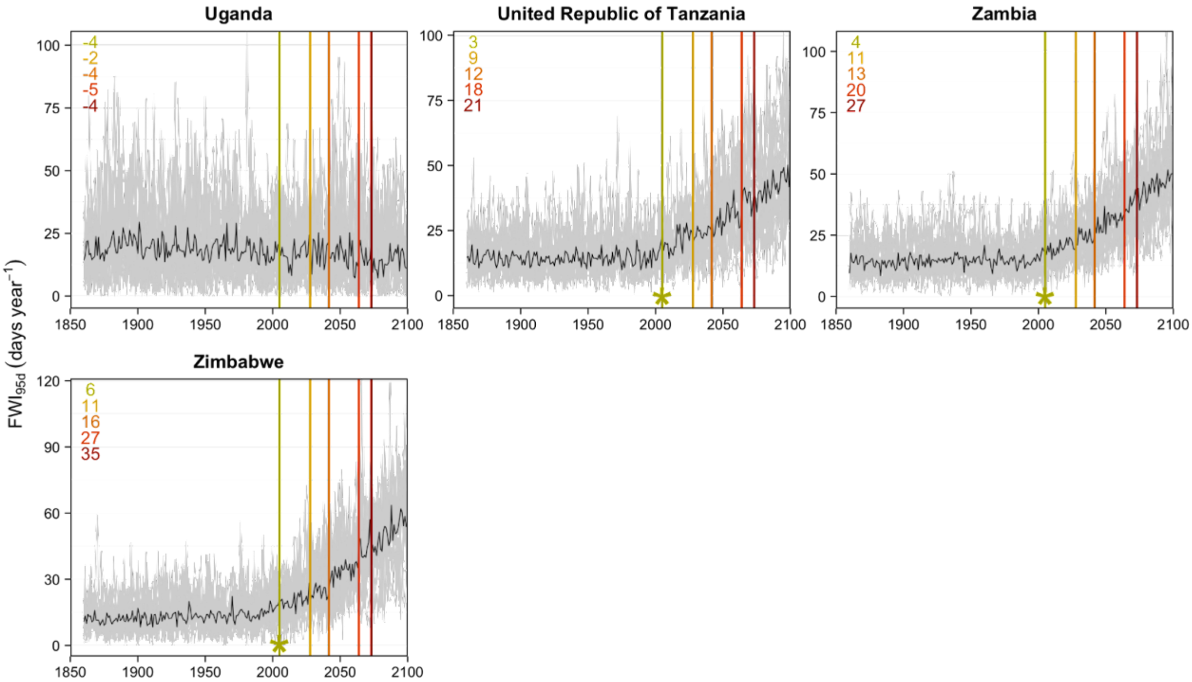

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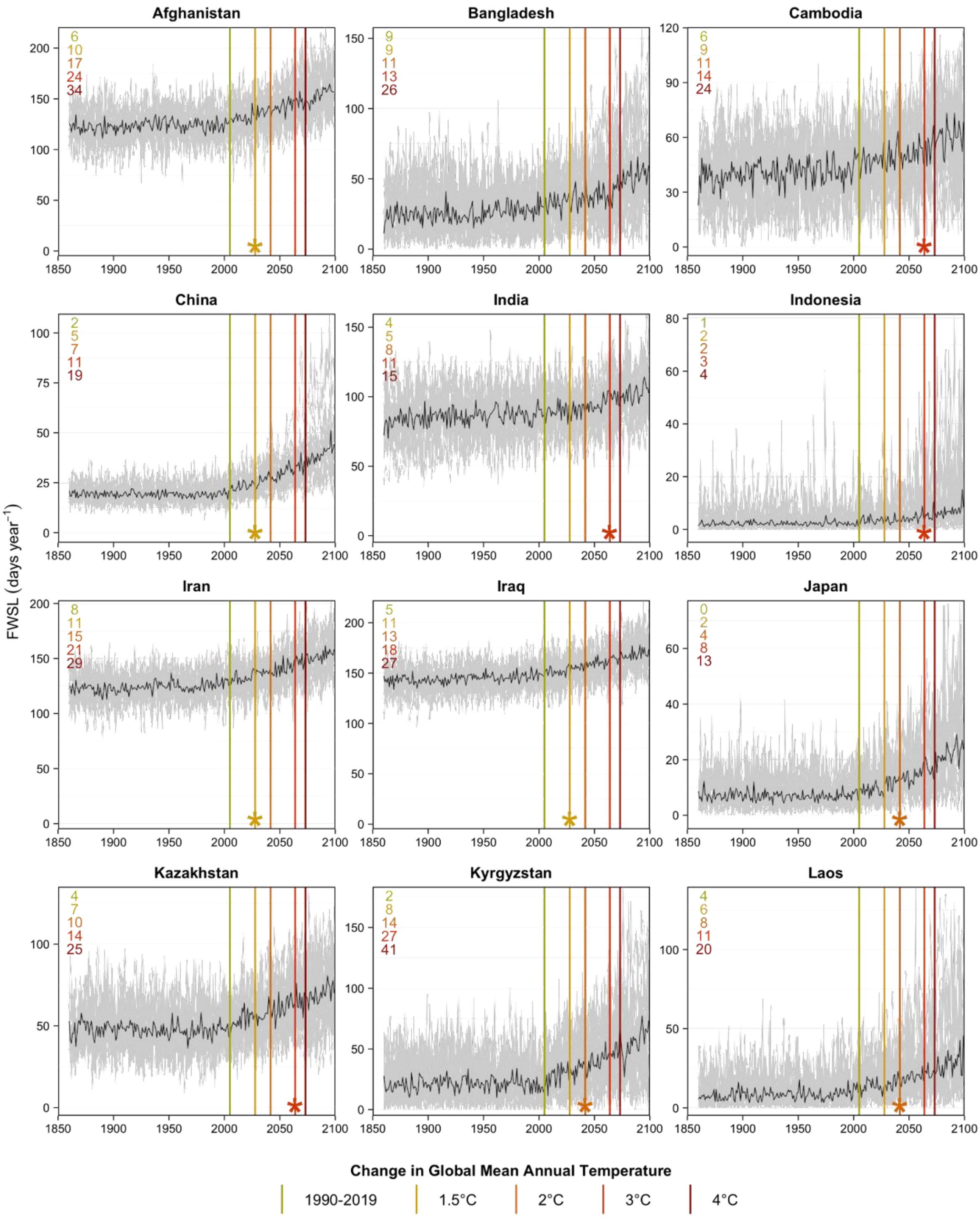


Figure A9.4: Simulated changes in the frequency of fire weather season length (FWSL; days year-1) for countries in Asia. See the caption of Figure 17 for a description of the elements plotted.

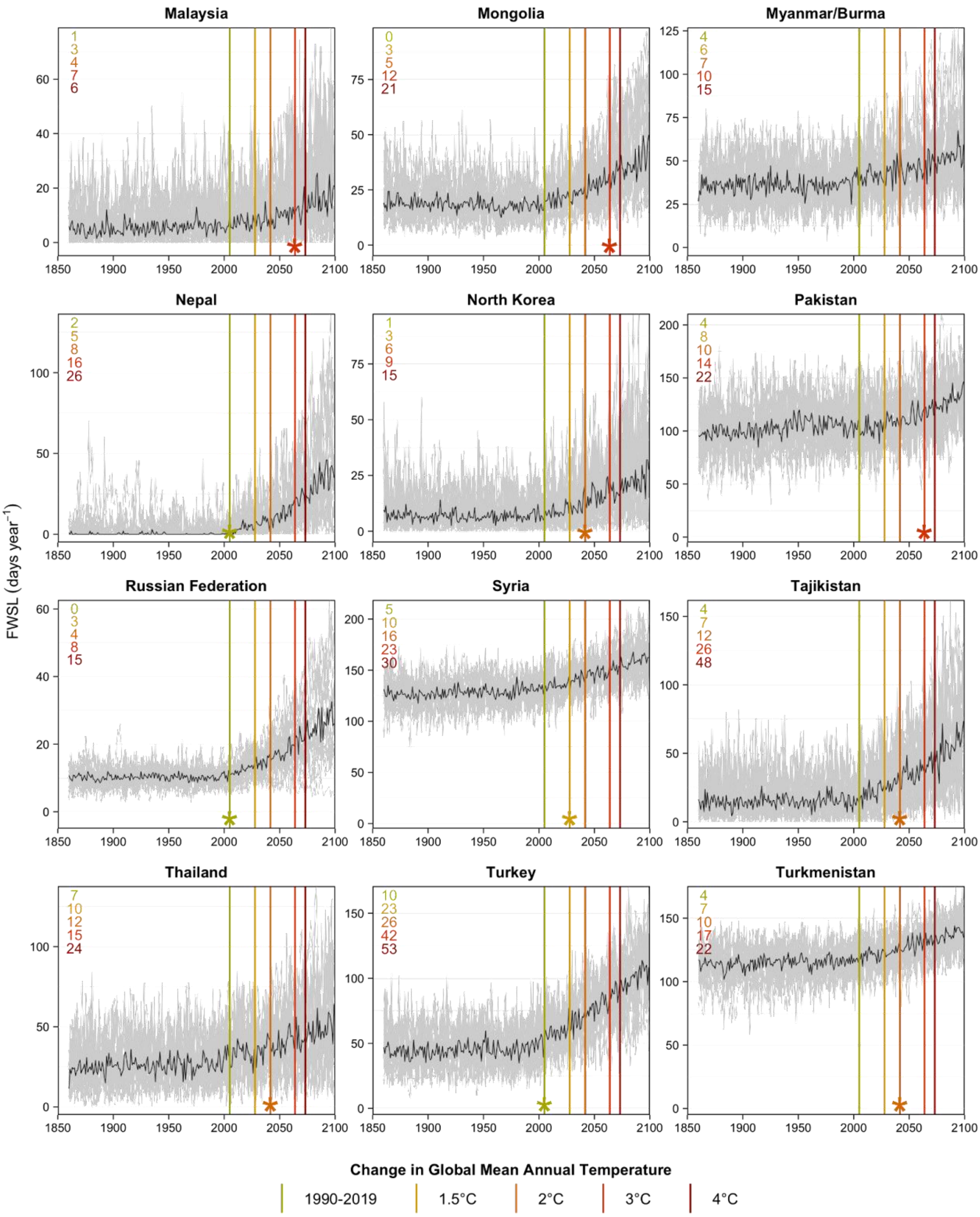


Figure A9.4 **(cont.)**

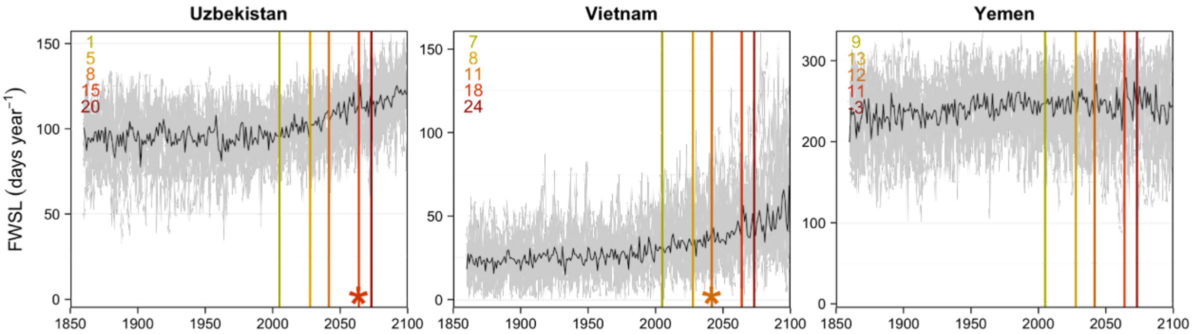


Figure A9.4 **(cont.)**

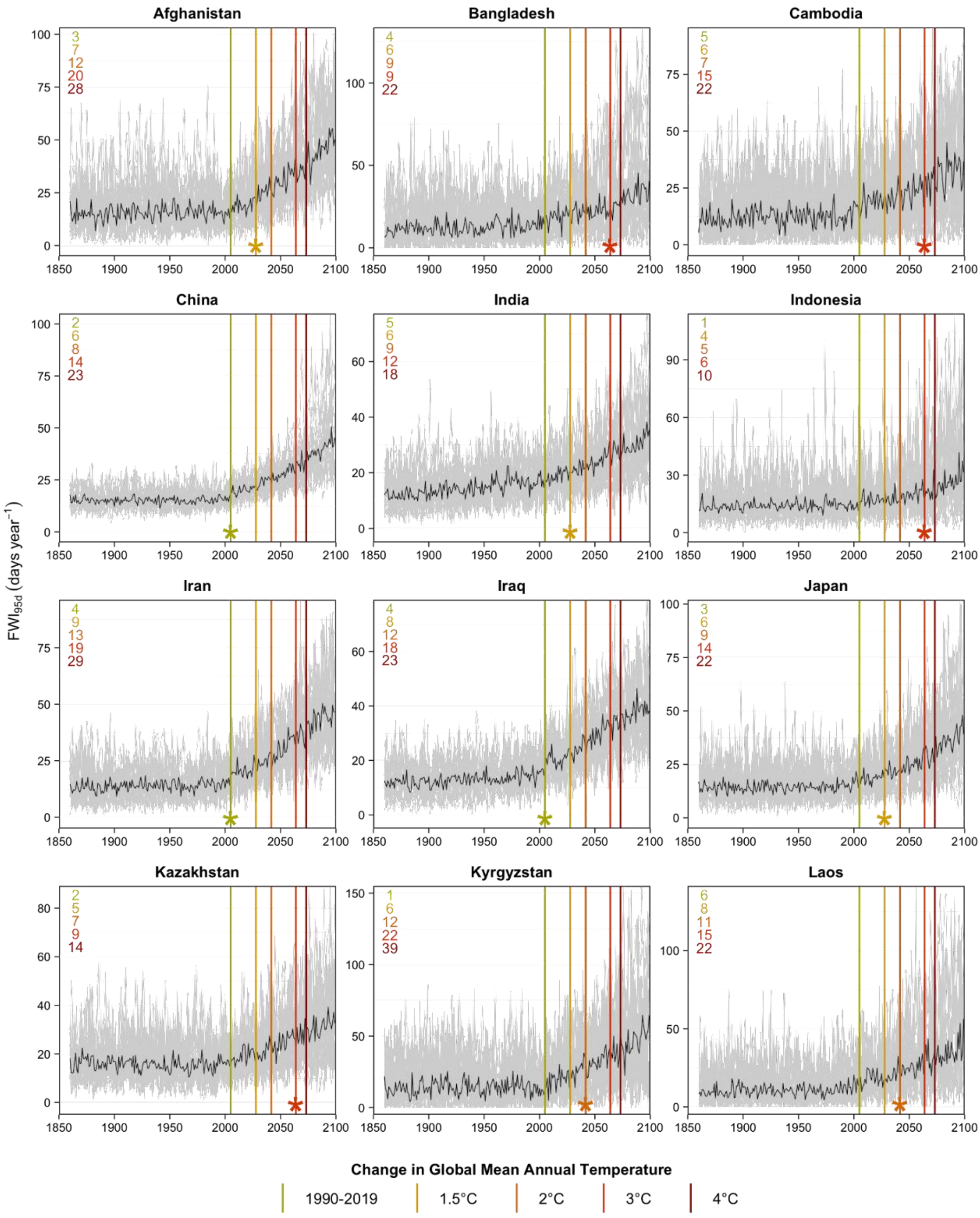
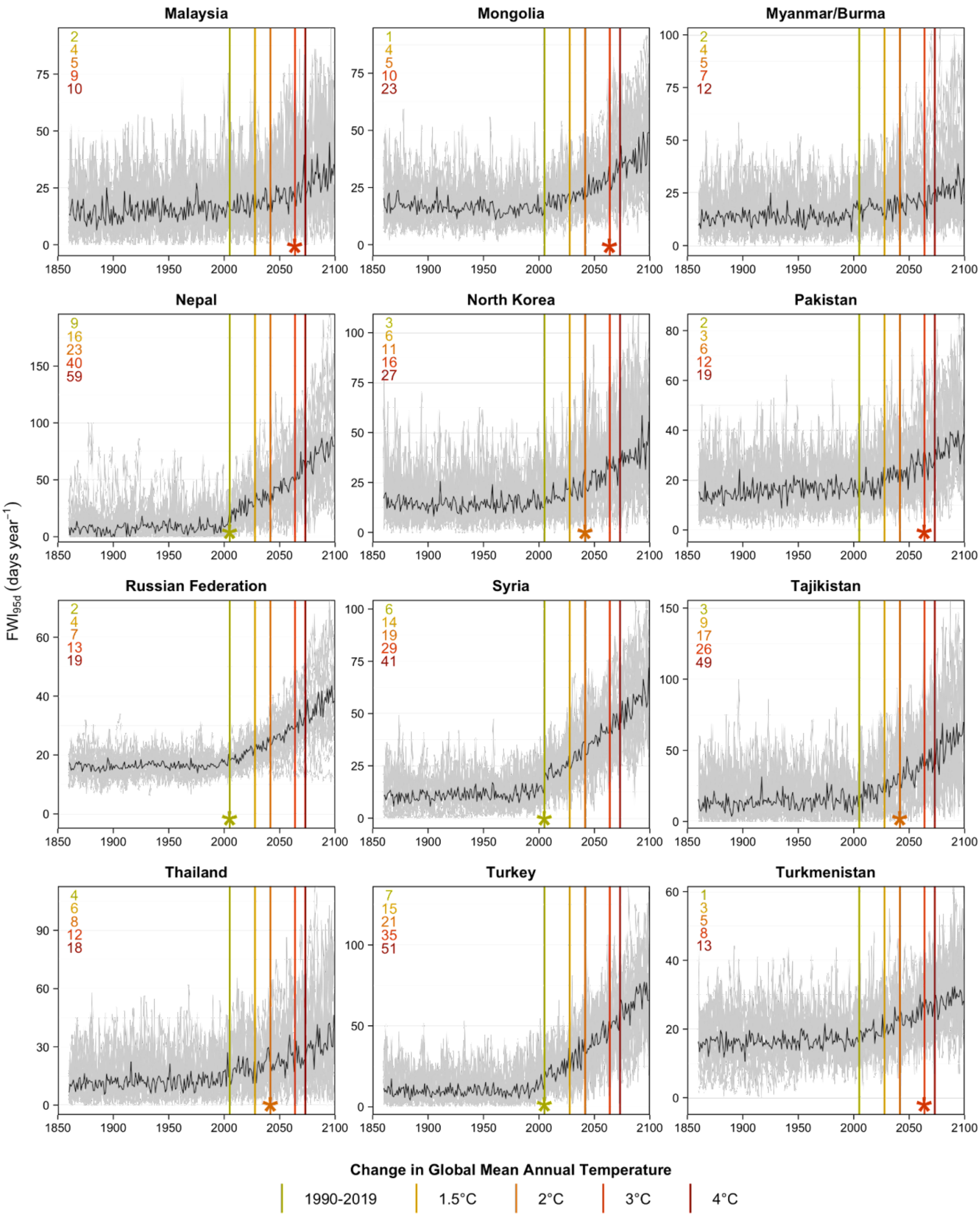


Figure A9.5: Simulated changes in the frequency of 95th percentile fire weather (FWI95d; days year-1) for countries in Asia. See the caption of Figure 3 for a description of the elements plotted.



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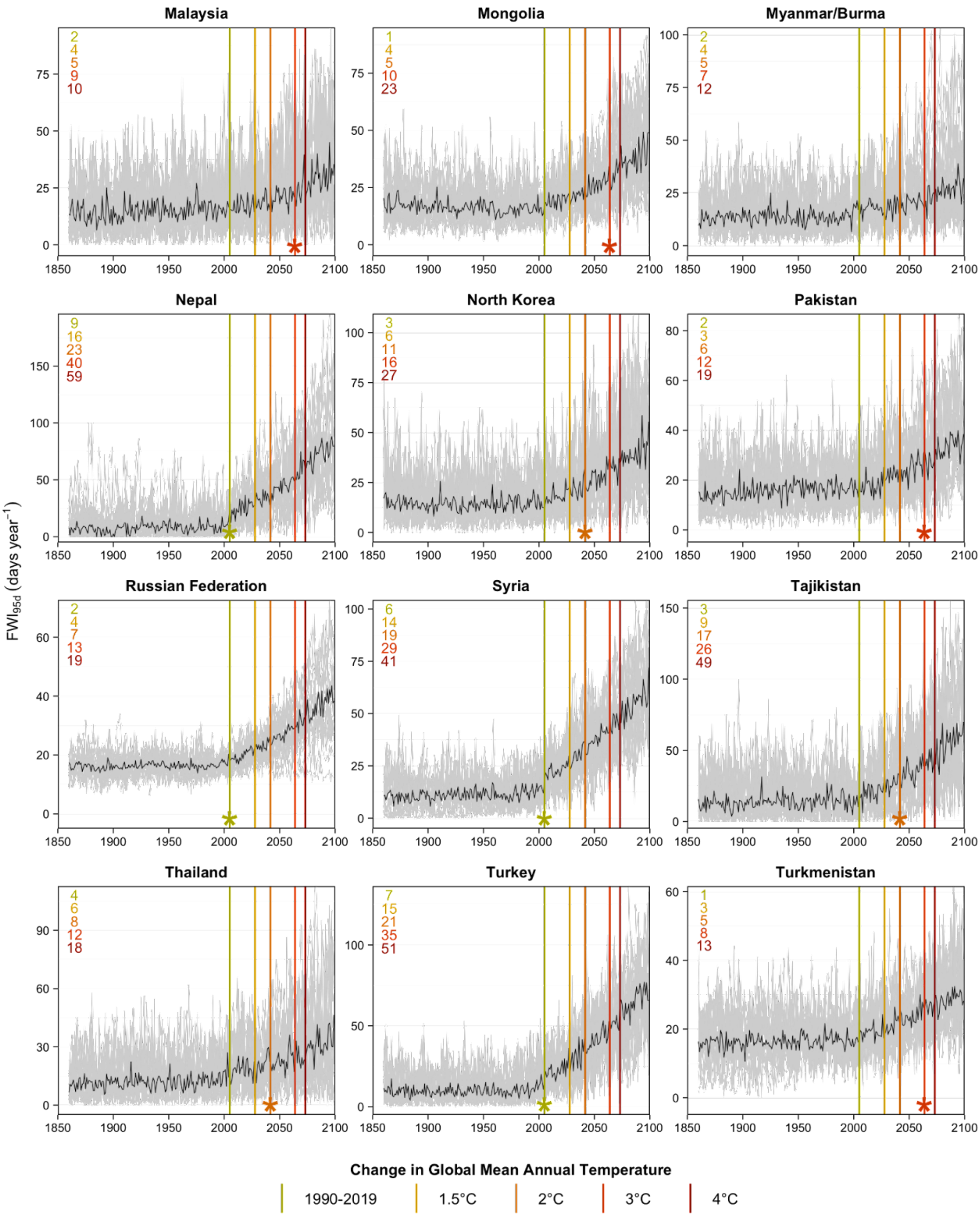

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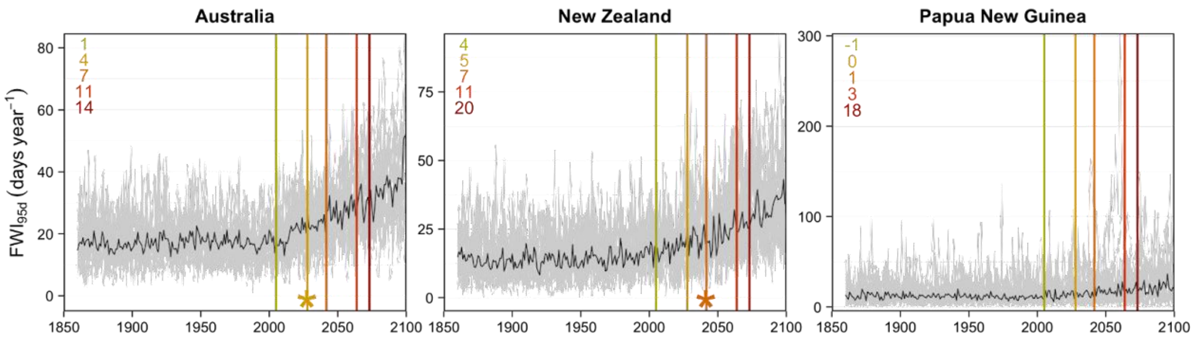


Figure A9.6: Simulated changes in the frequency of fire weather season length (FWSL; days year-1) for countries in Australasia. See the caption of Figure 2 for a description of the elements plotted.

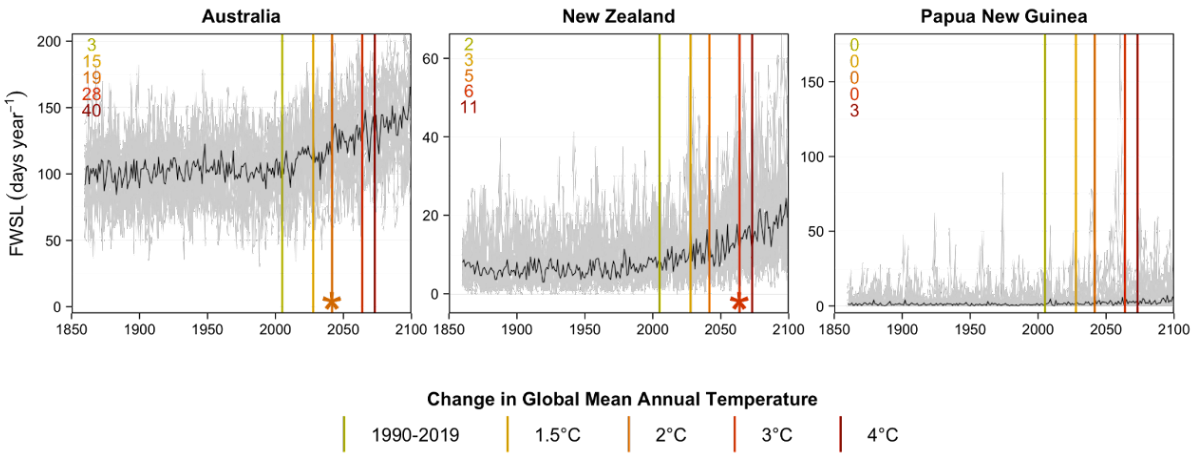


Figure A9.7: Simulated changes in the frequency of 95th percentile fire weather (FWI95d; days year-1) for countries in Australasia. See the caption of Figure 3 for a description of the elements plotted.

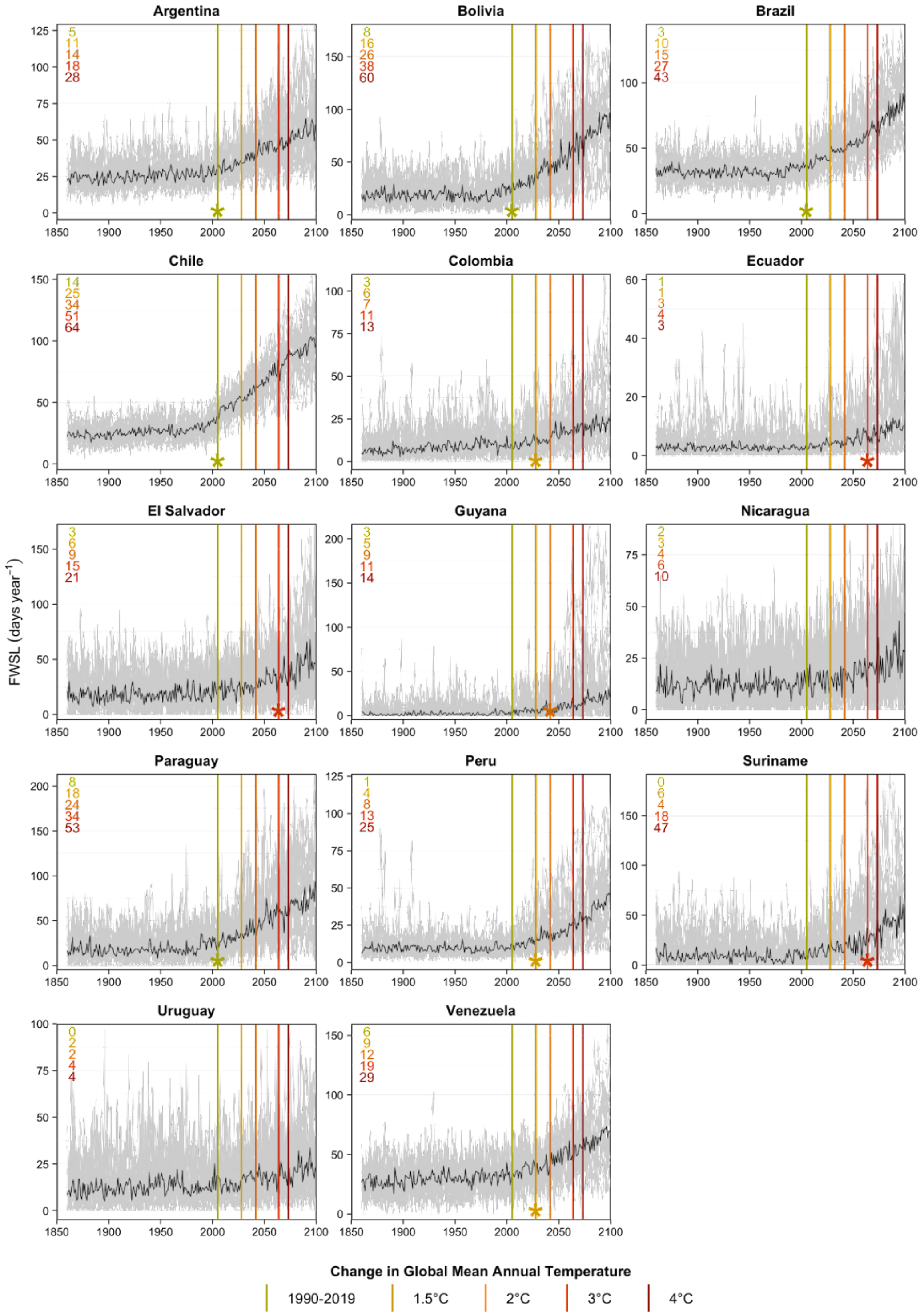


Figure A9.8: Simulated changes in the frequency of fire weather season length (FWSL; days year-1) for countries in Central and South America. See the caption of Figure 2 for a description of the elements plotted.

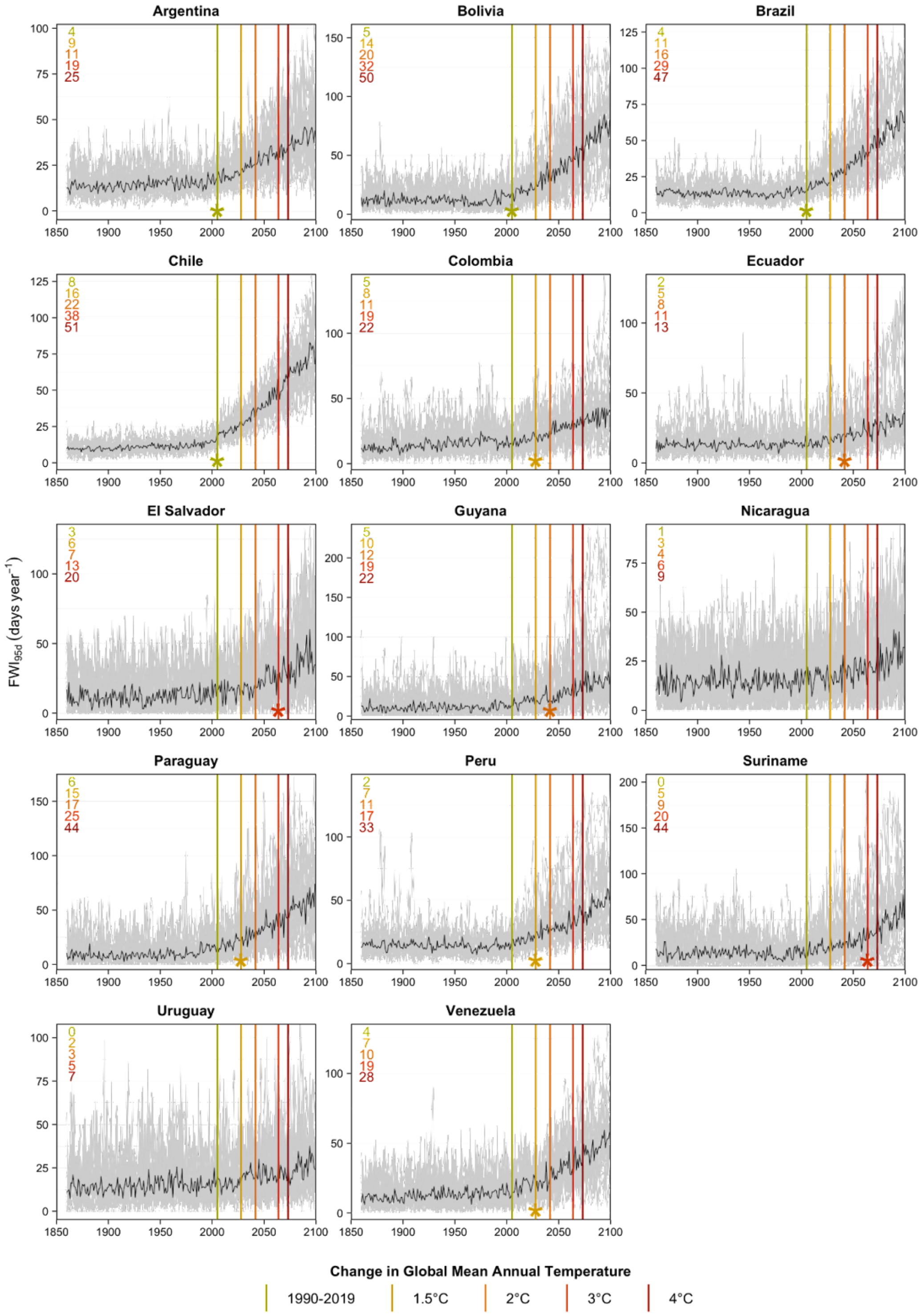


Figure A9.9: Simulated changes in the frequency of 95th percentile fire weather (FWI95d; days year-1) for countries in Central and South America. See the caption of Figure 3 for a description of the elements plotted.

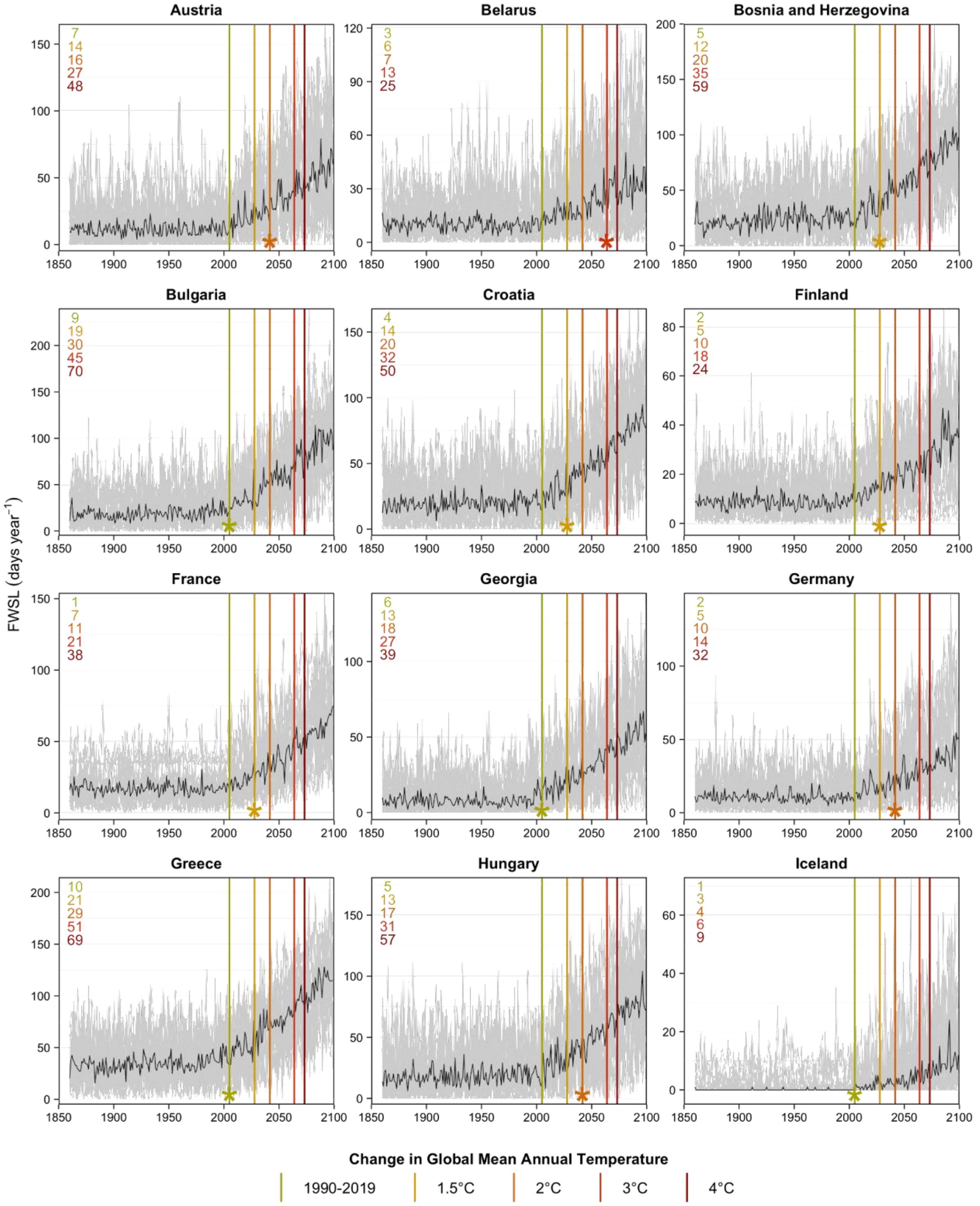
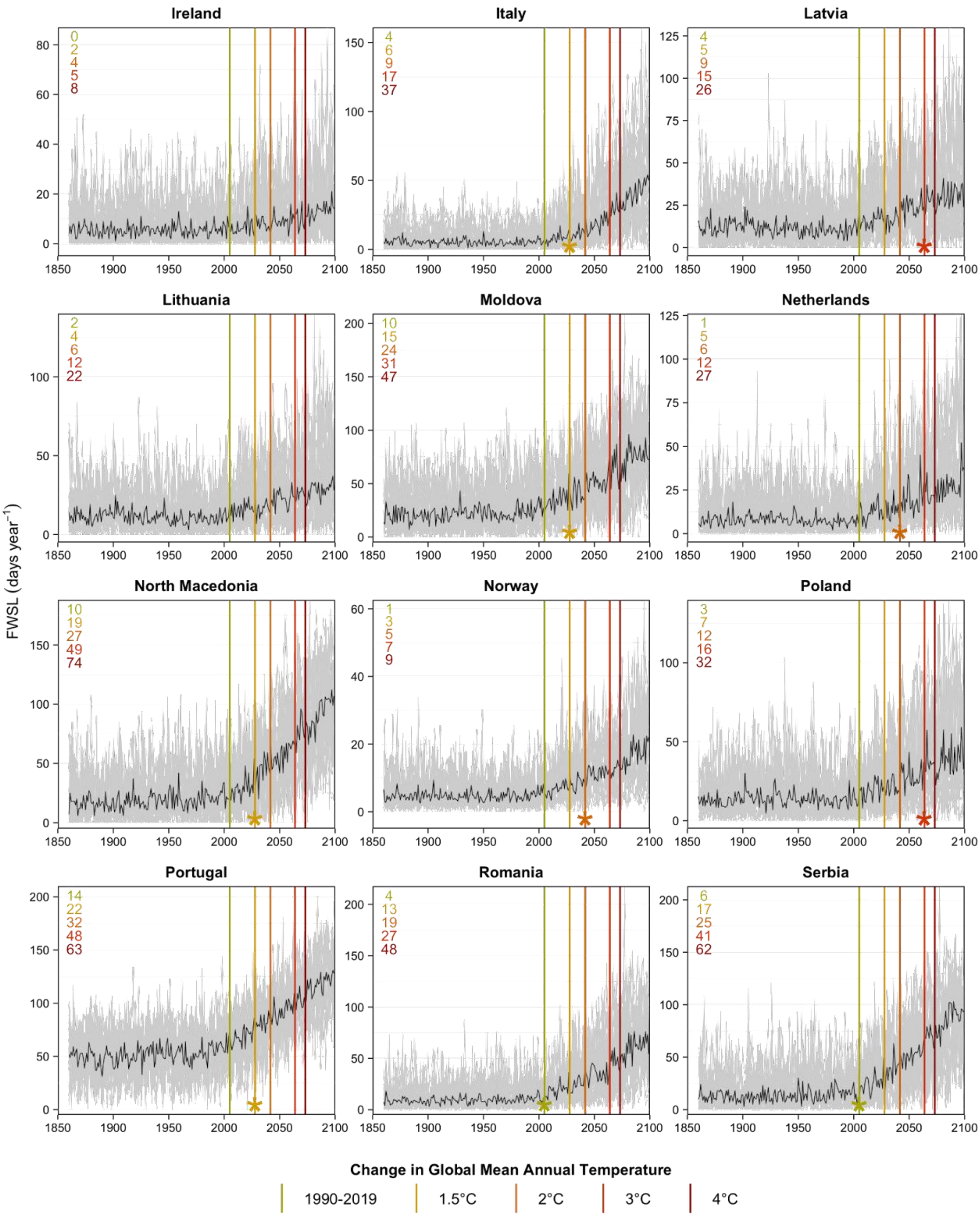


Figure A9.10: Simulated changes in the frequency of fire weather season length (FWSL; days year-1) for countries in Europe. See the caption of Figure 2 for a description of the elements plotted.



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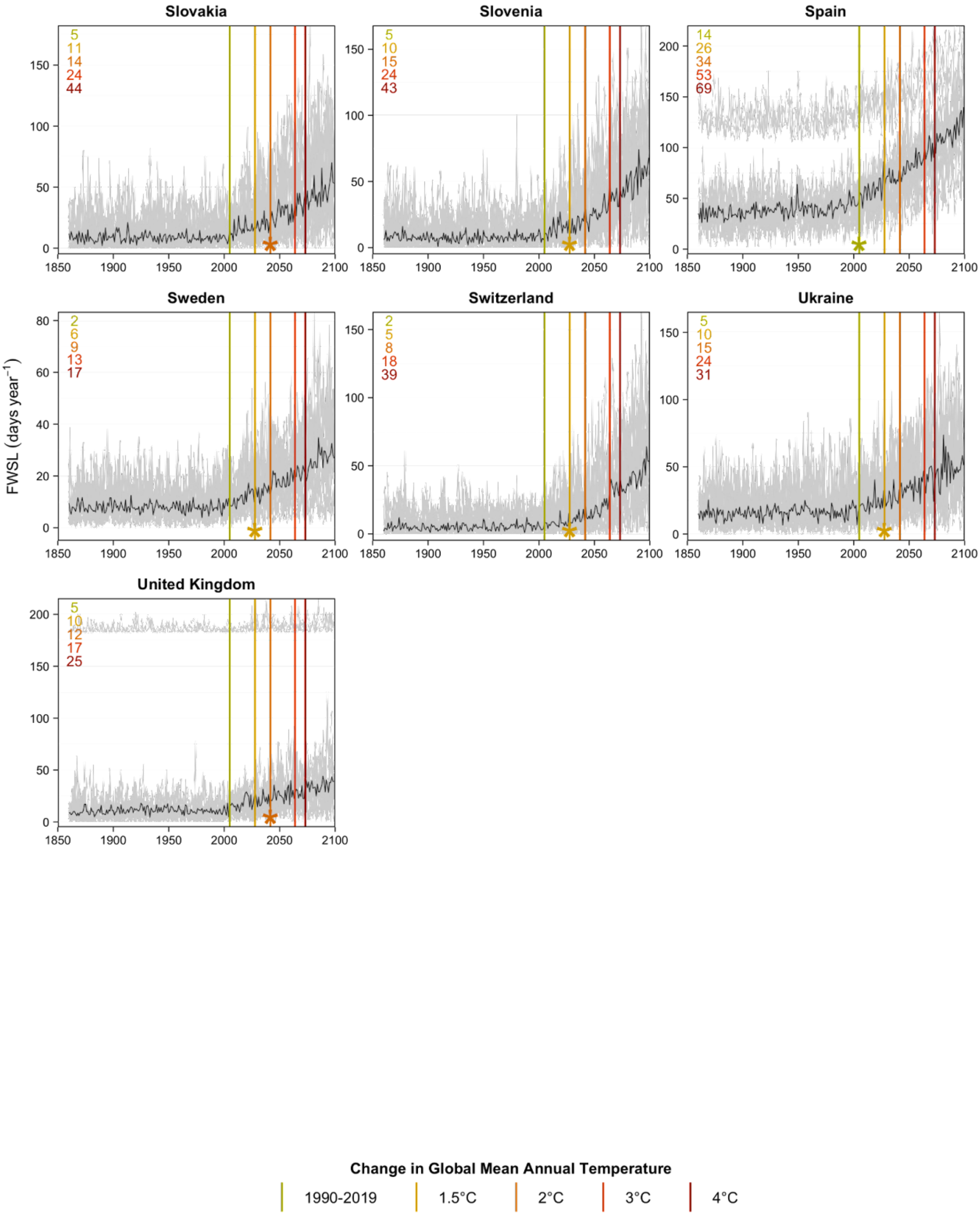

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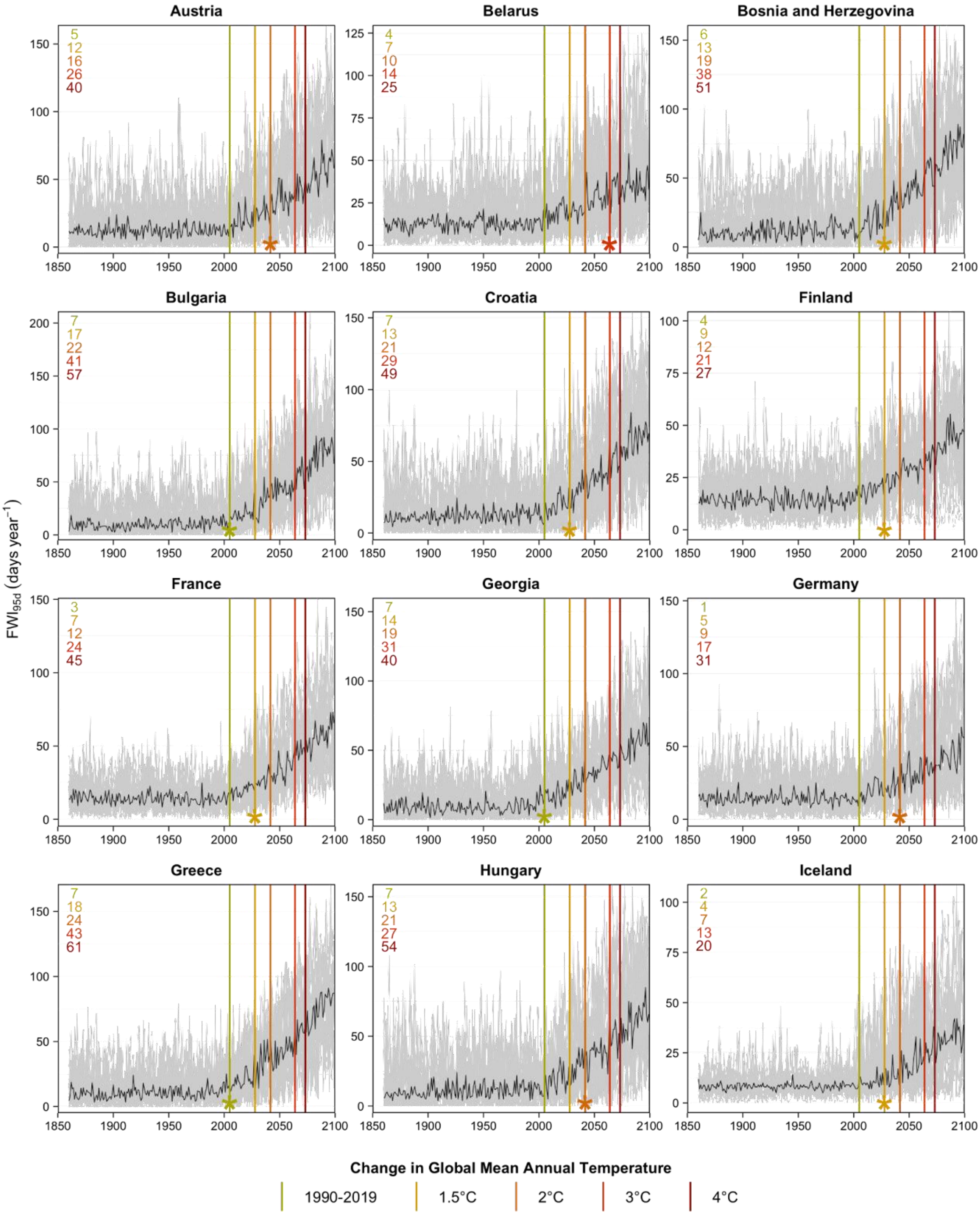
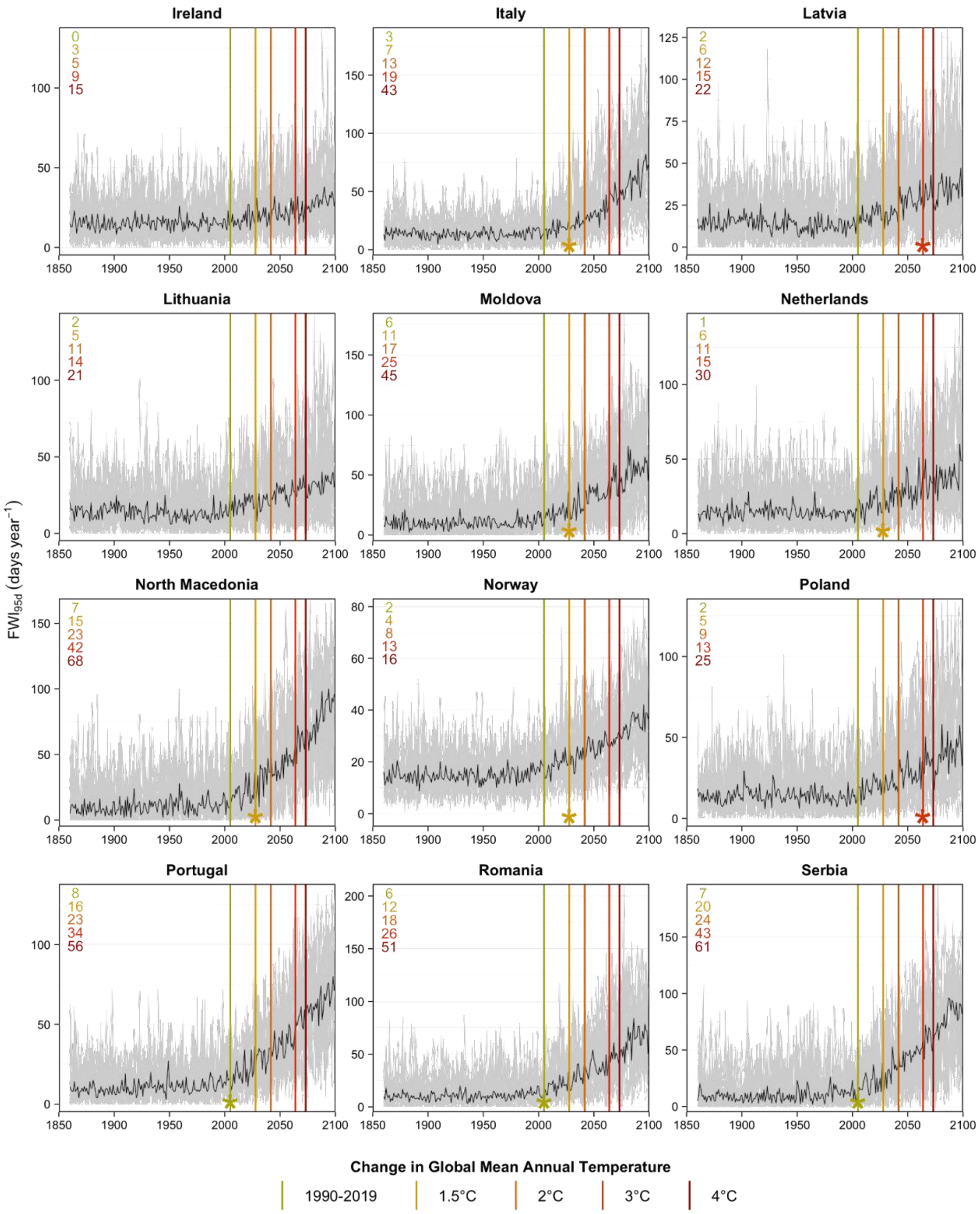


Figure A9.11: Simulated changes in the frequency of 95th percentile fire weather (FWI95d; days year-1) for countries in Europe. See the caption of Figure 3 for a description of the elements plotted.



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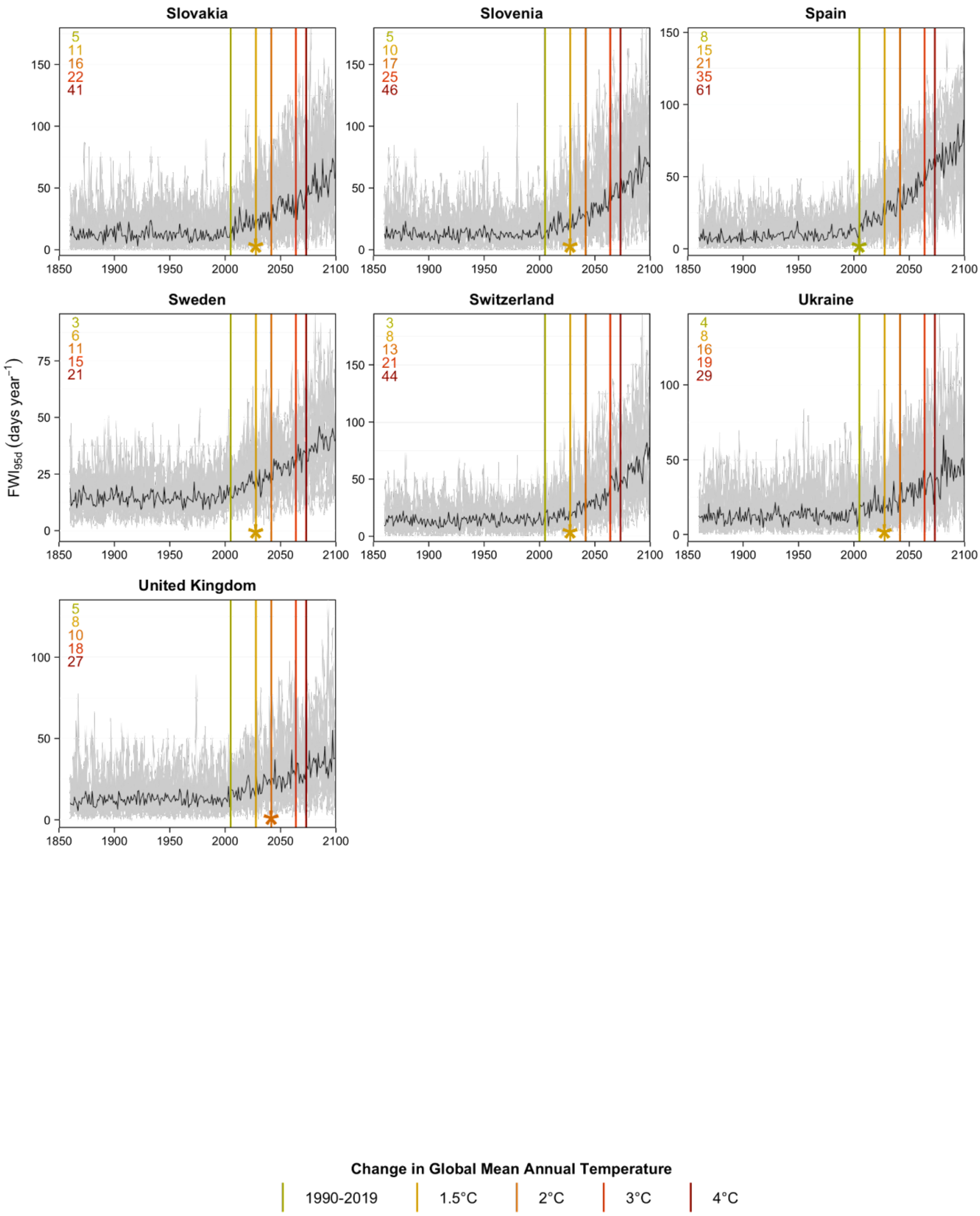

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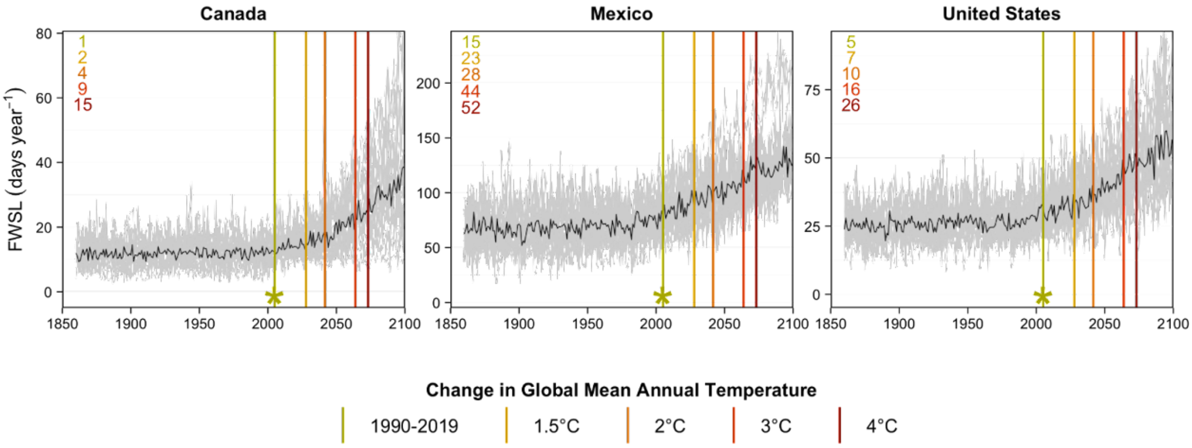

Figure A9.12: Simulated changes in the frequency of fire weather season length (FWSL; days year-1) for countries in North America. See the caption of Figure 2 for a description of the elements plotted.

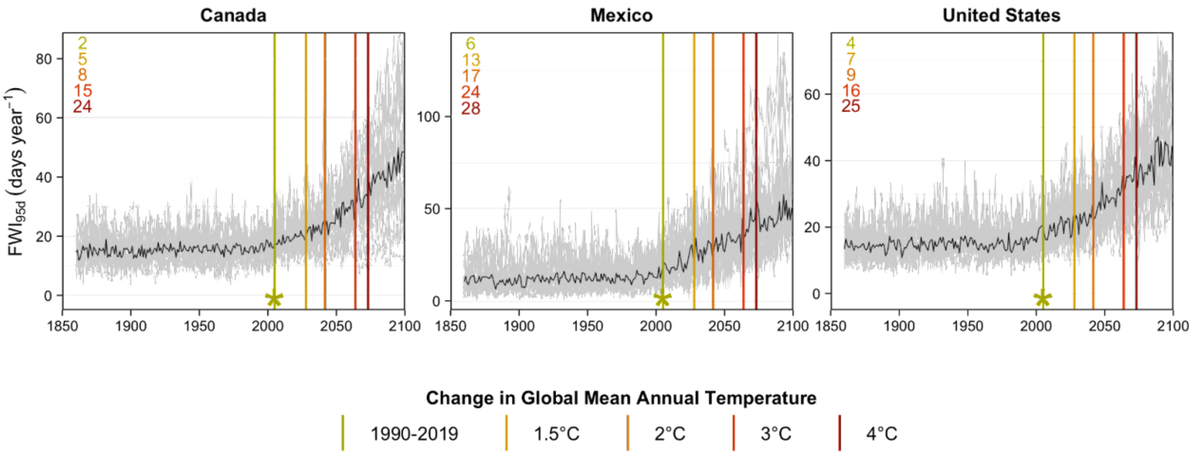

Figure A9.13: Simulated changes in the frequency of 95th percentile fire weather (FWI95d; days year-1) for countries in North America. See the caption of Figure 3 for a description of the elements plotted.

A.10: Direct, indirect and induced economic impacts - State-of-the-art-modelling

In an ideal world, decision-makers (e.g., economic agents) would have perfect information, bounded rationality, fully functional markets and their choices would lead to efficient allocation of resources. However, climate change is the most famous global market failure or worst externality in human history (Yang 2020). In economic terms, it represents a flow of bad services (GHG emissions) that are co-produced with other market activities (e.g., cars production or food consumption) and produce global damages. Furthermore, the economic agents responsible for emissions can often be hard to identify and regulate. Therefore, traditional policy instruments such as regulation, taxes and subsides cannot function properly to tackle climate change.

Emissions in one single country can damage the entire globe, with varying intensity, and the permanence of gases in the atmosphere transfer the economic impacts from one generation to others – intra and intergeneration equity. Effects may be market or non-market (both direct and indirect) and tangible or intangible.

The economic approach to climate change is therefore to measure *some* of these effects (most of which are expected events) through macro (national or international) or micro (economic agent's effects) approaches. While the micro approaches respond to specific local research questions and needs (Veronesi et al 2014, Remoundou et al 2015) their results are of limited global interest and they are frequently overlooked. The dominant models use macro approaches that consider national or international economies either for specific sectors or the full economy. These approaches are sometimes classified as top-down and bottom up (Piontek et al 2021) and include econometric approaches, agent-based models, and integrated assessment models (IAMs).

Top down

Multi discipline approaches

Integrated Assessment Model (IAM) – DICE, PAGE, FUND	Computational General Equilibrium model, Agent based IAM
Cross section (Ricardian approaches) and panel econometric models	Input Output model Observational data/enumeration system

Traditional approaches

Bottom up

Figure A10.1: Differentiation of macroeconomic models

IAMs are adopted by different disciplines and can predict climate change effects but each of these IAM focuses on one or more aspects[1]. One of the most renowned IAM in economics is DICE (Dynamic Integrated Climate-Economy model) developed in 1992 and revised and extended since then by Nordhaus and other scholars (e.g., see Nordhaus, 2017). Economic models, as all other disciplines' models, are a simplified version of reality and are built around a set of key assumptions:

[1] Others IAMs are predominately physical models (e.g., MAGICC), and some models have a global focus (e.g., IMAGE 2.4 or MiniCAM) while others are regional (e.g. AIM) http://www.perseus-net.eu/site/content.php?artid=2207

- Marginality of carbon effects
- Efficient economy – all crucial markets are fully operating including financial market
- Representative economic agents who maximize intertemporal utility
- Belief and preferences are standardised
- Stationarity of probability distribution of expected outcomes
- Perfect substitution of form of capitals – natural assets can be replaced by man-made assets
- Constant elasticity of demand and supply

As an example, the DICE model follows a normative approach and given a fixed target (e.g., cutting CO2 by X%) identifies the most feasible and least cost solution. Results are normally express as the percent of GDP loss due to climate change. The implicit cost of carbon (marginal social cost of carbon) is an output of this model and can be used to assess the costs and benefits of alternative climate change policies. Although there is not agreement on the price of carbon used, with the range spanning from a few dollars to more than five hundred dollars.

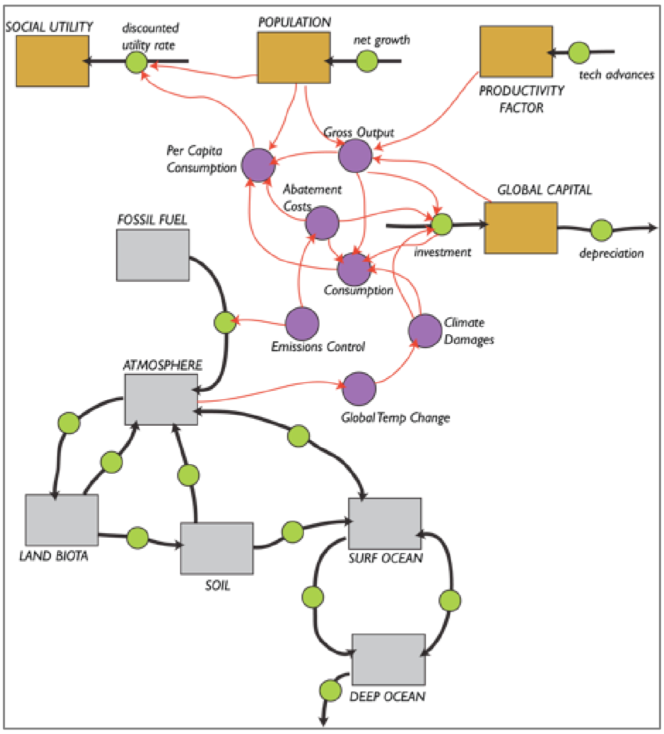

Figure A10.2: Highly simplified schematic of the economic components of the DICE model. Source: [DICE Model Background (psu.edu)]

The controversial assumptions of the DICE model are:

- tipping points are excluded
- preference homogeneity across time and space
- endogeneity of climate effects on economic decisions are ignored
- risk and time discounting factors are conflated

Econometric top-down approaches focus on output/productivity effects and predict short-term effects of climate change. Data availability and quality is critical within these approaches and for this reason the majority of these applications are in the agriculture sectors and in developed countries. Few applications consider growth rates of all countries as a function of annual temperature fluctuation (Burke et al 2016).

The bottom-up approaches are devised using Computation General Equilibrium (CGE) and agent-based models where the biophysical changes in climate and other natural resources can be captured at the level of firms and households to better capture the heterogeneity of economic agent's responses. Responses can then be aggregated to capture the tangible market effects of climate change, but these models are not well suited to handling uncertainty. Furthermore, when applied at the global level the spatial and temporal heterogeneity is not captured similarly to IAMs. Whereas in IAMs intangible market effects are currently accounted for.

The Input Output and Observational/numerical models are also limited in measuring observable tangible and market (direct and indirect) effects, with numerous examples for agriculture, labour productivity, drought and fluvial flooding. These models are based on traditional robust application and applicable in developed and developing countries.

Appendix B – Regional Summary Tables

AFRICA	Key statement (including Confidence level / agreement in studies where stated)
Biodiversity and Ecosystem Services	*High confidence* that biodiversity loss will worsen with higher levels of warming.
Coastal Flooding	Nations particularly at risk in Africa are those along lagoons and delta regions, cities with rapidly growing populations, plus western and eastern sub-Saharan nations.
Drought and Water Security	*High confidence* North Africa will see increases in aridity, hydrological and agricultural/ecological drought; the Western subregion of Southern Africa will undergo increased aridity and agricultural/ecological drought; the Eastern subregion of Southern Africa will become more arid.
Fire	Annual frequency of fire weather and annual frequency of fire weather extremes is projected to emerge and accrue with global warming across many countries in Africa.
Fisheries	*High confidence* that climate change is a significant threat to African marine and freshwater fisheries. Reduced fish catch potentials are projected to accrue with warming. *Very high confidence* that > 90% of warm-water coral reefs will be lost at 2.1C.
Fluvial Flooding	Whilst projections show evidence of increasing extreme river discharge and flood events for some river basins there is *low confidence* on the direction of future change of river flooding in Africa due to lack of data.
Food Security and Agriculture	*High confidence* that Africa is projected to be the region hardest hit by its impacts on food security
Health: Disease	The distribution, intensity of transmission, and seasonality of malaria across Africa is projected to alter.
Health: Heat Stress	A reduction in workability and survivability is projected across the region. Central African countries found to exhibit the highest heat-related mortality.

ASIA	Key statement (including Confidence level / agreement in studies where stated)
Biodiversity and Ecosystem Services	*High confidence* that climate change will lead to sizeable changes in the distribution of plant and animal species within Asia.

Coastal Flooding	*High confidence* that climate change will have adverse impacts to those who livelihoods depend on coasts and their ecosystems. Twelve of the top 20 countries exposed to sea-level rise and flooding are in Asia, dominated by low-lying areas including delta regions.
Drought and Water Security	Droughts projected to increase in likelihood across West, Central and South Asia. Most countries expected to experience increases in the land area under hydrological drought by the end of the century under a high warming scenario.
Fire	The annual frequency of fire weather and annual frequency of fire weather extremes is projected to emerge and accrue with global warming across many countries in Asia.
Fisheries	There is *high agreement* in the literature for high vulnerability of Asian fisheries to climate change. Negative impacts are projected to be large in the Indonesian Sea and the Gulf of Thailand.
Fluvial Flooding	Some of the largest increases in flooding are projected for Asia. *Medium confidence* in projections of regional changes. Flood frequency projected to increase across large areas of South and Southeast Asia and Northeast Eurasia.
Food Security and Agriculture	*Medium confidence* that climate change will have overall negative implications for food security across Asia. Many studies have projected reductions in crop production in South and Southeast Asia.
Health: Disease	In Asia there is a *high likelihood* that climate change will alter the geographical range of malaria vectors and change the risk of malaria infections.
Health: Heat Stress	Parts of South-East Asia, including Vietnam, Thailand and the Philippines are some of the countries projected to face greatest excess mortality from future global warming. More areas of South Asia will be exposed to extreme heat at 1.5°C.

AUSTRALASIA	Key statement (including Confidence level / agreement in studies where stated)
Biodiversity and Ecosystem Services	There is *high confidence* that climate change will have profound effects on the biodiversity of Australasia, including irreversible impacts, such as species becoming extinct.
Coastal Flooding	Local drivers for coastal flooding include subsidence and sea-level rise. Adaptation is undertaken, including consideration of vulnerable populations such as Aboriginal, Torres Strait Islanders and Tangata Whenua Māori.

Drought and Water Security	There is *high confidence* that droughts will increase in Australasia due to climate change, particularly in southern and eastern Australia and New Zealand.
Fire	Australia and New Zealand are projected to experience unprecedented fire weather under future warming increments relative to the natural variability simulated for the pre-industrial period.
Fisheries	Climate change is already impacting fisheries in Australia through shifting the range of species poleward. For Australasia as a whole, fish catch potentials are projected to decline as temperatures rise. Effects of extreme weather events driving rapid mortality of corals is already evident.
Fluvial Flooding	Projected decrease in floods in southern Australia with warming (high model agreement) and increasing magnitude/volume of floods in northern Australia (high uncertainties). *Medium confidence* that river flooding will increase in New Zealand.
Food Security and Agriculture	Projections suggest reductions in wheat yield in Australia with warming of 1.5°C and above, particularly across the northeast wheat belt, but there are regional/model disparities in the direction of trend.
Health: Heat Stress	Dangerous humid heat thresholds, with the potential to affect health, are projected to be exceeded more frequently over the 21st century in Australia, with Northern Australia particularly vulnerable.

CENTRAL AND SOUTH AMERICA	Key statement (including Confidence level / agreement in studies where stated)
Biodiversity and Ecosystem Services	*High confidence* that biodiversity loss will worsen with higher levels of warming. *Medium confidence* that the biodiversity of Central and South America, within the region's biodiversity hotspots is likely to be particularly negatively impacted.
Coastal Flooding	Mangroves in Latin America and the Caribbean are threatened, as are tourist beaches and fishing zones. Limited information on vulnerability related to sea-level rise e.g., people exposed, means there is *low to medium* confidence in risk.
Drought and Water Security	*High confidence* that drought frequency and severity will expand in south-western South America. With 2°C warming, the South American Monsoon subregion is projected to have increases in agricultural/ecological drought (*high confidence*).

Fire	At 1.5°C fire weather season length is projected to emerge in Colombia, Peru, and Venezuela. Patterns of deforestation are the dominant driver of fire patterns in Amazonia.
Fisheries	Fish catch potential projected to decline as temperatures rise. V*ery high confidence* that the worst impacts will be in the Eastern Tropical Pacific, including the Humboldt Current System.
Fluvial Flooding	Extreme precipitation events and total rainfall projected to increase over most of South-eastern South America and western Amazonia. Models project an increase in frequency and duration of river flooding in the Uruguay and Paraná basins with >3 °C warming.
Food Security and Agriculture	*High confidence* that agricultural production will decrease as a result of climate change. Reduced yield projected for beans, coffee, maize, plantain, and rice.
Health: Disease	With warming of ~3°C the distributions of malaria vectors are projected to increase to 35-46% of the continent. The number of dengue cases in Latin America and the Caribbean are projected to increases as warming increases.
Health: Heat Stress	South America would be exposed to dangerous or extremely dangerous days over 40.6°C for vulnerable groups at 1.5 °C increasing in frequency at 2°C.

EUROPE	Key statement (including Confidence level / agreement in studies where stated)
Biodiversity and Ecosystem Services	*Very high confidence* that risks to terrestrial ecosystems in Europe will increase with warming, with southern Europe generally at greater risk than northern Europe.
Coastal Flooding	*High confidence* that an increase in sea-level rise will result in an increased risk to people and infrastructure with current adaptation measures.
Drought and Water Security	*High confidence* that drought frequency and severity will expand in some regions with climate change. *High confidence* at ~2°C warming that the Mediterranean will see increases in aridity, hydrological and agricultural/ecological drought.
Fire	Many countries in Europe will experience *unprecedented* fire weather under future warming relative to the natural variability simulated for the pre-industrial period. *Good model agreement* for Mediterranean which shows an increase in fire probability.
Fisheries	*High confidence* that climate change has already negatively impacted marine fisheries in Europe.

Fluvial Flooding	Some of the largest changes in fluvial floods globally are seen in Europe. By 2100, mean annual precipitation and average discharge projected to decrease in southern Europe. Flood frequency decreases in many regions of northern and eastern Europe.
Food Security and Agriculture	*Medium confidence* that some crop yields (e.g., wheat) may increase in Europe with warming of up to 2°C. However, gains would be offset by negative effects seen in other crop yields across Europe (*high confidence*).
Health: Disease	Climatic suitability for malaria transmission in Europe is increasing. Some regions currently at risk of malaria will see a reduction in risk in the future, while others will see an increase. Other diseases are projected to increase (e.g., Lyme disease).
Health: Heat Stress	In Europe critical thresholds relevant for humans would be exceeded for global warming of 2°C and higher. *Good agreement* that countries in Southern Europe would be exposed to excess mortality from future global warming of 1.5°C and above.

NORTH AMERICA	Key statement (including Confidence level / agreement in studies where stated)
Biodiversity and Ecosystem Services	There *is high confidence* that climate change will increase risks to the biodiversity of North America, with greater risks projected with greater levels of warming.
Coastal Flooding	The region is threatened by hurricanes, and locally subsidence can enhance the rate of relative sea-level rise. Protection against extreme events is comprehensive, yet this is still insufficient for the major hazards.
Drought and Water Security	There is *high confidence* that drought frequency and severity will expand in some regions with climate change. This includes western North America
Fire	Canada, Mexico and the United States have already experienced an *unprecedented* shift in fire weather relative to the natural variability simulated for the pre-industrial period. *Substantial* increases in future fire weather have been modelled in North American boreal regions, western US, the northwest US and Canada.
Fisheries	Fish catch potential is projected to decline as temperatures rise. There is *high confidence* that climate change will intensify losses in North American fisheries, with declines in yield and poleward range shifts found by several regional studies.
Fluvial Flooding	Globally, regions projected to face the largest increases in fluvial flooding include the USA. *Medium confidence* that climate change will increase river floods over the United States and Canada.

Food Security and Agriculture	There is *high confidence* that warming temperatures and projected reductions in freshwater availability are very likely to alter crop production in North America with climate change.
Health: Disease	Climate change is projected to increase the spread of the most prevalent Lyme disease vector in North America and lead to an increase in cases of Lyme disease.
Health: Heat Stress	Under future projections of warming studies suggest an increase in mortality in southern and eastern counties in the USA, particularly for elderly populations.

SMALL ISLANDS	Key statement (including Confidence level / agreement in studies where stated)
Biodiversity and Ecosystem Services	There is *high confidence* that increased climate change will significantly affect the biodiversity and ecosystems of small islands. Endemic species are particularly at risk of extinction.
Coastal Flooding	*High confidence* that tropical cyclones are already impacting small islands and will continue to do so. There is *very high confidence* that atolls are particularly susceptible to rising sea-levels, including effects of ground salinisation that can impact ground water.
Drought and Water Security	*Medium confidence* with ~2°C warming of increases in aridity and agricultural/ ecological drought in the Caribbean and increases in aridity in the Pacific islands.
Fisheries	Small island countries are often more dependent on fisheries for national income and food security than other countries. Direction of trends depends on the region and species. *High confidence* that tropical corals in the Pacific and Indian Oceans will experience 70-90% loss of coral reefs at 1.5°C of warming and 99% loss at >2°C.
Fluvial Flooding	Limited evidence on observed changes in river flooding in small islands and *low confidence* on the direction of future change of river flooding in the small islands.
Food Security and Agriculture	*High Confidence* that small islands are extremely vulnerable to sea level rise, freshwater stress and extreme weather such as cyclones, which impact food security.
Health: Disease	Tropical and sub-tropical islands face health risks from vector-borne diseases, and these are expected to increase with future climate change. The Caribbean region has a *high probability* of mosquito distribution increasing the risk of contracting Zika.
Health: Heat Stress	The effect of extreme heat is expected to exacerbate health impacts in small Islands, especially for more vulnerable populations

POLAR REGIONS	Key statement (including Confidence level / agreement in studies where stated)
Biodiversity and Ecosystem Services	High Arctic biodiversity is particularly vulnerable to climate change. There is *high confidence* that the encroachment of woody shrubs, reducing the area of tundra, will continue with higher levels of warming
Coastal Flooding	Although a long coast, limited information is known for risk related to potential land lost, people impacted and economic effects, and their vulnerability.
Fisheries	Global-scale models often project increases in catch potential, while regional, high-resolution models often project declines in catch due to warming and loss of sea ice.

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