CVF V20

CLIMATE **VULNERABLE** FORUM

VULNERABLE TWENTY GROUP

CLIMATE VULNERABILITY MONITOR

A PLANET ON FIRE

CVM3

3rd Edition

GLOBAL CENTER ON ADAPTATION

CLIMATE ANALYTICS

LANCET COUNTDOWN: TRACKING PROGRESS ON HEALTH AND CLIMATE CHANGE

finres financing for resilience

Publisher: Aroha on behalf of Climate Vulnerable Forum (CVF) and Vulnerable Twenty (V20) Group Secretariat, Global Center on Adaptation, Climate Analytics, Lancet Countdown, and finres

Report commissioned by the Climate Vulnerable Forum (CVF) and the Vulnerable Twenty (V20) Group

Title: Climate Vulnerability Monitor, 3rd Edition: A Planet on Fire
Type: eBook
Release date: 2 November 2022

Report citation:
Climate Vulnerable Forum & V20, 2022: Climate Vulnerability Monitor, 3rd Edition: A Planet on Fire [M. McKinnon, T. Lissner, M. Romanello, F. Baarsch, M. Schaeffer, S. Ahmed, A. Rosas (eds.)]

Includes bibliographical references

ISBN: 9 782839 937764

GENEVA OFFICE
Maison de la Paix (Bld.5), 2E Chemin
Eugène-Rigot 1202 Geneva, Switzerland
Tel: +41 22 740 44 00 | Fax: +41 22 740 44 40

ROTTERDAM OFFICE
Wilhelminakade, 149C 3072 AP
Rotterdam, The Netherlands
Tel: +31(0) 88-3717800

CVF V20 — CLIMATE VULNERABLE FORUM | VULNERABLE TWENTY GROUP

The Climate Vulnerability Monitor ("the Monitor" or "CVM") is a unique global assessment at the national level of present and potential future climate change impacts on the environment, economy and public health. The Monitor consolidates the latest research from the scientific literature on the attribution of climate change in 32 distinct indicators of socioeconomic and environmental change and impact phenomena. The Monitor projects and compares how, for a wide range of countries, these impacts evolve throughout the 21st century under a climate and socioeconomic scenario that limits warming to 1.5°C, versus a below 2°C scenario, and a high emissions scenario without climate action to reduce emissions or mobilize additional adaptation efforts. The CVM3 and its scenarios and modeling are informed by the Intergovernmental Panel on Climate Change's (IPCC) latest report, *Sixth Assessment Report*.

The Monitor is commissioned by the Climate Vulnerable Forum (CVF) and the Vulnerable Twenty Group (V20). Climate Analytics, finres, the Lancet Countdown, and the CVF and V20 secretariat, hosted at the Global Center on Adaptation, formed the Consortium of organizations contributing to the CVM3, and supported by dedicated expert panels and regional partners.

Cover photo:
A woman looks at wildfires tearing through a forest in the region of Chefchaouen in northern Morocco on August 15, 2021.
Photo by FADEL SENNA/AFP via Getty Images

Back cover photo:
A picture taken late on August 15, 2021 shows burning forests in the region of Chefchaouen in northern Morocco.
Photo by FADEL SENNA/AFP via Getty Images

Chapter 1 : Introduction
HURT EARTH, 2022
Video projection
Hollywood Forever Cemetery, Los Angeles
Text: "Declaration of the CVF 2009" by the Climate Vulnerable Forum, © 2009 by the authors, from the CVF website, November 9, 2009. Used with permission of the authors.
© 2022 Jenny Holzer, member Artists Rights Society (ARS), NY
Photo: Steven Calcote

Chapter 2 : The Monitor Explained
Name: Aéreo, Capim, Wildfire, Forest., Queimadura, Árvores, Secos, Panorama
Link: https://www.canstockphoto.com.br/aéreo-capim-wildfire-forest-92468640.html

Chapter 3 : Biophysical Impacts on Climate Change
Page number 132
Dry weather and drought conditions
by Brian Scantlebury
Link: https://stock.adobe.com/fr/images/dry-weather-and-drought-conditions/324114873

Chapter 4 : Health Impacts of Climate Change
People Walking on Water near Green Trees
by Kafeel Ahmed
Link: https://www.pexels.com/photo/people-walking-on-water-near-green-trees-13455964/

Chapter 5 : Economics Impacts on Climate Change
Page number 77
AERIAL TOP DOWN FOOTAGE OF MALAYSIA AFTERMATH BIGGEST FLOOD COVERING MAJOR AREA IN SELANGOR AND KLANG VALLEY. IT SIDE IMPACT FROM THE RAI TYPHOON.
by MuhammadSyafiq

Link : https://stock.adobe.com/fr/images/aerial-top-down-footage-of-malaysia-aftermath-biggest-flood-covering-major-area-in-selangor-and-klang-valley-it-side-impact-from-the-rai-typhoon/479745078

Chapter 6 : Black Matter
sunset obscured by wildfire smoke
By MarekPhotoDesign.com
Link: https://stock.adobe.com/fr/images/sunset-obscured-by-wildfire-smoke/113999850

Image 1
Page number 101:
The Department for International Development (DFID)
Link: https://www.flickr.com/photos/dfid/

Image 2
Page number 101:
Top down view of the shallow river. You can see tracts of sand that revealed a water shortage. This predicts drought and crop failure in agriculture
by Ungrim
Link : https://stock.adobe.com/fr/images/top-down-view-of-the-shallow-river-you-can-see-tracts-of-sand-that-revealed-a-water-shortage-this-predicts-drought-and-crop-failure-in-agriculture/376254766

Collaborators

A. Research Consortium

1. CVF and V20 secretariat, Global Center on Adaptation (GCA)

- Matthew Mckinnon, CVM3 Lead Editor
- Dr Michiel Schaeffer, CVM3 Lead Scientific Editor
- Sara Jane Ahmed, CVM3 Coordinating Editor
- Alexandra Jewel Rosas, CVM3 Assistant Coordinating Editor

2. Science Consortium

Climate Analytics

- Dr Tabea Lissner, CVM3 Co-Lead Editor (Science Consortium & Biophysical)

Contributors:
- Dr Tabea Lissner, Head of Adaptation and Vulnerability
- Dr Rosanne Martyr-Koller, Coastal Hazards and Adaptation Scientist
- Dr Fahad Saeed, Scientific Model and Data Manager / Regional Climate Scientist
- Shalom Udechukwu, Student Research Assistant
- René Rott, Research Analyst
- Tessa Möller, Student Research Assistant
- Kouassigan Tovivo, Senior Implementation Specialist - Climate Finance and Adaptation
- Jessie Schleypen, Development Economist
- Winnie Khaemba, Adaptation Strategies Analyst
- Dr. Nandini Das, Energy Research and Policy Analyst

Mercator Research Institute for the Global Commons and Climate Change (MCC)

- Dr Max Callaghan, Postdoctoral Researcher
- Dr Sarah Lück, Postdoctoral Researcher
- Dr Jan Minx, head of working group Applied Sustainability Sciences

Global Data Lab (GDL)

- Dr. Janine Huisman, Senior Researcher and Data Specialist
- Prof. Dr. Jeroen Smits. Professor of Economic and Human Development
- Anne Lieke Ebbers MSc, Junior researcher

Climate Media Factory (CMF)
- Dr Bernd Hezel, CEO Climate Media Factory

3. finres

- Florent Baarsch, CVM3 Co-Lead Editor (Economic)

Contributors:
- Charles Fondecave, Economic Analysist
- Issa Awal Mohamed, Economic Analyst

4. The Lancet Countdown

- Marina Romanello, CVM3 Co-Lead Editor (Health)

Contributors:

Lead coordinating authors:
- Dr Marina Romanello, University College London and Executive Director for Lancet Countdown on Health and Climate Change
- MSc Laura Donovan, University College London and Evidence Translation and Engagement Manager for Lancet Countdown on Health and Climate Change
- MSPH Maria Walawender, University College London and Health and Climate Change Research Fellow for Lancet Countdown on Health and Climate Change

Indicator authors:

Exposure of vulnerable populations to heatwaves
- Dr Jonathan Chambers, University of Geneva

Heat and physical activity
- Dr Samuel Gunther, National University of Singapore
- Dr Troy Cross, University of Sydney
- Professor Ollie Jay, University of Sydney
- Dr Jason Lee, National University of Singapore

Loss of labour productivity
- Professor Tord Kjellström, Health and Environment International Trust, Nelson, New Zealand
- Chris Freyburg, Massey University
- Dr Bruno Lemke, Health and Environment International Trust, Nelson, New Zealand
- MEng Matthias Otto, Health and Environment International Trust, Nelson, New Zealand

Heat-related mortality
- Dr Zhao Liu, Tsinghua University

Wildfire risk
- Dr Liuhua Shi, Emory University
- Dr Pengfei Liu, Georgia Institute of Technology
- Dr Qiao Zhu, Emory University

Dengue
- Dr Stella Dafka, Heidelberg Institute of Global Health
- Professor Joacim Röcklov, Umeå University and University of Heidelberg

Vibrio
- Professor Jan Semenza, University of Heidelberg
- Professor Jaime Martinez Urtaza, Universitat Autònoma de Barcelona
- Joaquin Trinanes, Universidade de Santiago de Compostela

Malaria
- Professor Rachel Lowe, ICREA/Barcelona Supercomputing Center (BSC)
- MSc Martín Lotto Batista,

ICREA/Barcelona Supercomputing Center (BSC)

Crop yield potential
- Professor Nigel Arnell, Reading University

Heat and food insecurity
- Dr Shouro Dasgupta, Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC) and Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science
- Professor Elizabeth Robinson, Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science

5. CVF Expert Advisory Group (EAG)

- Dr Saleemul Huq, Chair
- Farhana Yamin, Deputy Co-Chair
- Renato Redentor Constantino, Deputy Co-Chair
- Mohamed Adow, Member
- Dr Bill Hare, Member
- Agripina Jenkins, Member

B. Contact Groups

Private Sector
- Jessica Turner, Catastrophe Advisory, Guy Carpenter
- James Havard, Head of Exposure Management, Convex

UNFCCC Negotiators and Advisors
- Yamide Dagnet, Director for Climate Justice, Open Society Foundations (OSF)

Development, Humanitarian, and Disaster Risk Practitioners
- Mizan R Khan, Deputy Director, International Centre for Climate Change and Development (ICCAD)

International Development Agencies and Multilateral Funds
- Delia Kaiser on behalf of Bernd-Markus Liss (GIZ), Advisor, InsuResilience Secretariat

Economists and Integrated Assessment Model Developers
- United Nations Economic Commission for Latin America and the Caribbean (ECLAC)

National Government Climate Policy and Rule-Making Authorities
- Antje Kästner, Senior Policy Officer, Federal Ministry for Economic Cooperation and Development (BMZ) Germany

C. Regional Partners

East Asia
- Institute for Global Environment Strategies (IGES)

Central and South Asia
- Bangladesh Centre for Advanced Studies (BCAS)
- Sustainable Development Policy Institute (SDPI)

Southeast Asia
- Global Green Growth Institute (GGGI)

Australasia and Pacific
- Aroha

Europe
- Financial Futures Center (FFC)

North America
- Boston University, Global Development Policy Center (BU GDPC)

Latin America
- Centro Brasileiro de Relações Internacionais (CEBRI)
- United nations Economic Commission for Latin America (ECLAC)

North Africa and Middle East
- Sahara and Sahel Observatory (OSS)

Central Sahel and Africa
- African Centre for Meteorological Application for Development (ACMAD)
- African Economic Research Consortium (AERC)

Southern Africa
- Food, Agriculture and Natural Resources Policy Analysis Network (FANRPAN)
- Economic Research Southern Africa (ERSA)

D. Expert Reviewers

1. Dr Osamu Mizuno, Programme Director, Adaptation and Water Area, Institute for Global Environment Strategies (IGES)
2. Dr Sivapuram Venkata Rama Krishna Prabhakar, Principal Policy Researcher, Adaptation and Water Area, Institute for Global Environment Strategies (IGES)
3. Dr Dwijen Mallick, Senior Fellow, Bangladesh Centre for Advanced Studies (BCAS)
4. Dr Shafqat Munir Ahmad Research Fellow/Director Policy, Sustainable Development Policy Institute (SDPI)
5. Dr Hina Aslam, Research Fellow/Director Policy, Sustainable Development Policy Institute (SDPI)
6. Dr Francisco Gaetani, Senior Fellow, Centro Brasileiro de Relações Internacionais (CEBRI)
7. Mr André Luiz Campos de Andrade, Researcher, University of Potsdam
8. Dr Felipe Vásquez Lavín, Associate Professor, Universidad del Desarrollo, Chile
9. Dr Omar Masera Cerutti, Researcher, Ecosystem and Sustainability Research Institute, UNAM Mexico
10. Dr Pierre Honore Kamsu Tamo Senior Forecaster, African Centre for Meteorological Applications for Development (ACMAD)
11. Dr Kamoru Abiodun Lawal, Thematic Expert Climate Change, African Centre for Meteorological Applications for Development (ACMAD)
12. Dr Andre KAMGA FOAMOUHOUE Director, African Centre of Meteorological Application for Development (ACMAD)
13. Prof Asafu Adjaye, Professor, African Economic Research Consortium (AERC)
14. Prof Théophile Azomahou, Professor, Director of Training.African Economic Research Consortium (AERC)
15. Dr Stephen Whitfield, Associate Professor in Climate Change and Food Security and Associate Director, Global Food and Environment Institute, University of Leeds
16. Prof Brent Cloete, Director, DNA Economics
17. Comlan Médard Ouinakonhan, Expert in Climate Change, Sahara and Sahel Observatory (OSS)

E. Editorial Team

- Eric Meijer, Copy Editor
- Caitlin Meijer, Copy Editor
- Keanu Villanueva, Illustrator
- Henry Tam, Illustrator

Foreword

Foreword to Climate Vulnerability Monitor, Third Edition (CVM3)

by H.E. Ken Ofori-Atta, Minister for Finance, Ghana and Chairman of the V20

The twin goals of shared prosperity and bringing an end to poverty is irrevocably tied to the mission to realise climate resilient growth amongst the climate vulnerable countries of the world. Climate vulnerability and poverty must be tackled together if we are to realise the Sustainable Development Goals by 2030. According to a World Bank report on Attacking Poverty**,** climate change could plunge 32 to 132 million people worldwide into extreme poverty by 2030. The grave economic consequences of climate change on the developing world is further confirmed by the V20-commissioned 'Climate Vulnerable Loss Report', which revealed unprecedented wealth destruction. Climate change has wiped out a fifth of the wealth of climate vulnerable countries over the last 2 decades - meaning that V20 economies have lost approximately US$525 billion because of anthropogenic global warming and its horrific effects on lives and livelihood.

Payment is overdue for the loss and damage suffered by our most vulnerable and least responsible nations. We are first and foremost the victims of dismal global leadership on climate action that has led to insufficient action to deliver the Paris Agreement. We thus call on COP27 in Egypt to, once and for all, establish dedicated efforts andfunding to address the climate change loss and damage of the world's poor and most vulnerable. And because we have a sense of urgency, we offer our own CVF and V20 loss and damage funding program as a vehicle to channel support to frontline communities.

Representing the climate vulnerable countries of the developing world as the President of the Climate Vulnerable Forum (CVF) and as Chair of the V20, Ghana would like to take this opportunity to mobilise support for a move beyond aid. We do not ask for charity. What we need is stronger economic cooperation through programmes such as the CVF and V20's Climate Prosperity Plans which enables the developed world and the climate vulnerable countries of the world to support one another. Both developed and developing countries need to urgently understand the positive global impact generated when climate resilient investments are channeled towards V20 economies. In these times, we require unprecedented cooperation, with developing countries extending mutual support to other developing countries and with developed countries demonstrating how their very wellbeing is irrevocably tied to the fate of the most vulnerable. Not only will thisunderstanding enable us to fortify our respective economies with sustainable financing and infrastructure; it also improves our adaptive capacity andensures resilient growth even as it benefits the economies of both the global north and south.

It is also time for our developed country partners to take a realistic view of current debt service payments across the V20 which is expected to reach half a trillion US dollars over the next four years. It's time to consider opportunities that address long-term economic stability by advancing debt-for-climate swaps that prioritise the welfare of people and the planet. Such collaboration, coupled with South-South support can, and will enable the global economy to benefit from developing partners determined to translate climate action into economic transformation, especially as transformed, emerging economies become capable of contributing significantly to the transition to low carbon and climate resilient economies.

The CVF and V20 commissioned this third edition of the 'Climate Vulnerability Monitor' research project in order to make available a comprehensive data bank of the estimated future impact of climate change based on the latest scientific evidence and Intergovernmental Panel on Climate Change scenarios.

We are very grateful to the V20 secretariat, the Science Consortium, and all the regional partners and experts who participated in this project. The findings confirm the global injustice of the climate crisis and provides clarity on how those hardest hit are also those least responsible for, and least equipped to tackle the climate crisis. The findings also demonstrate the extent of future impacts as we close in on 1.5 degrees Celsius, as well as provide scenarios on how significant the avoided impacts will be versus higher levels of warming. Let the world pay attention to these gloomy findings of the CVM3, and use these to catalyse a renewed sense of urgency to champion current mitigation and adaptation efforts to preserve our common humanity.

Preface

Foreword to Climate Vulnerability Monitor, Third Edition (CVM3)

by H.E. Ban Ki Moon, Chair of the Board of the Global Center on Adaptation and 8th Secretary-General of the United Nations

The climate crisis is the defining crisis of our time. That point has never been more clear than with the findings of this report, the Climate Vulnerability Monitor (CVM). The Global Center on Adaptation is proud to have led this research collaboration with the Climate Vulnerable Forum (CVF) and V20. We are proud to be the Managing Partner to the CVF and V20.

With this third edition of the CVM, we see clearly just how much humanity finds itself at the crossroads. Sadly, we have become a "Planet on Fire," as the report's title highlights. If we do not act now, by the end of the century, millions of lives will be lost every single year because of scorching heat. If we do not intervene, within the next decade tens of millions more people will face food insecurity, higher exposure to extreme wildfires, and, as many as eight times the number of extreme drought events. All this would dramatically undermine progress on the Sustainable Development Goals for 2030.

But this report also provides us with a source of hope. It makes it so very clear how serious a priority it is to invest heavily in adaptation today. If we do so, we can limit catastrophic losses and damage. And if we mobilize to limit warming to 1.5°C, we will dramatically reduce the future human, economic, and environmental toll of this worldwide climate calamity.

I encourage everyone to pay close attention to the findings of this report.

We must all confront the horrific standoff between our way of life, between our main modes of development, and the crystal clear incompatibility of these with a safe and viable planet for us all.

I hope the findings of this CVM research project will spur collective action to chart a different path in all urgency.

Table of Content

Executive Summary

Introduction

The Climate Vulnerability Monitor (CVM) is an independent global assessment of the impacts of human-induced climate change in the 21st century. It presents national-level data (summarized in this report) across 32 distinct impact indicators, mainly through regional analysis, supplemented by select country examples. In its third edix`tion (CVM3), this report's entire underlying national-level database will be made available for free public access from November 2022 via a dedicated online data portal.

The CVM3 consolidates the wealth of the latest scientific research into climate change, in particular building on the *Sixth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC), and distinguishes itself by presenting specific estimated climate change–attributable impact data that is internationally comparable in 32 biophysical, human health and economic indicators for most countries and all world regions for near-term (2030–mid-point year for 2021–2040), medium (2050) and end of the century (2090) timeframes.

The CVM3 presents the data according to climate scenarios and modeling frameworks that are consistent with the IPCC's *Sixth Assessment Report* (AR6). Specifically, these are a 1.5°C scenario, a below 2°C scenario and a "no climate action" scenario (assuming no significant additional climate mitigation), with no special or additional adaptation action foreseen in any scenario, with the latter scenario approaching peak warming of 3.6°C by the end of this century.

Such a high warming scenario is not to be ruled out given the world is on track to continue the prolonged general increase in warming emissions with new record highs in 2022, while countries collectively fall short on the decarbonization ambition of new pledges that would also need to be four times higher in ambition to get on track to limit warming to 2°C, and seven times higher to get on track to 1.5°C.[1] In addition, this scenario of higher warming levels captures an alternative risk of the climate system being more sensitive to rising greenhouse gases than central estimates.[2] Unfortunately, there is therefore still a risk that warming reaches the higher levels, even for a scenario that does include major additional global mitigation efforts.

Through innovative applied statistical and modeling approaches, climate science is rendered tangible and evident with the CVM3 in terms of the direct and implied effects for human society in each country and region globally. The CVM report builds on the IPCC's work, providing comparable, worldwide country-by-country estimates of the cost of climate change to GDP growth, expected changes in infectious disease risks due to climate change, or likely crop failure rate changes caused by climate change. Such estimates, at national level, though qualified by inherent statistical error margins, underlying data limitations, and varying confidence intervals, are less relevant to policy makers and to economic, health and political decision-making processes. This is especially true as governments, business, communities, and institutions weigh important decisions locally, nationally, regionally, and worldwide on the focus and scale of responses to the fast-progressing and far-reaching impacts of the global climate crisis.

As the third edition of the CVM (the previous CVM was produced a decade ago), this report charts new territory for the research series. In the decade since the last CVM, climate science has expanded hugely in scale, and includes two additional IPCC Assessment Reports (5th and 6th). This means that compared to previous iterations, this CVM3 not only provides an updated global assessment of climate impacts, but one that is also far more sophisticated in terms of the scientific evidence underpinning the impact estimations. In the continuation of a long-term trend, around 15% of all climate science publications produced in the three decades since 1991 were released in 2019.[3]

Each CVM has been commissioned by the Climate Vulnerable Forum (CVF).[4] This third edition was jointly commissioned with the V20. Based on earlier commissioning activities and with research commencing in 2021, the CVF and V20 secretariat convened a global Science Consortium at the Global Center on Adaptation. It was led by Climate Analytics and included the Lancet Countdown, finres and a range of other specialist partners worldwide. The CVM3 has also been developed and reviewed in collaboration with a number of leading expert panels and reviewers, as well as 14 regional knowledge partners.

Key Messages

The key messages that result from the CVM3's two-year collaborative research undertaking are as follows:

1. Climate change impacts generate loss and damage, creating crises for society, human health, and development globally

Based on the findings of this CVM3 report, the impacts of climate change are negative in most regions, countries, scenarios, and timeframes, including for virtually every individual indicator of impact considered in this report, with only a handful of exceptions.

Impacts are also already uniquely significant in scale compared to other challenges facing society. Economic losses from climate change, for example, range from estimated levels of 1–2% in the near term to exceeding 10% reductions in annual GDP per capita growth for entire regions (Asia and Europe) by the end of the century in a no climate action scenario.

Such impact levels do not compare in scale to temporary losses of over half of potential GDP growth experienced during 2020–2021, for example, by the G20 with the recent COVID-19 pandemic.[5] However, rebound from that economic crisis was quick and is still expected to continue, while estimated climate change losses are primarily distinguished by being permanent, continuous on average, and constantly growing over time except where counteractive measures would intervene, such as limiting warming to 1.5°C, accelerating adaptation, and addressing losses and damage to speed recoveries.

Comparatively small economic losses due to climate change will also accumulate rapidly: for example, the CVF and V20 members that commissioned this report are estimated to experience economic losses due to global warming of 0.9% of GDP per capita growth on average between 2000 and 2019, resulting in a cumulative loss of 20% of all economic growth potential, in absolute terms, for these countries over that time period.[6]

Climate shocks can, moreover, also manifest as large-scale temporary economic losses, such as occurred in Vanuatu following the Category 5 super cyclone Pam in 2014, which caused losses and damage equivalent to 64% of the Pacific island nation's annual GDP output at the time.[7] It has been well demonstrated that such extreme cyclones are likely to occur with increasing frequency due to climate change. The proportion of the most intense tropical cyclones (categories 4 and 5) is projected by the IPCC to increase by 10%, 13%, and 20% in a 1.5°C, 2°C, and 4°C warmer world respectively, compared with their prevalence in the recent past (IPCC, WG1, Chapter 11). At the same time, a 4°C warming world could see 28% heavier rainfall for all tropical cyclones, making less intense storms much more destructive compared to now.

Risks in each of the other biophysical and health domains considered by this report – such as crop losses, extreme heat events, and disease risks – have also become challenges for the world to grapple with, and they have similar permanence as the economic consequences of climate change. Compared to the recent norm (from 1995 to 2014), as soon as 2030 an eight-fold increase in drought events is projected for key world regions (Africa and the Americas). This trend will continue if warming is allowed to progress further into the future. It will put food and water security, energy production, and economies at risk.

Today, climate change is already responsible for around one third of all heat-related deaths, and the risks of heat-related mortality in over-65s could scale enormously: India alone would see almost 1 million additional heat-related deaths by 2090 without global climate action reducing greenhouse gas emissions and introducing effective adaptation.

2. Asymmetric impact deepens global inequalities and injustice

Poorer and more vulnerable nations are by far the hardest hit. Whether impacts are economic, though especially in biophysical and human health terms, they are overwhelmingly most pronounced in countries and communities with lower income and human development levels. In the CVM3, the Global Data Lab Vulnerability Index (GVI) and Human Development Index (HDI) are referred to for understanding and identifying multi-dimensional vulnerability interactions with climate change impacts.
As a result of the combination of changing climate risk exposures and underlying socioeconomic vulnerabilities, climate change is already considerably worsening global income, health, and other environmentally related inequalities, both between and within countries, and will continue to deepen such inequalities. Progress on the UN 2030 Sustainable Development Agenda is also directly imperiled by these climate change loss and damage implications, with progress on key Sustainable Development Goals (SDGs) on poverty, hunger, health, water, energy, work, and economic growth, life below water and on land, and inequality, among others, all facing setbacks from the accelerating impacts presented in this report.

By way of specific impact examples, the highest increases in climate-attributable food insecurity presented in this CVM3 are projected to be in Sierra Leone, Liberia, Central African Republic, and Somalia, all low HDI countries and least developed countries (LDCs) that already face high levels of food insecurity.[8] "If no climate action is taken, the increase in heatwave events is projected to cause global food insecurity to rise by 12.8 percentage points. The highest increases in the loss of labor hours are likewise projected in the CVM3 to be located in the planet's warmest latitudes – Central Africa, West Africa, South Asia, and Southeast Asia – regions that are also home to the bulk of the world's lower HDI countries and LDCs. Decreases in yields are, moreover, most acute across Africa, with CVM3 projections of 5–30% decreases in maize and rice, and from 10% to more than 40% decreases in wheat yields by the end of the century.

Indeed, heavily affected vulnerable countries – whether the 46 LDCs (responsible for 1% of global GHG emissions to date), the 38 Small Island Developing States (less than 1% of global emissions), the 58 Climate Vulnerable Forum and V20 member states (4–5%), or the 54 African nations (3–4%) – have contributed marginally to the causes of anthropogenic global heating.

3. Nobody is spared

Although many countries that are the least responsible for the climate crisis are among the hardest hit, no country is spared from the impacts of climate change. Indeed, countries once thought to potentially benefit economically from global heating, such as those with present low annual temperature averages (for example, Canada, Russia and Scandinavia), this CVM3 assessment shows they would incur significant economic losses due to the effects of climate change based on already observed disturbances in the real economy.

As global heating progresses over time, more and more countries will experience the types of impacts that are so far only registered in highly vulnerable lower income and least developed nations and regions. For example, in the absence of climate action, the European Mediterranean (including Greece, Italy, and Spain) is projected by the CVM3 to be at risk of re-emergence of dengue fever, despite having long demonstrated its eradication. As much as 100% of the Baltic coastline could become suitable for *Vibrio*, the food-borne bacteria behind gastrointestinal and potentially lethal skin infections that affect tens of thousands of people globally each year.

Wealthier, high-capacity regions, although less vulnerable and better equipped to adapt and to minimize and address losses and damage, will nevertheless experience substantial negative economic impacts from climate change. For example, Europe consistently sees the largest relative estimated losses to GDP per capita growth of any macro-region for every scenario and time period assessed here. The mechanism explaining this also applies to some other countries, like Canada, where any possible benefits for the agricultural sector and hydropower are insufficient to compensate for the negative consequences of climate change on the rest of the economy. Examples include heat-related declines in labor productivity and increases in mortality, weather-related disasters such as flooding, and increasing electricity demand for cooling.

A key difference compared with socioeconomically vulnerable countries is that wealthier regions are far better positioned to cope, with better access to financing for adaptation, insurance cover, and risk management instruments more robustly in place. Far more limited resources and options are a major reason why more vulnerable countries are as vulnerable as they are to climate-related shocks. For example, the most vulnerable regions have much less visibility in the scientific literature. Still, if confirmed in studies for high-income and Northern economies, the implications of the results presented here could be wide-ranging, and would further stress the need for global cooperation to limit warming to 1.5°C.

4. World should urgently prepare for and adapt to rapid escalation in climatic shocks

The world is already heading for 1.5°C of global heating, and it will be reached in the near-term period of 2021–2040 according to every single one of the IPCC's latest AR6 future climate scenarios. While the Paris Agreement targets climate stabilization on time scales of average temperatures over more than a decade, the planet is already knocking at the door of what a 1.5°C world will be like. As warming has progressed, the number of hydrometeorological-related disasters has increased by a factor of five over the past 50 years, according to the World Meteorological Organization's report *United in Science 2022*.

Negative impacts will continue to scale enormously across the spectrum of biophysical and population health as emissions rise. Global warming that is unprecedented in its pace in over 2,000 years of records is driving an accelerating escalation of impacts.

Underpinning the CVM3's title of "A Planet on Fire," part of the increasing climatic risks mapped by this report is a projected 8.5% global increase in human exposure to days of very high or extremely high wildfire danger as 1.5°C is reached (versus 1995–2014 levels). The rise in extreme heat at 1.5°C will also result in a 350% increase in the number of heatwave exposure events among people over 65 years of age, who are particularly vulnerable to the most adverse health outcomes of extreme heat exposure.

At just 1.5°C of warming, rising heat at just 1.5°C of warming, the rising heat will result in 4.7 trillion more person-hours per year exceeding moderate heat stress risk during outdoor physical activity of moderate intensity in the near term. As temperatures rise to 1.5°C in the coming decade, 12% of the areas with no historic malaria suitability will also become newly suitable for the transmission of this disease.

5. Absent climate action, end-of-century impacts dwarf climate shocks to date

In addition to the extreme climate impacts projected for the coming decade at around 1.5°C of warming, the assessments of CVM3 enable comparison with higher warming scenarios over the longer term. This illustrates the extent to which the near-term escalation of climate impacts could pale in comparison to the potential scale of loss and damage in the absence of climate action as time progresses towards the end of this century.

Drought events in all regions of the world, for example, are projected to become 5–11 times more frequent by 2050 in a below 2°C scenario compared with the recent past. By the end of the century, they would be 8–12 times more frequent, increasing to 12–14 more frequent for a no-action scenario. Exposure to life-threatening heatwaves for vulnerable age groups would, moreover, increase by 650% in the same scenario by the end of the century.

Illustrating once more why the CVM3 is entitled "A Planet on Fire," under a no climate action scenario, exposure to very high wildfire risk is projected to increase by the end of the century in the Middle East by 74 days, or 250%, and by 65 days, or 500% in Southern Africa, with respect to the recent past.

Without climate action, heat-related mortality among the vulnerable elderly population (over 65 years old) alone would reach as much as 3.35 million deaths annually by the end of the century, a 1,550% increase above current annual mortality levels. As also outlined in this CVM3 report, 20% of all hours of heavy physical labour, and 11% of those of moderate physical labour, would be lost due to workplace heat challenges by 2090 if no climate action was taken, while more than 1 billion additional people would be put at risk of *Vibrio* transmission.

In economic terms, the costs of climate change to GDP growth per capita seen today, and in the recent past, would increase by 100–182% through the mid-century, and by 439–763% by the end of the century across every world region. In the same timeframe, climate change pressures that increase inflation rates would rise by 212–266% and those that increase interest rates would rise by 336–561% in all but one region.

6. Limiting warming to 1.5°C will prevent a potentially massive expansion in climate impacts beyond 2030

Even if global warming were to stabilize at close to 2°C by mid-century, adverse impacts would be markedly worse across most aspects monitored than if temperature rise was capped at 1.5°C. The seemingly marginal difference between 1.5°C and below 2°C belies a very considerable difference in climate change impacts that society would in fact experience at those two levels, as illustrated in this report.

The CVM3 presents clear insights into the extent to which limiting warming to 1.5°C, as enshrined in the temperature goal of the Paris Agreement, can reduce the multidimensional impacts of climate change, even as compared to a below 2°C scenario of global mean temperature rise.

Climate-related hazards that cause crop losses are increasing, leading to decreased global average yields of major crops, including wheat, maize, rice, and soy. 58% of the potential projected shortening in the growth duration of the key global staple of maize could be avoided globally if global temperature rises were kept at 1.5°C. Precipitation decreases are projected to reach as much as 20% or more in a below 2°C scenario for the Mediterranean basin and in Western and Central Africa are halved at 1.5°C of warming.

In terms of human health, 91% of the potential annual global heat deaths projected under a no climate action scenario by the end of the century would be avoided by limiting warming to 1.5°C, compared with a reduction of just 56% in such mortality if temperatures rise to just below 2°C. The number of person-hours exceeding the moderate heat stress risk threshold during moderate physical activity would also be halved at 1.5°C of warming compared to a no climate action scenario by the end of the century. In a no climate action scenario, 26 more countries around the world would experience conditions suitable for dengue outbreaks by the end of the century. However, this number is projected to fall to just 6 more countries if global mean temperature rise is kept at 1.5°C

Economic damages more than double globally on average in a below 2°C scenario versus 1.5°C. Inflation is up 66% in the below 2°C scenario compared to inflation estimated at 1.5°C, with climate change–fueled interest rate increases also following similar patterns.

A drastic scaling up of climate action must happen in the remaining years of this decade to avoid the worst repercussions of climate change, given the short and fast-shrinking window to limit temperature rise to 1.5°C. Advance action is needed to prevent future warming from becoming inevitable, so if sufficient action is not mobilized to curb warming in the decade ahead, the higher warming levels detailed in this report, and the much higher climate change impacts projected here, could become unavoidable.

7. Accelerated adaptation action and efforts to address loss and damage are essential

The world has yet to come to terms with the breadth, scale, and severity of the impact of climate change; hence, the already major, widespread, and growing negative impacts of climate change that affect every country and region are presented in this report.

The project of adapting to climate change and its impacts is the primary tool available to human society to limit the damages of the level of climate change to which the world is already heading. Research independent of the CVM3, from the United Nations Environment Programme (UNEP), indicates that adaptation financing needs in developing countries – which depend on the level of climate impacts – are estimated to be five to 10 times greater than current international public adaptation finance flows.[9] Some 21% of all countries also lack any form of national climate adaptation planning document. As these points highlight, climate adaptation planning and financing need to expand substantially to cope with today's level of impacts.

Lower income countries' climate adaptation finance needs are estimated by IPCC AR6 to be US$100–400 billion by 2030, while UNEP estimated developing countries' adaptation financing needs in 2030 to be US$100–300 billion. Per the findings of this CVM3, the scaling of impacts expected in the midterm and longer term indicate that greater levels of adaptation action will be necessary to contain damages for all future warming scenarios considered in this report.

IPCC's AR6 clearly showed that climate-change impacts, losses, and damage cannot be fully eliminated even if all options for adaptation were implemented everywhere, given physical and circumstantial limits to adaptation that vary across countries. That presents a real and present danger, in particular for highly exposed and vulnerable countries. This also suggests that the rising impacts of climate change presented in this CVM3 would lead to an ever higher risk.

However, limits to adaptation aside, until adaptation "catches up" with the impacts that result from different climate mitigation strategies and their shortcomings, dealing with losses and damage will be a tremendous challenge. This is especially true for the most vulnerable countries and groups, which include those living in extreme poverty or with disabilities, the elderly, women, children, infants, and indigenous groups.

This CVM3 documents just how much impacts that may lead to loss and damage are estimated to increase, without additional investments in adaptation or in averting, minimizing, and addressing loss and damage. It underscores, over a broad set of parameters, with impact estimates and comparable worldwide data, exactly how much is at stake. It shows that investments in adaptation and in dealing with losses and damage would help communities to avoid, manage, and recover from impacts. This will make for a more resilient society that also rebounds faster from climate disasters, shocks, and pressures.

8. Increased knowledge and data essential

Although this report has benefited from the contributions of a wide range of agencies, scientists, and science groups and organizations, in a multi-year research effort, the findings of each AR6 working group, and advanced supercomputing and artificial intelligence modeling and computational capacity, there are numerous areas where estimations, results, and methodologies could be better.

While the CVM3 is distinctly comprehensive in spanning biophysical, health, and economic impacts at regional and national levels, there are also distinct gaps in the analysis, including in estimating the impacts of sea-level rise and storm surges from tropical cyclones. There is also a gap in indicators for the mental health implications of climate change, poverty, and disposable income levels, transnational economic effects transmitted, for example, through supply chains, and the impacts for fisheries and freshwater resource stocks. Certain more indirect second- or third-order impacts, such as climate-attributable displacement and migration, have also not been addressed in this report.

Standard resolutions of global climate models (for example, of 0.5° x 0.5° of geographic spatial resolution) that provide for a degree of worldwide comparability undermine the accuracy of modelling results for small nations, especially small island states with very limited land compared with ocean territory (such as the atoll nations of Kiribati and Tuvalu). Further investment is needed to overcome this hurdle.

Modelling the future based on the observed past also results in an assessment that cannot fully factor in potential discontinuous, low-probability events or impact events that might only occur at higher warming levels. Often such events would be absent from observational records but could be of significant importance given the climatic conditions ahead that are uncharted for modern human society.

A number of these shortcomings imply that CVM3 results mapping the negative impacts of climate change may be both inaccurate and potentially underestimated for small island states and possibly also for other countries.

Therefore, the CVM project does not stop with this CVM3 report. Further updates, including expanded indicators and derivative studies, are planned. These include a series of regional studies examining region-by-region implications of this latest Monitor.

The critical importance of ongoing investment in knowledge and data is echoed in the expanding and increasingly sophisticated work of the IPCC, with its wide and growing significance for the fields of economics and finance, energy, health, industry, agriculture, and education, among many other domains. The scale of projected impacts from the near to longer term presented in this CVM3, implying that so much is at stake, also constitutes a new contribution to making the investment case for further advancements in climate science and vulnerability research. In its recent Accra-Kinshasa Communiqué, the CVF, moreover, called for the United Nations Framework Convention on Climate Change (UNFCCC) to commission a standalone special report of the IPCC dedicated to the topic of climate change loss and damage.

Key Findings and Observations

The following are highlights of the CVM3's assessments for anthropogenic climate change impacts:

1. Biophysical Impacts

According to the Intergovernmental Panel on Climate Change, the changes to the climate system we are seeing today are unprecedented. Temperatures are higher than they have ever been in the last 125,000 years. Human influence is unequivocal.

- Further increases in average and extreme surface temperature are projected across all scenarios and timeframes, with higher increases corresponding to scenarios with higher emissions.
- Across all biophysical indicators, the difference between 1.5°C of mean global warming above pre-industrial levels, and below 2°C, show in stark detail how essential it is that governments limit warming to the Paris Agreement's 1.5°C temperature limit. For example, in a 1.5°C scenario, the number of drought events per 20 years is projected to increase 4- to 8-fold relative to the baseline. In the long term (2090), the number of drought events per 20 years for a below 2.0°C scenario is projected to increase by 8- to 12-fold, and by 12- to 14-fold for the no climate action scenario.
- In a 1.5°C scenario, extreme precipitation (the kind that can lead to flooding) is projected to increase by 4% to 8% relative to the baseline. In the long term (2090), extreme precipitation is projected to increase by 3% to 8% for a below 2.0°C scenario, and by 4% to 22% (with significant regional variability) for the no climate action scenario.

<u>Food Production, Food Insecurity, and Undernutrition</u>

Findings show that key crop yields, including maize, rice, soy, and wheat, are projected to decline as global warming increases. Access to food is also projected to decrease under future climate change, increasing the prevalence of undernutrition.

- Changes in crop production and yields will affect both food supply and income for about 600 million farms globally, 90% of which are operated by smallholder and subsistence farmers.
- Climate-related hazards that cause crop losses are increasing, leading to decreased global average yields of major crops, including wheat, maize, rice, and soy. For example, changes in wheat yield are minimized when warming is held to 1.5°C. In a no climate action scenario, spring wheat yield would decrease in the long term by 15% in Africa, 10% in the Americas, and 2% in Asia-Pacific, and it would increase by 6% in Europe.
- 58% of the shortening in crop growth duration could be avoided globally if climate commitments were met and global temperature rise was kept at 1.5°C.
- If no climate action is taken, moderate or severe food insecurity will increase by 12.8 percentage points globally towards the end of the century. Under a scenario compatible with 2°C warming, it will rise by 10.9 percentage points.

2. Damages to Wellbeing and Health

<u>Heat and Wildfires</u>

- Hot areas, including Africa (particularly Central and West Africa), and South and Southeast Asia, are expected to experience the worst heat-related adverse health outcomes if no climate action is taken – these low-middle-income regions are likely to have limited capacity to cope and adapt to climate hazards, and are therefore highly vulnerable to adverse health outcomes.
- If global warming is kept below 1.5°C, a 350% increase in the number of vulnerable people exposed to heatwaves above 1995–2014 levels is projected globally. If no climate action is taken, this rises to 630%.
- Assuming no further adaptation, heat-related deaths will increase by 1,540% above the baseline towards the end of the century if no climate action is taken. By keeping global temperature rise below 1.5°C, 91% of this increase could be avoided.
- Under the high-emissions, no climate action scenario, there will be 218% more person-hours of at least moderate heat stress risk during physical activity of moderate intensity towards the end of the century, compared to the 1995–2014 baseline. Keeping global temperature rise under 1.5°C reduces this to 118%.
- By the end of the century, about 20% of the total hours of heavy physical labor undertaken in the sun will be lost if no climate action is taken. Under a scenario compatible with 1.5°C of warming, this loss would be 7.6%.
- If global temperature rise is kept below 1.5°C, human exposure to days of very high or extremely high wildfire danger is projected to increase by 8.5% above 1995–2014 levels. If no

climate action is taken, this risk will more than triple towards the end of the century.

Infectious Diseases

- The number of countries with conditions that are suitable for dengue transmission is projected to increase by 4% as global mean temperature rise reaches 1.5°C. Under the high-emission, no climate action scenario, the number of countries with conditions suitable for outbreaks rises by 22% towards the end of the century.
- The length of the transmission season for malaria is expected to increase substantially in northern latitudes under all future scenarios, with particularly sharp increases towards the end of the century in a no climate action scenario.
- 10% of the global coastal area is projected to be suitable for transmission of *Vibrio* by the end of the century if no climate action is taken, a 103% increase from 1995–2014 levels. Under a scenario compatible with 1.5°C of warming, this falls to 12%.

3. Economic Damage

At all levels of warming analyzed, climate change will have detrimental macroeconomic consequences. Due to climate change, lower-than-expected incomes are projected to result across all nations, as well as higher inflation. Together, they will translate in worsened living conditions. Combined with increased interest rates, governments and households will have a limited ability to invest in sustainable development, mitigation, and adaptation at the required scale.

GDP

- Decreased GDP per capita growth will lead to lower income levels across all countries, with some countries facing up to 30% decrease in their growth potential (for example, Central Asian economies), particularly in a scenario without climate action.
- On average, across all continents, the additional 0.5°C of warming rising from 1.5°C to 2.0°C would lead to a more than doubling in the negative consequences of climate change on incomes.

Inflation

- With more frequent precipitation extremes affecting countries, prices are projected to increase. Across all nations, the study finds inflationary trends from limited levels below 1 percentage point (median) in the Americas at 1.5°C of warming to 2.4 points in Asia and Africa in a scenario without further climate action.
- This represents inflation being up to 66% higher in a 2.0°C world compared to a 1.5°C world.
- These figures are continental-mean estimates for the periods, while climate-related annual fluctuations at country level can be far higher.

Interest Rates

- As a response to more variable GDP per capita growth and increasing inflation, interest rates are projected to increase across all regions. Measured in basis points, the study finds that median interest rates could climb above 65 points in Asia and Europe. Numbers would be up to 50% for European countries at 2°C warming compared to 1.5°C.
- Such increases in the cost of borrowing across all nations will limit their ability to invest in mitigation and adaptation, accelerating the downward spiral of under-investment in mitigation and adaptation aggravating the levels of consequences observed on incomes and inflation.

4. Global Context

Current warming of around 1.1°C is already leading to climate impacts with negative effects for people's health, economies, and habitats across the world. They are observable and scientifically documented. Already, 85% of the global population live in areas that are experiencing significant changes in temperature and precipitation that is attributable to human-induced global warming. The negative impacts of these changes are observed across natural and human systems: from terrestrial to coastal to ocean ecosystems, and through several aspects of human life, including economies, food systems, and health and wellbeing, as well as in cities and infrastructure.

Every fraction of a degree of further warming adds to this mounting damage, increasing the challenges to adapt. Impacts and risks for each country and community, as well as each ecosystem and species, is a function of both biophysical changes caused by global warming and location-specific vulnerabilities. Existing socioeconomic vulnerabilities interact with and exacerbate negative climate impacts, leading to overall higher climate risks and damage. This Monitor quantifies for different countries and the world today just how much risk and damage is expected due to climate change escalation as temperatures rise incrementally over the 21st century.

Scenarios

The Monitor highlights the impacts, risks, and damage, alongside the distinct trajectories that socioeconomic conditions could take, for three climate scenarios:

1) A synthetic scenario in which median warming of 1.5°C in the near term is kept constant to the end of the 21st century
2) A below 2°C scenario (the IPCC's SSP1-2.6), with median warming of 1.8°C by end of century: this scenario, however, would not reduce emissions fast enough to be considered compatible with the Paris Agreement
3) A no climate action scenario (IPCC's SSP 3-7.0), with median warming of 3.6°C by the end of the century: this scenario shows very high levels of emissions – higher than those currently projected for current government policies for climate action – put in place by governments.

Across the many dimensions of change documented in this report, the divergence in projections between low- and high-warming scenarios increase as we move towards the end of the 21st century.

Recommendations

Biophysical Impacts

Limit warming to 1.5°C

Limiting warming to 1.5°C or below is essential to reduce risks and allow for adaptation and climate-resilient development. Above 1.5°C, vulnerable countries and communities will reach the limits of what they are able to adapt to – there is therefore no amount of adaptation efforts that can make up for delayed efforts to reduce emissions in this critical decade for climate action.

Limiting global warming close to 1.5°C would substantially reduce climate change loss and damage. Adaptation and adaptation finance are essential to reduce climate risks at present-day levels and into the future.

Access to Climate Finance

Finance remains a key barrier to effective adaptation and climate finance needs to be made available urgently to enable adaptation.

Access to sufficient finance is also key to address other barriers, such as education and institutional barriers, etc. Finance access needs to be flexible to address these underlying drivers of vulnerability.

Addressing Loss and Damage

Losses and damage are occurring today and will continue to increase. The most vulnerable need support to cope with these effects, to enable resources to be put into adaptation and resilience.

Priority of Building Resilience

Vicious cycles of damage–to–recovery–to–damage need to be broken by providing adequate support as increasing damage limits the resources that are available to build resilience– this is a global responsibility that needs to be addressed by wealthy countries to support the most vulnerable.

Health

<u>Heat and Health</u>
To minimize the health impacts of heat exposure, countries must implement surveillance systems, early warning systems, and response systems that target vulnerable groups. In addition, urban redesign measures that provide sustainable cooling benefits should be unrolled, including increasing urban green space cover, improving building insulation, and implementing low-cost and effective solutions such as cool roofing and cool pavements.

<u>Wildfires</u>
As wildfire danger increases, wildfire prevention and management efforts must be increased, and surveillance, early warning, and response systems that target those living in at-risk areas must be implemented. Health systems should increase the capacity to manage the associated adverse health outcomes.

<u>Infectious Diseases</u>
To protect populations from the rising risk of infectious diseases as global temperatures rise, governments must implement surveillance, early warning, and response systems to help identify, prevent, and manage outbreaks. The implementation of the core capacities under the International Health Regulations should be a priority, particularly those related to health emergency management, for the adequate management of infectious disease outbreaks.

Food Insecurity and Undernutrition
To minimize the impacts of climate vchange on food security, policies should increase both the affordability and availability of food, targeting the most vulnerable populations; for example, expanding safety nets, and investing in climate-smart agriculture and resilient food systems.

Economic

<u>Macroeconomic planning</u>
Macroeconomic planning needs to progressively integrate the effect of climate-related disasters and climate change on the GDP per capita and inflation so that investment decisions are made in light of this evolving environment.

<u>Public and private economic decision-making</u>
Public and private economic decision-makers need to be increasingly trained and aware of the consequences of climate change and climate-related disasters on micro- and macroeconomic variables. Institutions such as International Monetary Fund or the World Bank could play a significant role in training or re-training public decision-makers. Courses on the relation between climate and economic variables could become a requirement in business schools and universities teaching economics.

Long-term investments and debt
Long-term investment decisions or uptake of loans with long repayment periods need to factor in the effects of climate change on the financial viability and profitability of the operation.

<u>Central Banks</u>
Beyond stress testing, central banks should ordinarily be required to take into consideration the influence of the direct and indirect effects of climate change and climate-related disasters on interest rates in order to ensure effective monetary policy.

Technical Summary

- Human-induced climate change already causes negative impacts, losses, and damage. Climate attribution science is increasingly able to directly link climate change caused by human activities with detrimental outcomes.
- The amount of scientific literature on observed impacts of climate change is large and growing quickly. Through machine-learning techniques, documented impacts of climate change on people and nature can be analysed at a national to regional scale to understand the magnitude and distribution of climate impacts around the globe.
- Despite the large amount of scientific literature, the most vulnerable regions have much less visibility in documented impacts.
- Climate change's negative impacts are observed in all aspects of natural and human systems, from terrestrial to coastal and oceanic ecosystems, as well as economies, agriculture, fisheries, and health, and in cities and rural settlements.
- Further negative impacts are projected with each additional fraction of a degree of warming, increasing the challenges to adapt, especially for the most vulnerable regions and communities.
- The climate science community has developed various frameworks to assess future changes in climate, including 1) scenarios, 2) global warming levels, and 3) cumulative CO_2 emissions.
- This report assesses projected impacts based on a subset of five illustrative scenarios that cover the range of possible future development of anthropogenic drivers of climate change used by the IPCC in the *Sixth Assessment Report*. The five pathways, based on the Shared Socioeconomic Pathways, cover a broad range of emissions pathways including high-emissions pathways without climate mitigation and low-emissions pathways compatible with the Paris Agreement.
- Projection of socioeconomic variables considers two illustrative pathways: the low-emissions SSP 1 pathway, leading to 1.5°C to 2°C of warming by the end of the century, depending on the level and speed of climate action undertaken; and the high-emissions SSP3 pathway with no climate action.
- A subset of these pathways is applied to project biophysical indicators: 1) SSP1-2.6, a scenario leading to 1.8°C warming by the end of the 21st century (a "below 2°C" pathway); and SSP3-7.0, the high-emissions pathway with no climate action, leading to a warming of 3.6°C by the end of the century compared to the pre-industrial period. These pathways are explored to understand changes in biophysical and socioeconomic conditions in the near term, mid century, and end of the century.

A quick note on below 2°C and how it relates to the Paris Agreement

In 2013–2015, before the Paris Agreement was signed, the UNFCCC conducted its first Periodic Review[10] of the goal the international community was working toward at the time – the "hold below 2°C" goal, supported by scenarios that generally limited warming to 1.7–1.8°C. The review established that warming of 2°C "could not be considered safe" and provided justification for strengthening the temperature goal. This led to the Paris Agreement's adoption of the 1.5°C warming limit, with a provision to always "hold" warming "**well below** 2°C," reflecting a clear strengthening of the likelihood of warming of 2°C, which should be avoided. Scenarios previously used to inform the below 2°C limit, therefore, are not characterized by stringent enough emissions reductions to be considered compatible with the goals of Paris.

When looking at the likelihood language set out in the IPCC AR6 mitigation report, it is clear that "well below 2°C" falls into the same pathway category as pursuing efforts to limit global warming to 1.5°C. This confirms that they are not two separate temperature thresholds – they are part and parcel of the same long-term temperature goal under the Paris Agreement.

- Analyses of biophysical conditions of temperature, water and the agricultural sector show unequivocally that further negative impacts of climate change are minimized when warming is held to 1.5°C.
- The Monitor's assessment indicates that socioeconomic projections reveal the co-benefits of holding warming to 1.5°C: higher GDP, less poverty, and longer life expectancy are achieved by pursuing pathways compatible with 1.5°C.
- The IPCC has assessed many more pathways in its Working Group III report on mitigation, which shows that accelerated action to reduce emissions and energy demand in the next 10 years can hold temperature rise to 1.5°C, with low or no overshoot this century.

The Research Process

7
STAKEHOLDER REVIEW
Monitor, 3rd Ed.
March 2022

8
IMF/WB SPRING MEETINGS 2022
The V20 Commissioned the development of the Climate Vulnerability Monitor, 3rd Ed at its Ministerial Dialogue VIII
April 2022

9
METHODOLOGY UPDATE AND REVIEW CONFERENCE
Monitor, 3rd Ed.
September 2022

10
METHODOLOGY AND PRELIMINARY RESULTS REVIEW
Monitor, 3rd Ed.
October 2022

11
WASHINGTON, D.C.
Presentation of the CVM3 Executive Brief to at the V20 Ministerial IX
October 2022

6
GLASGOW
The CVF Commissioned the development of the Climate Vulnerability Monitor, 3rd Ed at its High Level Meeting at UNFCCC COP26
November 2021

Research Consortium (RC) - a mandated group of leading scientific organizations forms a highly competent interdisciplinary consortium managing the project and forming the research team for the CVM3.

Regional Partners (RP) - 14 research organizations (think tanks) from 12 regions that will partake in the Monitor's internal review, to develop regional analysis and to support dissemination.

Contact Groups (CG) - 6 pre-defined sets of priority users involved in policy and program formulation, implementation or investments.

Expert Reviewers (ER) - 26 Expert Representatives of from the 14 Regional Partners who will participate in the Monitor's internal review process.

12
DRAFT REVIEW
Monitor, 3rd Ed.
October 2022

5
FRAMEWORK REPORT
Monitor, 3rd Ed.
November 2021

13
ACCRA (VIRTUAL)
Launch of Monitor, 3rd Ed.
November 2022

4
INCEPTION REPORT
Monitor 2nd Ed.
May 2014

3
WARSAW
The CVF Commissioned the development of the Climate Vulnerability Monitor, 3rd Ed with its Costa Rica Action Plan.
November 2013

2
NEW YORK
Launch of Monitor 2nd Ed.
September 2012

1
LONDON
Launch of Monitor 1st Ed.
December 2010

14
SHARM EL SHEIKH
Launch of Monitor, 3rd Ed. Data Portal at COP27
November 2022

KEY POINTS

Climate Vulnerability Monitor, 3rd Edition (2022)

3rd Edition CVM3

Economic and Financial Impacts

Decreased GDP per capita

Below 2.0℃ scenario, economic losses measured in deviation of GDP per capita growth remain at a low level, between **-10% and 0%** deviation compared to the baseline

Doubling of Negative Consequences

On average, across all continents, the additional 0.5℃ of warming rising from 1.5℃ to 2.0℃ would lead to more than a doubling in the negative consequences of climate change on incomes

Accelerating Inflation

Up to **66% higher** at 2℃ than 1.5℃

Higher Interest Rates

Median interest rates could climb above **0.65%** in Asia and Europe

Over 10% Reduction in Annual GDP Growth per capita

Economic losses from climate change to exceed **10%** reductions to annual GDP per capita growth for entire macro regions (Asia, Europe) by end-of-century in a no climate action scenario. For example, Europe consistently sees the largest relative estimated losses to GDP per capita growth, with spillover effects globally

Loss of Labor Hours

Highest loss projected in the warmest latitudes (Central Africa, West Africa, South Asia, and Southeast Asia)

Food Security at Risk

Extreme Surface Temperatures

Temperatures are higher than they have ever been in the last **125 000 years**

Droughts

Drought events per 20 years to increase 4-8 fold at 1.5℃, 8-12 fold below 2.0℃, and **12-14 fold** for the long-term no climate action scenario

Extreme Precipitation

Extreme precipitation projected to increase by 4% -8% at 1.5℃, 3% -8% below 2.0℃, and **4% -22%** for the long-term no climate action scenario

Food Supply and Income

600 million farmers globally will be affected, **90%** of which are small-holder and subsistence farmers

Severe Food Insecurity

linked to heatwaves will increase by **12.8 percentage points** globally if no climate action is taken. This increase would be limited to 1.9 percentage points if global temperatures are limited to 2℃.

Drought Events in All Regions of the World

are between 5-11 times more frequent in occurrence by 2050 in a below 2℃ scenario compared with the recent past. But they would be 8-13 times more frequent by the end of century in a no climate action scenario

Heavier Rainfall for Tropical Cyclones

A high warming scenario world will see 20% heavier rainfall for all tropical cyclones, making less intense storms much more destructive than now

Health Impacts

Heat-related Deaths

of people over 65 years of age could increase by 1,540% by the end of the century if no climate action is taken, reaching 3.4 million deaths annually.

Global Deaths

91% of the projected increase in heat-related deaths could be avoided by limiting global mean temperature increase to 1.5°C, against just 56% avoided if temperatures are allowed to rise to just below 2°C.

3.35 million Heat Deaths among Vulnerable Age Groups

Heat deaths among vulnerable age groups alone would reach as much as 3.35 million annually by the end of the century if no climate action is taken.

Almost 1 Million Additional Heat-related Deaths by 2090 in India

Without accelerated climate change adaptation and mitigation, India alone could see almost 1 million additional heat-related deaths by 2090.

Exposure to Days of High Wildfire Danger

is projected to increase by 8.5% at 1.5°C. This could triple by end of the century if no action is taken.

Exposure to life-threatening heatwaves

Exposure of vulnerable age groups to life-threatening heatwaves could increase by 350% with temperatures rising to 1.5°C. By the end of the century, this could rise further to 2,510% if temperatures rise to just below 2°C, and to 6,310% if no climate action is taken.

218% More Person-Hours Exposed to Heat Stress During Phsiycal Activity

if no climate action is taken, posing at least moderate heat stress risk during physical activity of moderate intensity by the end of the century. These at-risk person-hours could be halved by limiting temperature rise to 1.5°C.

4.75 Trillion More Person-Hours Exposed to Heat Stress During Physical Activity

at just 1.5°C of warming, exceeding moderate heat stress risk during physical activity of moderate intensity.

20% of Hours of Heavy Physical Labor Lost

by end of the century if no action is taken. Under a 1.5°C scenario, this loss would be 7.6%.

Labour Losses Affect Warmer Latitudes Most

The highest increases in the loss of labour hours are located in the planet's warmest latitudes – Central Africa, West Africa, South Asia, and Southeast Asia.

Dengue Transmission

The number of countries with conditions suitable for dengue is projected to increase by as much as 22% by end of century. This increase would be just 4% if temperature rise is limited to 1.5°C.

Re-emergence of Dengue in European Mediterranean

Risk of Dengue Re-emergence in the European Mediterranean (including Greece, Italy and Spain) is projected to be at risk of re-emergence of dengue transmission by the end of the century if no climate action is taken.

Dengue Conditions

77% of the countries that could potentially develop suitable conditions for mosquito borne illnesses like dengue this century could be avoided if temperatures are capped at 1.5°C.

Malaria Outbreaks

As temperatures rise to 1.5°C in the coming decade, **12%** of the areas with no historic malaria suitability will become newly suitable for the transmission of this tropical disease.

Vibrio[1] Transmission

The global coastal area suitable for transmission of Vibrio is projected to increase by **103%** if no action is taken. This falls to **12%** at 1.5°C

Baltic Coastline

As much as **100%** of the Baltic coastal waters could become suitable for the transmission of Vibrio bacteria, which is responsible for severe gastroenteritis, wound infections, ear infections and life-threatening septicaemia.

1 Billion Additional People at Risk of Vibrio Infections

Without climate action, more than **1 billion** additional people would be put at risk of Vibrio transmission by 2090

Current warming of around 1.1°C is already leading to climate impacts with negative effects for people's health, economies and habitats across the world

[1] Vibrio: a water-borne bacterium of a group that includes some pathogenic kinds that cause cholera, gastroenteritis, and septicaemia

The Monitor

The Monitor

I. The Monitor Explained

The CVM3's global assessment of the impact of climate change in estimated, climate-attributable loss and damage is comprised of three distinct bodies of work, with each developed by a lead member of the Monitor's Research Consortium. In all, there are 32 climate impact indicators, as follows:

A. Biophysical: Biophysical Impacts of Climate Change

This section lists 19 indicators of the impact of climate change in biophysical terms, including temperature changes, drought, precipitation, and runoff/discharge, wind speed, soil moisture, and crop yields.

The biophysical section has been developed by Climate Analytics.

B. Health: Climate Change and Health

This section lists 10 indicators of the impact of climate change on human health, including through infectious disease and exposure to risks like heat, wildfires, and food insecurity.

The Health section has been developed by the Lancet Countdown.

C. Economic: Macroeconomic Consequences of Climate Change

This section lists three indicators of the economic impacts of climate change on GDP per capita growth, inflation, and interest rates.

The Economic section has been led by Finres.

Each section of the Monitor has been developed according to a specific methodology, which is presented in the end matter. Each of the three CVM3 sections have aligned on common scenarios and 21st century timeframes as explained in the Key Concepts section of this report.

HURT EARTH, 2022
Video projection
Hollywood Forever Cemetery, Los Angeles
Text: "Declaration of the CVF 2009" by the Climate Vulnerable Forum, © 2009 by the authors, from the CVF website, November 9, 2009. Used with permission of the authors.
© 2022 Jenny Holzer, member Artists Rights Society (ARS), NY
Photo: Steven Calcote

Biophysical Indicators

Temperature
Daily maximum near-surface air temperature
Daily minimum near-surface air temperature
Daily mean near-surface air temperature
Water
Precipitation (rainfall+snowfall)
Snowfall
Surface runoff
Discharge
Maximum daily discharge
Minimum daily discharge
Drought Index
Extreme precipitation
Wind
Horizontal wind speed
Agriculture
Total soil moisture content
Maize yields
Rice yields (first growing period)
Rice yields (second growing period)
Soy yields
Winter wheat yields
Spring wheat yields (summer wheat)

Health Indicators

Heat and Health
Exposure of vulnerable populations to heatwaves
Heat and physical activity
Loss of labor productivity
Heat-related mortality
Wildfires
Exposure to very high or extremely high wildfire risk
Infectious Diseases
Dengue
Vibrio
Malaria
Heat and Food Security
Crop yield potential
Heat and food insecurity

Economic Indicators

GDP Per Capita Growth
Inflation
Interest Rates

Key Concepts and Definitions

Further increases in temperatures are strongly dependent on future developments of emissions. Some additional warming is inevitable, but the latest IPCC report on climate mitigation clearly shows that limiting temperatures to 1.5°C is still within reach, if ambitious climate action is taken immediately (IPCC, 2022a).

This report assessed potential impacts of climate change across different sectors using a set of common scenarios and timeframes across all report sections. Based on the latest scenarios developed for the IPCC's *Sixth Assessment Report* (see Table 1), this report assesses impacts for three scenarios and three time slices (further details on methods and data are provided in the section Methodology in the Annex):

- **Near term (2030)**: impacts are assessed for a 20-year period (2021–2040), centered around the year 2030
- **Mid term (2050)**: impacts are assessed for a 20-year period (2041–2060), centered around the year 2050
- **End of century (2090)**: impacts are assessed for a 20-year period (2081–2100), centered around the year 2090.

- **1.5°C scenario**: in line with the temperature limit specified in the Paris Agreement, the report assesses impacts in a scenario that assumes temperatures stabilize around a median warming of 1.5°C, based on the results out of the SSP126 scenario in the near term (2030).
- **Below 2°C scenario**: this scenario is based on the results for the SSP126 scenario, which leads to a best estimate of 1.8°C by the end of the century.
- **No climate action scenario**: based on SSP370 results, this higher warming scenario would lead to a median warming of 3.6°C by the end of the century, above the estimated temperature that current climate policies would achieve.

The climate research community developed a new framework for climate scenarios that combines future greenhouse gas emissions and their associated climate changes with alternative pathways of socioeconomic development. These pathways, called the Shared Socioeconomic Pathways[11] (SSPs), look at different ways socioeconomic conditions around the world may change. These conditions include population, economic growth, education, and urbanization, and the challenges that arise for climate change mitigation and adaptation. In line with the climate scenarios used for impact assessment in the report, projections of future socioeconomic development and associated vulnerability are also based on the SSP1 and SSP3 scenarios.

SSP1 is the basis for a lower emissions scenario that emphasizes sustainable, more inclusive development, with low challenges to mitigation and adaptation. SSP3, a higher emissions scenario, considers resurgent nationalism and divergence between industrialized and developing nations, with high challenges to mitigation and adaptation. The SSP1 scenario is characterized by low challenges to mitigation and adaptation as a result of increased sustainable development, investments in education, health, and renewable energy, and declining inequalities. The SSP3 scenario is characterized by high challenges to mitigation and adaptation due to a growing divergence between economies, weak international cooperation, increases in internal and external conflicts, and high levels of inequality.

	Near-term, 2021-2040	Mid-term, 2041-2060	Long-term, 2081-2100
Scenario	Best Estimate in C° (Very likely range)	Best Estimate in C° (Very likely range)	Best Estimate in C° (Very likely range)
SSP1-1.9	1.5 (1.2 to 1.7)	1.6 (1.2 to 2.0)	1.4 (1.0 to 1.8)
SSP1-2.6	1.5 (1.2 to 1.8)	1.7 (1.3 to 2.2)	1.8 (1.3 to 2.4)
SSP2-4.5	1.5 (1.2 to 1.8)	2.0 (1.6 to 2.5)	2.7 (2.1 to 3.5)
SSP3-7.0	1.5 (1.2 to 1.8)	2.1 (1.7 to 2.6)	3.6 (2.8 to 4.6)
SSP5-8.5	1.6 (1.3 to 1.9)	2.4 (1.9 to 3.0)	4.4 (3.3 to 5.7)

Table 1: Changes in global surface temperature, which are assessed based on multiple lines of evidence, for selected 20-year time periods and the five illustrative emissions scenarios considered. Temperature differences relative to the average global surface temperature of the period 1850–1900 are reported in °C. For further details, see AR6 WG1 SPM and chapter 4. Source: IPCC AR6 WG1 SPM (IPCC_AR6_WGI_SPM.Pdf 1)

Climate and Impact Models

All indicators presented in this report are meant to provide information on projected changes for end-of-the-century no climate action (SSP370) and below 2°C (SSP126) scenarios. The information is derived from an ensemble of climate and climate impact models used in the latest Intersectoral Impact Model Intercomparison Project 3 (ISIMIP3).[12] All the Impact Models (IMs) employed in ISIMIP3 are forced with the latest generations of five Global Climate Models (GCMs) from Coupled Model Intercomparison 6 (CMIP6) initiative.

For both of the above scenarios, the time series is divided into following time slices:

- Baseline (1995–2014)
- Near term (2021–2040)
- Mid term (2041–2060)
- Long term (2081–2100)

ISIMIP3 does not have a 1.5°C compatible scenario; therefore, a 1.5°C compatible scenario is estimated by assuming that the temperature increases stay at approximately 1.5°C throughout the century. The near-term time slice out of SSP126, which reaches 1.5°C by 2030, is thus also used to represent the medium- and long-term projections for the 1.5°C assessment. The IPCC has assessed many more pathways in its Working Group III report on mitigation, which shows that accelerated action to reduce emissions and energy demand in the next 10 years can hold temperature rise to 1.5°C with low or no overshoot this century (*IPCC, 2022a*).

Vulnerability as a Key Component of Climate Risk

The severity of a given climate hazard is greatly affected by the conditions on the ground, so it is not the severity of climate change alone that drives impacts. Vulnerability is seen as a key contributor to understanding overall climate risk, which is the outcome of different biophysical and socioeconomic factors. Vulnerability as a component of overall climate risk is therefore essential to assess – and a key aspect that can be reduced through adaptation and building resilience.

Until 2012 and the publication of a special report on extreme events by the IPCC (*Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation — IPCC*), vulnerability was understood to be the outcome of the interplay of climate hazards (or climate stimuli), the sensitivity to suffer harm as a consequence of these hazards, and the system's capacity to adapt to the consequent climate impacts. The risk-based approach now adopted by the climate change community continues to consider the interplay of socioeconomic and biophysical aspects, but understands vulnerability as a key contributing factor to risk, rather than an outcome (Figure 1).

Changes in mean and extreme climate conditions determine the severity of climate hazards, which combine with exposure[13] of human, infrastructural, and natural assets, and are exacerbated by socioeconomic vulnerability. All of these dynamics can themselves evolve over time and in their interaction determine overall climate risk (Figure 1).

To reduce the impacts of climate change, there are several key entry points to reduce overall risks. While reducing the climate hazard by limiting warming to 1.5°C remains key, it is also people's exposure to climate events and their vulnerability to the effects of these events that need to be reduced.

In its *Sixth Assessment Report*, the IPCC defined vulnerability as "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" (IPCC, 2022b). Vulnerability refers to people's sensitivity to harm as well as their capacity to cope and adjust (Cardona et al., 2012). This perspective helps explain why in some cases non-extreme climate change events and chronic hazards can have severe impacts and lead to disasters, while in other cases more extreme events do not have disastrous effects. Consequently, the occurrence of an event related to climate change, together with the degree to which a society is exposed to its effects and the degree of vulnerability of this society, jointly determine the impact felt by this society (see Figure 1). Climate change events will lead to disasters if exposure to potentially damaging extreme events is accompanied by a high level of vulnerability (Cardona et al., 2012).

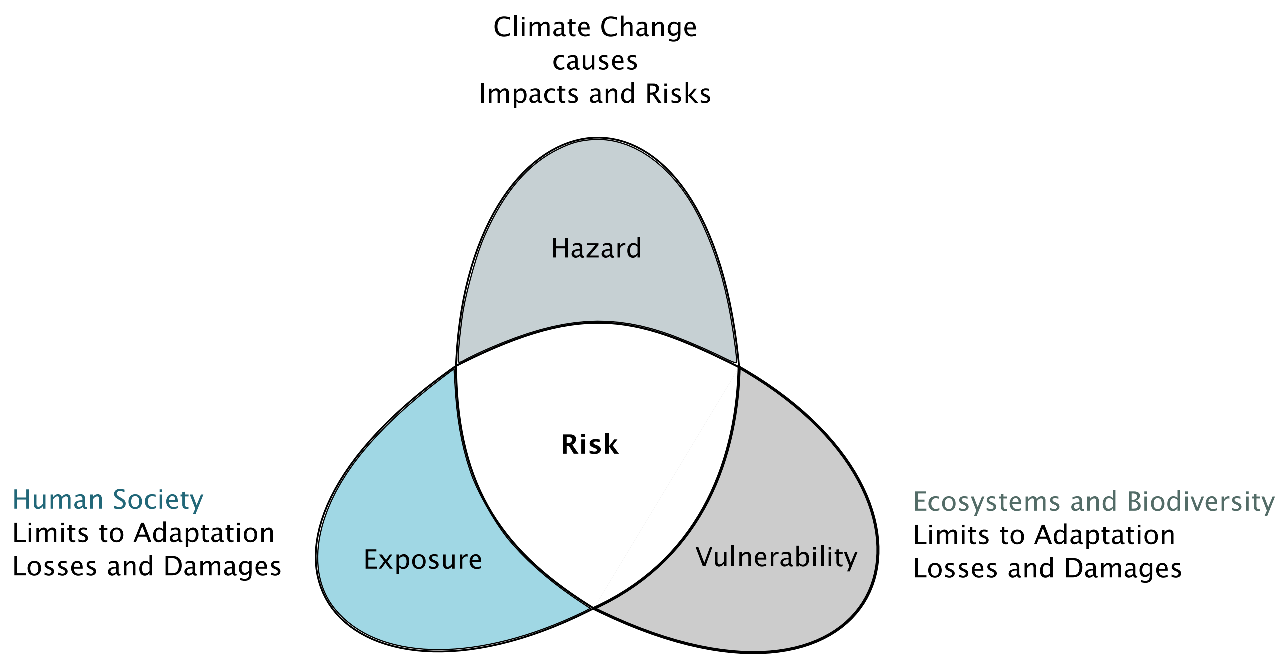


Figure 1: Vulnerability as it interacts with hazards and exposure, resulting in risk and impacts (IPCC, 2022)

II. Global Highlights

A. Biophysical: Biophysical Impacts of Climate Change

Current warming of around 1.1°C is already leading to severe documented impacts across the world and science is increasingly able to show the direct link between climate change caused by human activity and detrimental outcomes. Climate impacts can be seen, felt, and measured today. Every fraction of a degree of further warming adds to this mounting damage, increasing the challenges to adapt, especially for the most vulnerable regions and communities. This section highlights the many different biophysical changes that are projected globally for scenarios of warming of 1.5°C and below 2°C, showing in stark detail how essential it is that world leaders make true on the Paris Agreement 1.5°C temperature limit. It also shows the detrimental impacts that unabated climate change would have under a no climate action scenario (a high warming scenario leading to median warming of 3.6°C by the end of the century).

The effects of human-induced climate change can be reflected in several biophysical indicators, spanning dimensions such as temperature and water, as well as in extreme events such as storms. The impacts of these changes in biophysical indicators are felt in several aspects of natural and human systems. Evidence shows that climate change has already altered terrestrial, freshwater, and ocean ecosystems across the globe on all scales, impacting system structure, species, and timing of seasonal life cycles (IPCC, 2021a). These impacts directly affect key resources, sectors, and economic activities and have severe effects, especially for the most vulnerable. Impacts on the productivity of agriculture, forestry, fisheries, and aquaculture, for example, are posing a threat to food security. Water systems and water security are threatened by changes in the hydrological cycle, exacerbating existing water-related vulnerabilities, and human health and wellbeing are impacted by longer-lasting heatwaves and increasingly threatened by vector-borne diseases. The most vulnerable regions and population groups are also projected to be exposed to highly adverse climate impacts. They will therefore bear the brunt of adverse climate change and are often the least able to adapt.

Climate change's impacts on biophysical conditions have direct and indirect impacts on natural and human systems, and interact with and are exacerbated by socioeconomic vulnerability.

Climate Change is Causing Losses and Damage Today: Observed changes and Impacts

Human-induced climate change, including more frequent and intense extreme events, has caused widespread adverse impacts and related losses and damage to nature and people (IPCC, 2021). Widespread negative impacts have resulted from observed increases in the frequency and intensity of climate and weather extremes, including heatwaves, extreme rainfall, drought and fire weather, which are increasingly attributable to human-caused climate change (IPCC, 2021).

This section provides evidence of observed trends in temperature and precipitation globally, and evidence of climate change attribution in those trends. It also outlines how knowledge of climate impacts is distributed across the world in terms of scientific assessments. The amount of literature is enormous, but highly unevenly distributed: the most vulnerable regions have much less visibility in the scientific literature. Evidence on regional distribution of scientific literature of climate impacts is presented in Figure 2 below.

Human Influence is Changing the Climate

Currently, 85% of the global population live in areas that are experiencing significant change in temperature or precipitation and these trends can be attributed to human influence on the climate (Figure 3). These numbers likely underestimate the true extent of change, as 18% of the population of CVF/V20 countries,[14] for example, live in areas where data gaps make it difficult or impossible to calculate the direct attribution to climate change.

There is a large and fast-growing body of scientific literature that documents the impacts of observed climate change (Figure 2). It shows how those changes in temperature and precipitation (among other climate drivers) impact human and natural systems, and cause losses and damage across sectors and regions. A total of 27,737 studies provide evidence of climate change impacts in CVF member countries, corresponding to 22.8 impact studies per million inhabitants. This represents a large body of evidence, with the largest share of documents studying impacts on human and managed systems. However, this is much lower than the number of studies on climate impacts in high-income OECD countries, which stands at 80 per million inhabitants.

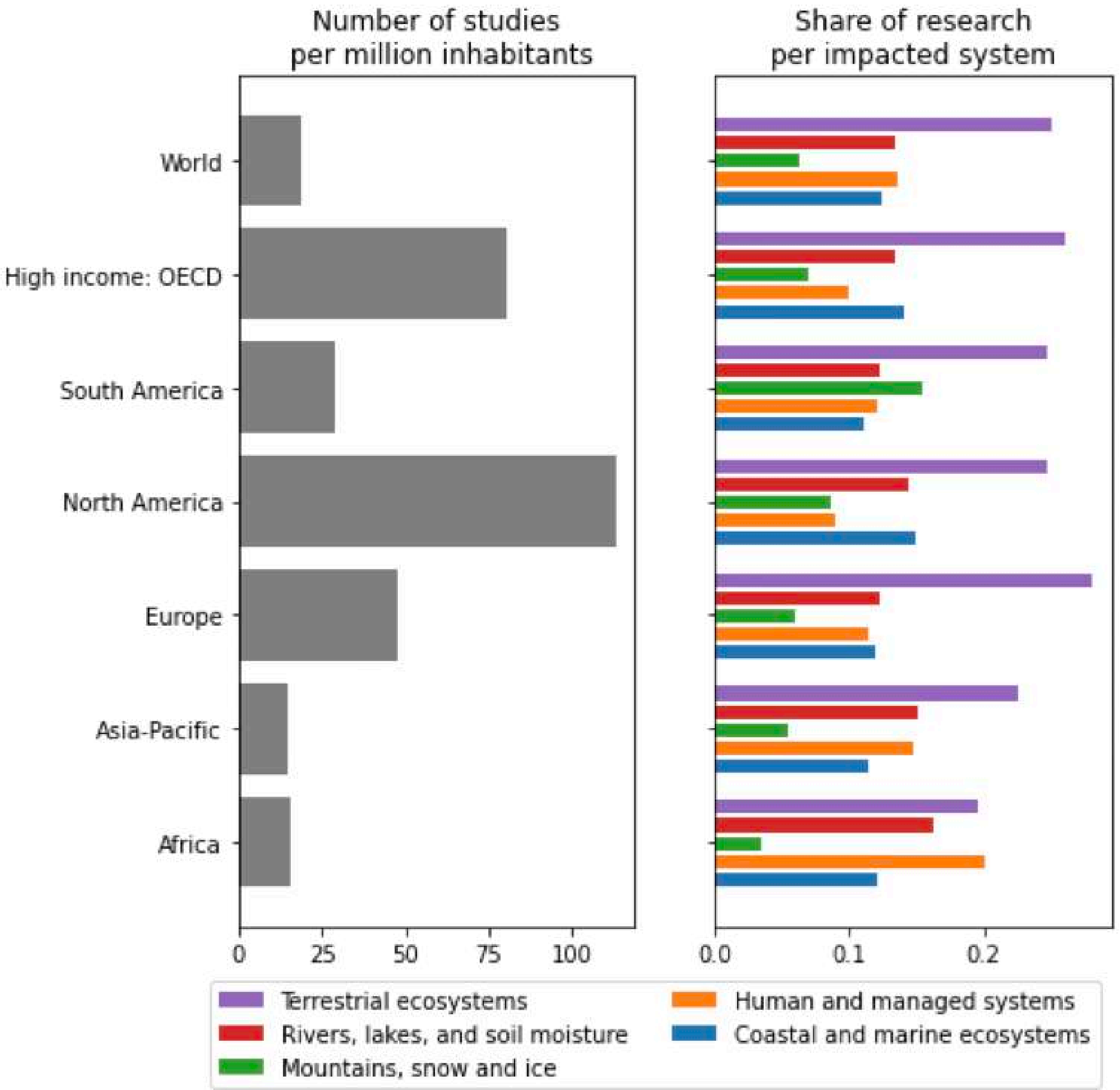


Figure 2: Scientific literature stocktake documenting climate change impacts in human and natural systems

Given the high vulnerability of CVF member countries to the impacts of climate change and the clear documentation of occurring changes, this gap in the distribution of evidence is a concerning sign of the global scientific community's blind spot on climate impacts in vulnerable countries and thereby our understanding of the global distribution of losses and damage (Figure 3).

What Changes are Being Felt Across the World?

The impacts of climate change are already observed in terrestrial, freshwater, and ocean ecosystems at the global scale, with evidence of several impacts at regional scales. Negative impacts include, for example, warm-water coral bleaching and mortality; drought-related tree mortality; increased burned areas through wildfires; local losses of species due to marine heatwaves; mass mortality events on land and in the ocean; and loss of kelp forests. Changes have been observed globally and across several regions in ecosystem structure, as well as shifts in the range and timing of species.

Negative impacts of climate change are also observed in human systems. Observed impacts include changes in food production, water availability, health and wellbeing, and in cities, settlements, and infrastructure. Climate change, especially through increases in frequency and intensity of extreme events, has reduced food and water security globally, reduced growth in agricultural productivity, and negatively impacted food production from shellfish aquaculture and fisheries in some ocean regions. The largest impacts of food insecurity and water scarcity are observed in many locations in Africa, Asia, Central and South America, Small Islands, and the Arctic.

Economic damage from climate change has been detected in agriculture, forestry, fisheries, energy, and tourism, as well as through outdoor labor productivity. Climate change has negatively impacted individual lives and livelihoods, through reduced agricultural productivity, destruction of homes and

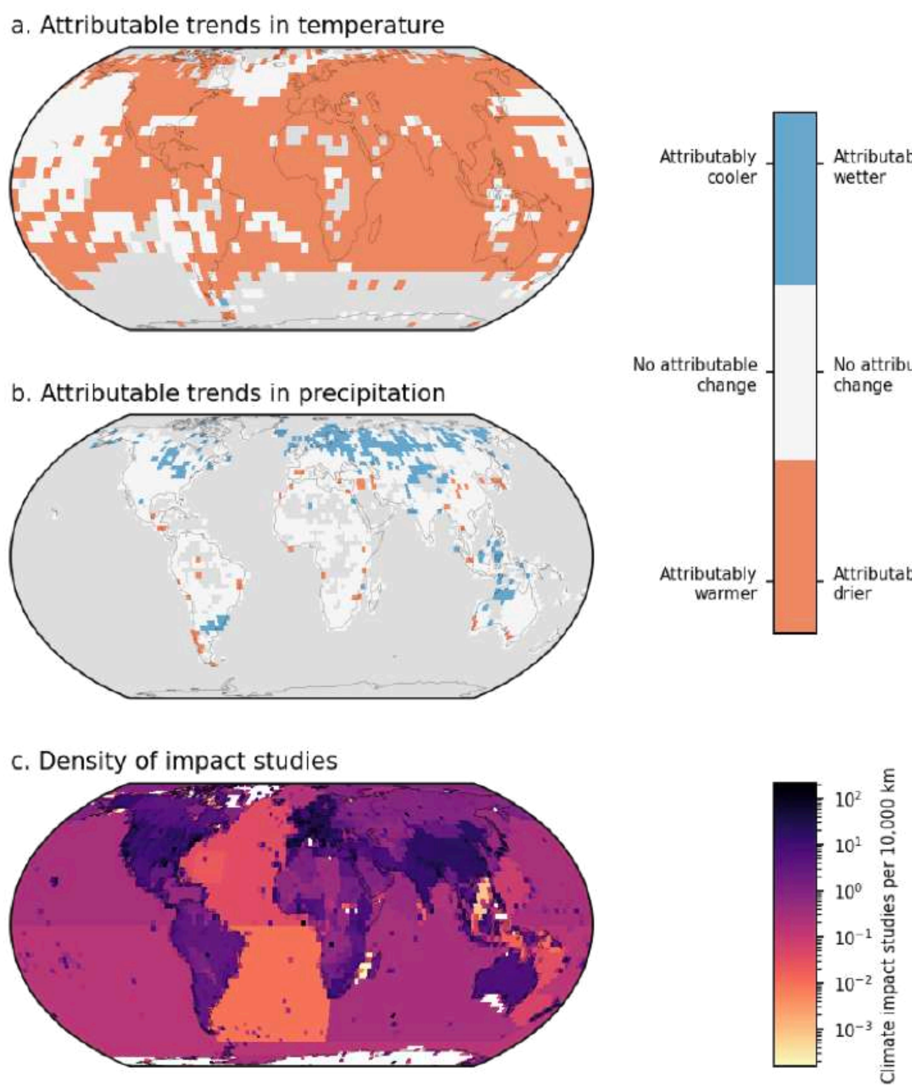


Figure 3: Evidence of the impacts of observed climate change. Plots a and b show trends in temperature and precipitation that are attributable to human influence (consistent with model estimates including anthropogenic forcing and inconsistent with model estimates with natural forcing only). Plot c shows studies identified using a machine learning classifier developed by Callaghan et al. (Callaghan et al. 2021), where locations were extracted automatically. The colour of each grid cell shows the number of studies per 10,000 km, where each study is distributed evenly across all grid cells it refers to, to avoid double counting.

infrastructure, and loss of property and income. These impacts have had negative effects on gender and social equity, as well as the health and wellbeing of people globally. In all regions, extreme heat events have resulted in increases in human mortality. Occurrences of climate-related food and waterborne diseases have increased, as have incidences of vector-borne diseases.

In 2022, extreme weather events around the globe that were unprecedented in their magnitude and negative impacts have borne the signature of climate change. Attribution studies have made it possible to determine the role climate change played in the likelihood and intensity of these events. An exceptional summer heatwave that severely impacted the UK, causing temperatures to reach 40°C and above – temperatures that have never been reached in the UK before – was, for example, shown to have been extremely unlikely without human-induced climate change (Zachariah et al., 2022a). Extreme rainfall over 24 hours caused catastrophic flooding and landslides in north-east Brazil, displacing thousands and incurring loss of life. This rainfall, which occurred over income-vulnerable communities, was demonstrated to have been made heavier due to climate change (Zachariah et al, 2022b). Pakistan and parts of India witnessed a deadly heatwave in March and April, with temperatures reaching all-time highs and rainfall levels at well below normal conditions. Climate change was attributed to making this heatwave 30 times more likely, with disastrous impacts on public health, agriculture, and infrastructure (Zachariah et al., 2022c). Pakistan then incurred record-breaking monsoon rainfall on the heels of that heatwave, with rains and flooding affecting over 33 million people and destroying over 1 million homes. Average August rainfall was reported to be more than eight times the usual amount for the month, likely increased due to climate change (Otto et al., 2022). These extreme events, made more powerful and more likely by climate change, and their disastrous impacts exacerbated by underlying vulnerabilities, show in grim clarity the negative effects of climate change felt across the world at present-day warming of around 1.1°C above pre-industrial levels.

Climate Impacts Increase with Every Fraction of Warming

Further increases in mean and extreme surface temperature are projected across all scenarios and timeframes relative to the baseline, with regional and country-level differences, with higher increases corresponding to higher emissions scenarios. Increases in extreme temperatures are also projected across all scenarios, with noticeable regional hotspots in the northern latitudes and southern Africa. Without additional mitigation efforts, global mean temperatures are projected to increase to approximately 1.5°C relative to pre-industrial times during the period before 2040. By mid century (2041–2060), the below 2°C scenario and no climate action (high warming) scenarios will exceed warming of 1.5°C, with projected global surface temperature increases of 1.7°C and 2.1°C, respectively. By the end of the 21st century, if climate emissions are not curbed in line with a 1.5°C pathway, projected global mean surface temperatures will reach 1.8°C in a below 2°C scenario, and 3.6°C in the high warming scenario assessed in this report. The IPCC has assessed many more pathways in its Working Group III report on mitigation, which shows that accelerated action to reduce emissions and energy demand in the next 10 years can hold temperature rise to 1.5°C with low or no overshoot this century (*IPCC, 2022a*).

Climate change is projected to cause changes in mean precipitation, snowfall, surface runoff, and extremes including peak river discharge, extreme precipitation, and drought. The range of projections is quite wide, particularly for the high-emission scenario – ranging from negative values indicating decreased future precipitation to positive values projecting increased precipitation – for every continent and also for several countries.

These results illustrate clearly the additional challenges posed by climate change for water management, with the increasing model range posing severe challenges not only from an impact point of view, but also in terms of uncertainty for planning. Limiting warming to 1.5°C not only reduces the potential impacts substantially, but also provides more clarity for planning responses. In a 1.5°C scenario, extreme precipitation (the kind that can lead to flooding) is projected to increase by 4% to 8% relative to the baseline. In the long term (2090), extreme precipitation is projected to increase by 3% to 8% for a below 2.0°C scenario, and by 4% to 22% (with significant regional variability) for the no climate action scenario. Australasia, the Indian subcontinent, and Central America are notable exceptions, projected to experience decreased extreme precipitation by the end of the century. Droughts are projected to increase, particularly across South America, Africa, and Australasia with increased global warming. For example, in a 1.5°C scenario, the number of drought events per 20 years is projected to increase 4 to 8 fold relative to the baseline. By the end of the 21st century, the number of drought events per 20 years for a below 2.0°C scenario is projected to increase by 8 to 12 fold, and by 12 to 14 fold for the no climate action scenario.

Intense tropical cyclones (categories 4 and 5) will increase as a proportion of all tropical cyclones, and peak winds in the most intense tropical cyclones are also projected to increase with increasing global warming (IPCC, 2021b). The proportion of intense tropical cyclones is projected to increase by 10% in a 1.5°C warmer world, 13% in a 2°C warmer world, and by 20% in a 4°C warmer world. Precipitation associated with tropical cyclones is also projected to increase with global warming: by 11% at 1.5°C, 14% at 2°C, and by 28% at 4°C, double the increase at 1.5°C (Lawrence et al., 2021).[15]

Climate change is anticipated to significantly impact the resilience of agricultural systems around the globe. Projections of key production

crops, including maize, rice, soy, and wheat, show negative impacts with increased global warming. Climate-related hazards that cause crop losses are increasing, leading to decreased global average yields of major crops, including wheat, maize, rice, and soy. Changes in crop yields due to climate change are minimized under a 1.5°C scenario. For example, changes in wheat yield are minimized when warming is held to 1.5°C. In a no climate action scenario, spring wheat yield would decrease in the long term by 15% in Africa, 10% in the Americas, and 2% in Asia-Pacific, and increase by 6% in Europe.

B. Health: Climate Change and Health

At 1.1°C of global heating, climate change is already having profound impacts on the socioeconomic and environmental conditions that human health depends on, making it the greatest threat to global health this century (Costello et al., 2022; Romanello et al., 2022). While no country remains unaffected, the health impacts of climate change are not homogeneously distributed, and affect vulnerable and disadvantaged populations the most, thereby exacerbating between and within-country inequalities (Romanello et al., 2022). With a further increase in global mean temperatures now unavoidable, monitoring the changing hazards of climate change is essential to identify populations at risk, and to develop adaptive and coping capacity mechanisms that can help minimize the associated health impacts. Many countries worldwide have already devised adaptation plans to curtail future climate change–induced health impacts. However, most still face ongoing challenges such as a lack of funding, capacity, and political will (Romanello et al., 2022). Understanding the potential health impacts of different emission trajectories is also necessary to fully understand the cost-benefit of different future climate scenarios.

Indicators presented in this report estimate changes in climate-related health risks that are driven by changing climatic conditions, to help understand the emerging risks that could be avoided through accelerated mitigation, or reduced with increased adaptation. The data exhibits the potentially catastrophic increase in the health risks of climate change, the potential health consequences of climate adaptation and mitigation inaction, and the major health gains that would arise from taking urgent measures today to meet international climate commitments.

Heat and Health

As temperatures rise, exposure to extreme heat will rise, putting people at risk of heat stress and heat stroke, exacerbating cardiovascular and respiratory disease, and causing acute kidney injury, adverse pregnancy outcomes, and mental health impacts (Székely et al., 2015; McElroy et al., 2022; Syed et al., 2022; Liu et al., 2021). A recent study estimated that about one third of all heat-related deaths occurring today can be attributed to climate change (Vicedo-Cabrera et al.). Projections presented in this report indicate that people over 65 years of age, who are one of the most vulnerable groups to the adverse health impacts of extreme heat, will be increasingly exposed to life-threatening heatwaves under all future climate scenarios. The increase will be considerably more if no climate action is taken, particularly towards the end of the century: while a 350% increase in person-days of exposure to heatwaves above 1995–2014 levels is projected in a scenario compatible with 1.5°C of heating, this rises to a 630% increase in a scenario in which no climate action is taken.

With the rising temperatures, heat-related mortality is also expected to rise. Without taking into account potential adaptation, heat-related deaths of people over 65 years of age would increase by 1,540% above baseline towards the end of the century if no climate action was taken. In all, 56% of this increase in heat-related deaths would be avoided in the low-emissions scenario that keeps global mean temperature rise below 2°C, and 91% of deaths would be saved by keeping temperatures below 1.5°C, underscoring the potential benefits of ambitious climate action.

Beyond the direct health outcomes, rising temperatures are also putting people at risk of exertional heat stress and reducing the hours available for safe outdoor physical activity, undermining health by limiting people's capacity to maintain an active lifestyle. Towards the end of the century, data in this report suggests that the high-emissions, no climate action scenario would result in 218% more person-hours of at least moderate heat stress risk than in the 1995–2014 baseline, and in 118% more person-hours than in a scenario compatible with keeping global temperature rise below 2°C.

In addition, the rising temperatures will increasingly affect laborers who work outdoors or in uncooled indoor areas, affecting their productivity, and putting their livelihoods and the socioeconomic determinants of health at risk. By the end of the century, about 20% of the total potential hours of heavy physical labor could be lost if no climate action was taken (assuming work is undertaken in the sun), due to the physiological restrictions imposed by the high temperatures. However, this loss would be almost halved (to 12% of work hours lost) if temperature rise is limited to below 2°C by the end of the century.

Hot areas including Africa (particularly Central and West Africa) and South and Southeast Asia are expected to be affected the most by heat-related adverse health outcomes if no climate action is taken. Low-middle-income regions are likely to have limited capacity to cope with, and adapt, to climate hazards, and are therefore highly vulnerable to adverse health outcomes.

In order to minimize the health impacts of heat exposure, surveillance, early warning, and response systems targeting vulnerable groups should be urgently rolled out. In addition, urban redesign measures can provide sustainable cooling benefits and reduce heat exposure, including by increasing urban greenspace cover, building insulation, or low-cost and high-impact solutions such as cool roofing and cool pavements.

Wildfires

The changing climate is also increasing the danger of extreme weather and weather-related events. Through a combination of increased temperatures, aridity, and drought, the meteorological risk of wildfires has been increasing worldwide (Jones et al., 2020). Wildfires put people at risk from life-threatening burn injuries, adverse respiratory outcomes and acute eye damage from exposure to wildfire smoke. There are also indirect health impacts through the loss of assets and infrastructure, and the disruption of essential services (Kollanus et al. 2017; Xu et al., 2020; Masson-Delmotte et al., 2021; Romanello et al., 2022). Detection and attribution studies have found that climate change increased the likelihood of recent lethal extreme wildfire events, including Australia's 2019–2020 "black summer" and the 2019 China wildfires. As the climate continues to change, the risk of wildfires is set to increase further (Jan Van Oldenborgh et al., 2021). Analysis presented in this report suggests that human exposure to days of very high or extremely high wildfire danger is projected to increase by 8.5% above 1995–2014 levels as temperatures rise to 1.5°C. In a trajectory compatible with 2°C of global mean temperature rise by the end of the century, exposure to very high or extremely high wildfire danger would rise further to 12.3% above baseline. However, the increase would be tripled if no climate action was taken, reaching an extra 27 days of exposure towards the end of the century (a 34% increase from the 1995–2014 baseline). In a future scenario compatible with no climate action being taken, the largest increases in exposure to very high or extremely high wildfire danger would occur in low-middle-income countries in the Middle East, Southern and North Africa, as well as in high-income countries in Southern and Eastern Europe, which have seen devastating wildfire seasons in recent years.

As wildfire danger increases, wildfire prevention and management efforts must be strengthened to protect against the detrimental impacts on human health, and the loss of the natural ecosystems that it depends on. Governments should implement surveillance, early warning, and response systems targeted to those living in at-risk areas, and health systems should increase the capacity to better manage the impacts of wildfires when these do occur.

Infectious Diseases

The changing weather conditions are also causing shifts in the distribution of climate-sensitive infectious diseases. The death, suffering, and profound disruptions caused by the COVID-19 pandemic serve as a bleak warning of the dangers of emerging infectious diseases, and have exposed the fragility of our health systems. Under this light, it is of particular concern that about half of known human pathogenic diseases are at risk of being aggravated by climate change (Semenza and Suk, 2018; Mora et al., 2022). The rising temperatures and altered rainfall patterns will make weather increasingly apt for the transmission of mosquito-borne diseases like dengue and malaria in colder latitudes, in which conditions are currently not suitable for local transmission. In the case of dengue, data in this report suggests that the number of countries with weather conditions suitable for outbreaks would increase by 4% as global mean temperature rise reaches 1.5°C, and by 22% towards the end of the century if no climate action was taken. Under a scenario of no climate action, countries in Southern Europe and the Balkans, regions where such diseases are not yet endemic, are projected to become suitable for local dengue transmission by the end of the century. Similarly, the length of the transmission season for malaria is expected to increase substantially in northern latitudes under all future scenarios, with particularly sharp increases towards the end of the century in a no climate action scenario.

As the temperature of sea waters increases, they will also become more suitable for the transmission of pathogens like *Vibrio* spp., which can cause gastrointestinal disease, wound infections, and life-threatening septicaemia (Osunla and Okoh, 2017). Projections suggest that the coastline suitable for transmission of *Vibrio* would increase by 103% towards the end of the century with respect to baseline years if no climate action was taken, reaching 10% of the global coastal area. If temperatures were kept within 1.5°C of global mean temperature rise, the percentage increase in suitable coastline would fall to 12%, exposing the benefits of meeting climate commitments.

As the climate becomes increasingly suitable for the transmission of infectious diseases, so will the risk of outbreaks increase. The impact will be highly dependent on a multiplicity of factors, including the socioeconomic and behavioral conditions that determine human exposure to the pathogens, and the capacity of health systems to detect, diagnose, treat, and contain the spread of disease. To protect populations, governments must implement surveillance, early warning, and response systems that can help identify, prevent, and manage outbreaks.

As recent grave epidemics and pandemics have demonstrated, managing infectious disease risks requires international leadership, cooperation, and coordination of financial resources and health systems responses (Seventy-Fourth World Health Assembly). The devastating impacts of the COVID-19 pandemic triggered a review of the functioning of the International Health Regulations – particularly those related to health emergency management (World Health Organization). As this unfolds, countries should closely follow the upcoming recommendations to strengthen their health systems, and implement the recommended measures to better manage infectious disease-related health emergencies.

Food Insecurity and Undernutrition

As the planet heats, climate-induced threats to food security are also rising: food production is compromised by the impact of extreme weather on crop yields, changes in soil and water salinity, and the incidence of crop pests and diseases, with recent studies increasingly attributing changes in food insecurity to climate change–related hazards (Dasgupta and Robinson, 2022; Chen et al., 2021). Recent data from the Lancet Countdown estimates that excess heatwave days in 2020 were associated with 98 million more people reporting moderate to severe food insecurity (Romanello et al., 2022). The impacts of climate change on labor and supply chains affect food prices and incomes, thereby reducing food affordability, while the nutritional content of some crops is affected by increasing carbon dioxide levels in the atmosphere, and the incidence of infectious diseases undermines effective food utilization (Capone et al., 2014).

Projections presented here show that the rising temperatures will continue shortening the duration of crop growth seasons, jeopardising crop yield potential. This reduction is expected to be particularly marked towards the end of the century if no climate action is taken, with a crop growth duration 20% shorter than in 1995–2014 globally. Countries in colder areas, including Europe, Russia/North Asia, North America, and South Africa, are expected to be the most affected. However, 58% of the shortening in crop growth duration could be avoided globally if climate commitments were met, and temperature rise was limited to 1.5°C.

The increased incidence of heatwaves is also projected to result in an increase in moderate to severe food insecurity. If no climate action was taken, moderate or severe food insecurity would increase by 12.8 percentage points towards the end of the century – 10.9 percentage points higher than in the low-emission scenario compatible with temperatures below 2°C of heating. The highest increases in food insecurity due to future climate change are projected to be in Sierra Leone, Liberia, Central African Republic, and Somalia, countries that already face high levels of food insecurity.

In order to minimize the impacts of climate change on food security, policies that increase both the affordability and availability of food should be implemented, targeting the most vulnerable populations. This could involve expanding safety nets and investing in climate-smart agriculture and resilient food systems.
Even under the most ambitious climate mitigation scenario, the committed temperature increase will already lead to an increase in the health risks of climate change. The identification of vulnerable and at-risk populations, as well as the implementation of surveillance, early warning, and early response systems, can help prevent and manage the increased impacts of climate change on human health.

The data in this section exposes the exacerbated health risks of delaying climate change mitigation, and the substantial health benefits of meeting international climate commitments. Keeping global temperature rise within 1.5°C will result in reduced health impacts of climate change across all health dimensions monitored. On the contrary, a future scenario in which no climate action is taken will result in catastrophic impacts on health all around the world, undermining a liveable future for populations globally.

C. Economic: Macroeconomic Consequences of Climate Change

This section presents findings of statistical research into the economic consequences of climate change, specifically focusing on growth rates in national output (expressed as GDP), inflation, and interest rates.

The report finds that more volatile and decreasing GDP growth combined with heightened inflation and interest rates – approximated using the Taylor rule, a common approach used by central banks – will increase across all geographies. Climate change will make investments more costly as it is projected to increase interest rates globally. Investments are the engine of economic and social development, even more so in a context of climate change where more investments in mitigation and adaptation are required.

The rise in interest rates projected in this report could have numerous implications on low- to high-income economies. For example, higher interest rates, as observed in Ghana as a response to the floods that hit the country in 2015, will limit the ability of governments to swiftly rebuild their countries in the aftermath of climate-related disasters. Also, higher interest rates can limit a government's ability to invest in emissions reduction and adaptation as the fiscal space available for investment will shrink due to higher debt repayment and lower income on which taxes can be levied.

Reduced investments in mitigation, adaptation, or loss and damage resulting from climate change could trigger a downward spiral of accelerated climate change (due to limited mitigation investment) and higher vulnerability (limited investment in adaptation and capacity to rebuild) that will also lead to higher interest rates.

The best insurance to prevent this downward spiral is to keep the global mean temperature increase at if not below 1.5°C as it will have undisputable macroeconomic benefits for all countries. For all three indicators analyzed in the report, preventing an increase in global mean temperature by 0.5°C above 1.5°C will bring significant rewards.

- On average, missing the Paris Agreement's temperature objective and reaching 2.0°C would lead to more than doubling the negative consequences of climate change on incomes compared to those observed at 1.5°C. The global region most affected by these changes would be Australasia (+220% between these two warming levels), South America, and West

Africa (+190%).

- As evidenced by the analysis presented here, keeping the rise in global mean temperatures below 1.5°C would also reduce pressure on consumer prices and hence inflation across all nations. Inflation would be up to 66% higher for Northern Europe in a 2.0°C world compared to inflation measured at 1.5°C. The global regions that would most benefit from limiting global mean temperature increases are in middle- and high-income regions along with Northern Europe. Other regions would include North Asia and Russia (+58%) and Eastern Europe (+43%). As the analysis shows, high-income nations are not immune to the negative consequences of climate change.
- As interest rates are estimated using the Taylor rule, they respond to similar dynamics as GDP growth and inflation. Across all regions and countries, interest rates are projected to increase as a response to an increase in global mean temperature from 1.5°C to 2.0°C. For example, the European continent could face up to a 50% increase in interest rates between these two levels of warming, with Northern Europe being again the most sensitive to such increase in temperature with a 64% increase in interest rates from 1.5°C to 2.0°C.

Limiting the global mean temperature increase to below 1.5°C, in line with the objective of the Paris Agreement, is the only viable global economic objective. Even though it will lead to higher investments in mitigation, it will massively reduce the need for adaptation, and losses and damage, while dramatically reducing the negative impacts on income, inflation, and interest rates – making it the only viable and safe macroeconomic trajectory for the 21st century.

Hitherto, most studies investigating the consequences of climate change on economic development found that developed nations would be among the least affected, with some even benefiting from increasing temperatures induced by climate change (see for example: Burke, Hsiang, and Miguel 2015; Kalkuhl and Wenz 2020; OECD 2015). The new methodological approach implemented in this analysis does not find that countries with a currently low mean annual temperature will experience an increase in GDP per capita or more favourable price conditions thanks to climate change. Indeed, for Canada, Russia, Scandinavian countries, and Mongolia, the projections show significant reductions in GDP per capita and inflationary trajectories. These findings are confirmed by bottom-up economic studies at the country level (Sawyer et al. 2022) as well as econometric studies using novel approaches (Kahn et al. 2019).

The results of the macroeconomic analysis on GDP growth, and inflation and interest rates undoubtedly show the benefits of keeping global mean temperature below 1.5°C in line with the objective of the Paris Agreement. Also, the estimates available in the report are a clear call for action for high-income nations towards faster and more stringent mitigation actions as their economies are also projected to face negative consequences even at low levels of warming and would be the ones benefiting the most from not exceeding 1.5°C of global mean temperature increase.

D. Climate Risks and Vulnerability (Dimensions of Risk)

Evidence of Observed Socioeconomic Vulnerability

Climate impacts take place against a backdrop of trends in exposure and vulnerability driven by demographics, socioeconomic development, and ecosystem degradation. Major socioeconomic dimensions of vulnerability (Table 2) include economy, education, gender, health, infrastructure, governance, and demography (IPCC, 2014). A broad set of indicators has been developed for assessing the performance of regions on these dimensions. These dimensions are often interconnected, and increasingly are affected by and interact with biophysical climate impacts to contribute to climate risk. Evidence on currently observed socioeconomic vulnerability is provided below for: *Economic Growth and Poverty*; *Demography*; *Education and Health*; *Gender Inequality*; *Governance*; and *Access to Basic Infrastructure*. In addition, a composite index has been developed to provide an overall picture of the challenges relating to socioeconomic vulnerability that countries face.

A Global View of Multi-Dimensional Socioeconomic

Dimension	***Description***
Economy	The ability of economic actors such as households, companies or states, to cope with the occurrence of climate change events, as well as the damage and economic loss caused by such events (Birkmann, 2013)(Birkmann and UNU-EHS Expert Working Group on Measuring Vulnerability). This is measured with GDP per capita, which indicates the overall capacity of a country or region, and the Poverty Headcount at USD 3.20, which signals the presence of vulnerable households.
Education	Affects the risk of suffering negative consequences of climate change since a well-informed population will be more aware of the possible risks of and the best ways to respond to climate change events and therefore prepare better, suffer less negative impact and recover faster (Muttarak & Lutz, 2014; Cutter et al., 2003)(Muttarak and Lutz; Cutter et al.). This is measured by the mean years of schooling of the adult (25+) population.
Gender	Gender inequality is important as women and girls often are at greater risk of dying in disasters and less included in decision making about preparation, recovery and reconstruction (Eastin, 2018; Cutter et al., 2003; Sultana, 2021)(Eastin; Cutter et al.; Sultana). Gender inequality is measured by the Gender Development Index of the UNDP.
Health	The health status of the population and quality of the health systems, including hospital and laboratory infrastructures, affect vulnerability considerably (Ebi et al., 2021; Tong & Ebi, 2019)(Ebi et al.; Tong and Ebi). Specific groups, such as the (very) young and old, and people with underlying health conditions are particularly vulnerable to climate change events and in the aftermath of such events (Watts et al., 2021; Cardona et al., 2012; Helldén et al., 2021) (Watts et al.; Cardona et al.; Helldén et al.). The health dimension is measured by life expectancy at birth.
Infrastructure	Access to clean water, electricity and information are among the most important drivers of vulnerability to climate change. Clean drinking water is essential for preventing infectious diseases (Miola et al., 2015)(Institute for Environment and Sustainability (Joint Research Centre) et al.). Communication means such as mobile phones and internet may issue early warning signals, spread information about the situation and help coordinate post-event responses (Hansson et al., 2020; (Dujardin et al., 2020) (Hansson et al.; Dujardin et al.)
Governance	Good governance is essential for developing climate change resilience and improving countries' coping capacity (Andrijevic et al., 2020)(Andrijevic, Crespo Cuaresma, Muttarak, et al.). It makes it easier to develop strategies and implement policies for dealing with climate change (impacts) and to act in times of crisis. Governance is measured by the World Governance Indicator of the World Bank.
Demography	The demographic window of opportunity, characterized by a large working-age relative to dependent population, is associated with less vulnerability as response and reconstruction capacity is higher and size of vulnerable groups (young and old) smaller (Thomas et al., 2019; Crombach & Smits, 2021; Miola et al., 2015) (K. Thomas et al.; Crombach and Smits; Institute for Environment and Sustainability (Joint Research Centre) et al.). Urbanization is also important, as rapid and unplanned city development is often associated with slums and informal settlements on peripheral lands that are more at risk of climate-related events (Lavell et al., 2012; Son et al 2019)(Lavell et al.; Son et al.). The demographic dimension is measured by the Dependency Ratio (dependent population divided by working age population) and the percentage of the population living in urban areas.

Table 2. Socioeconomic dimensions of vulnerability

Vulnerability

While each of the outlined indicators affects vulnerability directly, it is often the combined effects of different vulnerabilities that have a major effect on a region's exposure to harm from climate impacts (see for example, the United Nations Development Programme's Multidimensional Vulnerability Index for SIDS,[16] and the Climate Vulnerability Index targeting world heritage properties).[17] The GDL Vulnerability Index (GVI) is a composite index that brings together these different facets of vulnerability into a composite indicator to provide a global picture of differential vulnerability across the world.

The GVI is an encompassing, flexible, and easy to use index that brings together information about 11 different aspects of vulnerability into a single number. The GVI scale runs from 0 to 100, with 0 being lowest vulnerability and 100 meaning highest vulnerability.

Figure 4 presents a map of the 2020 values of the GVI for 184 countries across the globe. Socioeconomic vulnerability, as indicated by the GVI, is lowest in Europe, North America, Australia, and the wealthier countries in East Asia. Vulnerability levels are somewhat higher, but still relatively low, in parts of Central and South America, followed by some East and Southeast Asian countries and a number of small-island states. Vulnerability levels are again higher in the Middle Eastern countries, Southern Africa, South Asia, and some Central American and Caribbean countries.

The countries with the highest levels of socioeconomic vulnerability are in sub-Saharan Africa, due to high vulnerability across several socioeconomic dimensions (Figure 5). These existing socioeconomic vulnerabilities interact with and exacerbate negative climate impacts, leading to overall higher climate risk.

Projections of Socioeconomic Vulnerability

Along with a changing climate, socioeconomic vulnerability will also change over the next decades and will strongly influence the overall climate risk that regions will face. Based on the two different scenarios underlying the assessments in this report, vulnerability diverges strongly under the two scenarios, underlining that sustainable development is not only essential to reduce climate impacts, but also contributes to the ability to respond.

Economic Growth and Population

The climate scenarios envision two drastically distinct pathways: one pathway, the SSP1 scenario, with a global population comparable to present-day conditions and high economic growth, and the second pathway, SSP3, with a high global population and low economic growth. The global population at the end of the 21st century is 7 billion people in an SSP1 scenario, and almost double at 12.6 billion people in an SSP3 scenario (Figure 6). World population growth is lower in an SSP1 scenario, peaking mid century and decreasing to recent historical figures, compared to an SSP3 scenario, which projects a consistent increase in population to the end of the 21st century.

There are stark differences in economic growth between the more sustainable SSP1 scenario and the challenging SSP3 scenario. An

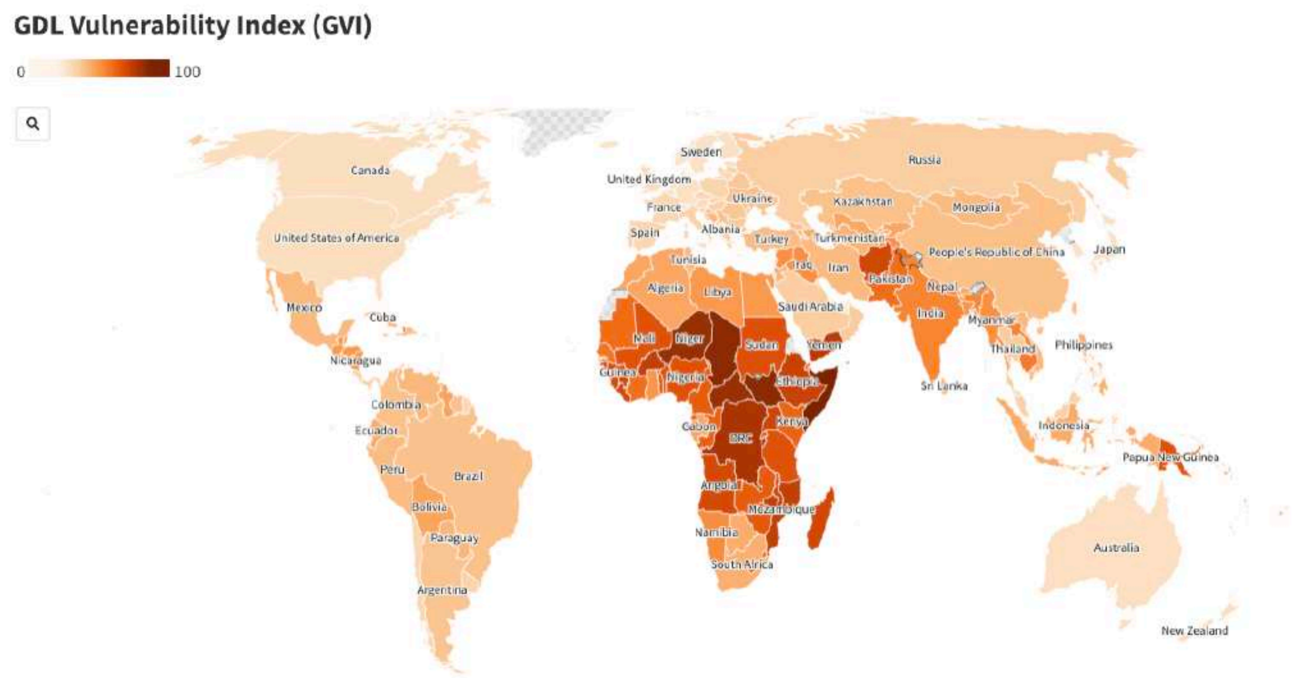


Figure 4: GDL Vulnerability Index (GVI)

SSP1 scenario is relatively optimistic in its economic outlook, and estimates rapid economic growth driven by a shift toward sustainable practices. This lower emissions scenario, with peak temperature rise below 2°C at the end of the century, projects double the global GDP of the higher emissions SSP3 scenario, which reaches 3.6°C by the end of the century. This increased wealth also lifts the world's poorest out of poverty: the number of people living in extreme poverty is significantly lower in a SSP1 scenario, at approximately 90 million people by the end of the 21st century, compared to 360 million people (four times as many) at the end of the century under an SSP3 scenario (Figure 6).

Education and Health

Projections of education and health differ strongly between the two scenarios: the more sustainable SSP1 scenario entails substantial investment in education and health, while the higher emissions SSP3 scenario is more pessimistic, with little investment in education and health in developing nations. These investments result in noticeably higher life expectancy for both men and women in the SSP1 scenario, as well as increases in mean years of schooling. In the near term, global median life expectancy is four years longer in an SSP1 scenario, compared to SSP3, increasing to approximately 20 years longer by the end of the 21st century. Mean years of schooling increases from over one year in the near term to almost five years by the end of the 21st century due to increased investment in the education sector in the SSP1 scenario compared to the SSP3 scenario (Figure 7).

Governance

Effective institutions have been shown to contribute positively to dealing with global challenges such as climate change. Conversely, weak governance is shown to be a key obstacle to sustainable development. A characteristic of the lower emissions SSP1 pathway is

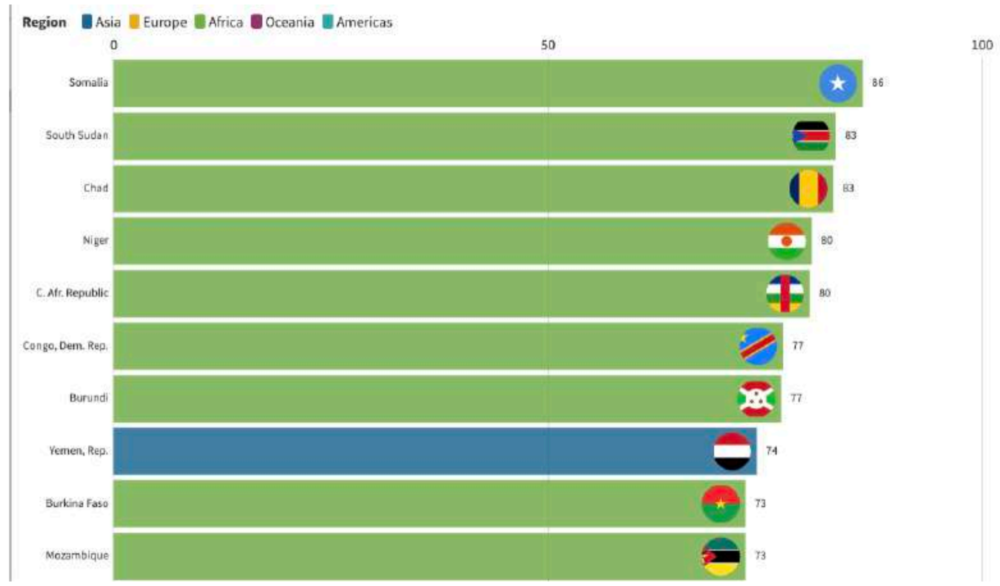


Figure 5: Countries with the highest socioeconomic vulnerability score (GVI score) for climate change impacts

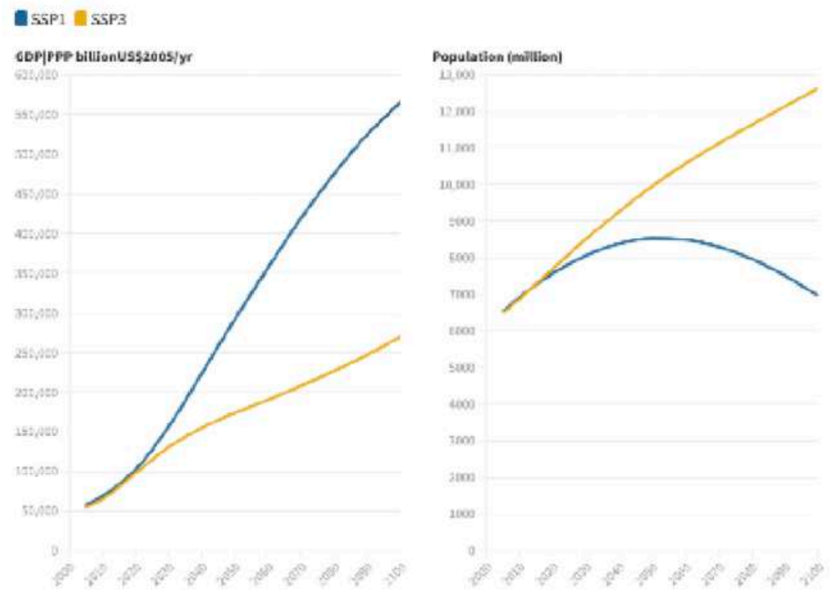


Figure 6: Economic and population growth under SSP 1 and SSP3 emissions scenarios. Source: Riahi et al., 2017 (Riahi et al.)

well-functioning institutions with improved management of the global commons. In contrast, the high emissions SSP3 scenario is characterized by ineffective governance and resurgent nationalism, with policies focused on national to regional issues, including regional conflicts. In this scenario, nationalist focus comes with low prioritization of environmental concerns at the expense of broader-based development.

Good governance is a key determinant in effectively leveraging private and public sector investment for adaptation actions. Projections show an increase in effective governance characterized by rising values toward SSP1 (fully effective governance) over the 21st century in a lower emissions SSP1 scenario (Figure 8). While developed nations see little difference between the lower and higher emissions scenarios, developing nations can see significant improvement in governance in the SSP1 scenario over the SSP3 scenario (Figure 8).

Gender Equality

Gender inequality, along with other social inequalities, compounds vulnerability to climate change impacts. The intersection of gender, power dynamics, socioeconomic structures, and societal expectations result in different climate impacts for women and girls. Gender inequality plays an important role in adaptive capacity, as gender inequality and discrimination are among the barriers to adaptation. Mitigation and adaptation responses to climate change influence inequalities such as gender inequality, poverty, and livelihood security and thereby aspects of climate justice. Narrowing gender gaps can play a transformative role in pursuing climate justice and achieving climate-resilient development.

Projections of gender inequality show noticeable disparities between countries within regions in the near term, with significant differences between climate scenarios arising by mid century and toward the end of the 21st century. In the near term, gender inequality is prevalent across countries and regions, with Africa and Asia having higher values of gender inequality than Europe and the Americas. By mid century, gender inequality is significantly reduced worldwide in an SSP1 scenario, most noticeably in Europe and the Americas, which exhibit rapid decreases in gender inequality toward the lowest gender inequality scores (Figure 9). Africa and Asia also see improvements in gender equality, though more moderate than in the Americas and Europe. By the end of the 21st century, gender inequality has declined significantly across the globe in the SSP1 scenario, with several countries in all regions overcoming barriers to gender inequality. In an SSP3 scenario, gender inequality persists across the globe, with very little improvement by mid century or by the end of the century. Wide disparities within regions remain, with several countries having high gender inequality values until the end of the century, and relatively few countries overcoming barriers to gender equality (Figure 9).

What Do We Know about Adaptation to Climate Change?

Climate change impacts are being felt today across every region and every sector, making adaptation an increasingly essential part of climate-resilient development (Schipper et al., 2022). Even with ambitious climate action to limit warming to 1.5°C, impacts will continue to increase from present-day levels and make adaptation an essential component of the response to the climate challenge and to building resilience, especially for the most vulnerable.

Climate adaptation refers to "adjustments in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts." These adjustments include changes in processes, practices, and structures, and can be incremental in a single

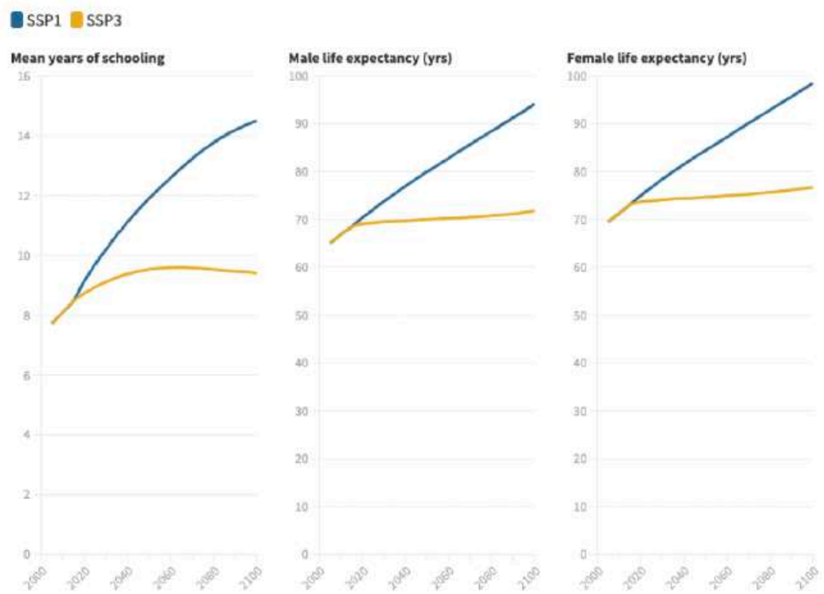


Figure 7: Education and health outlooks under SSP 1 and SSP3 emissions scenarios. Source: Lutz et al., 2017 (Kc and Lutz)

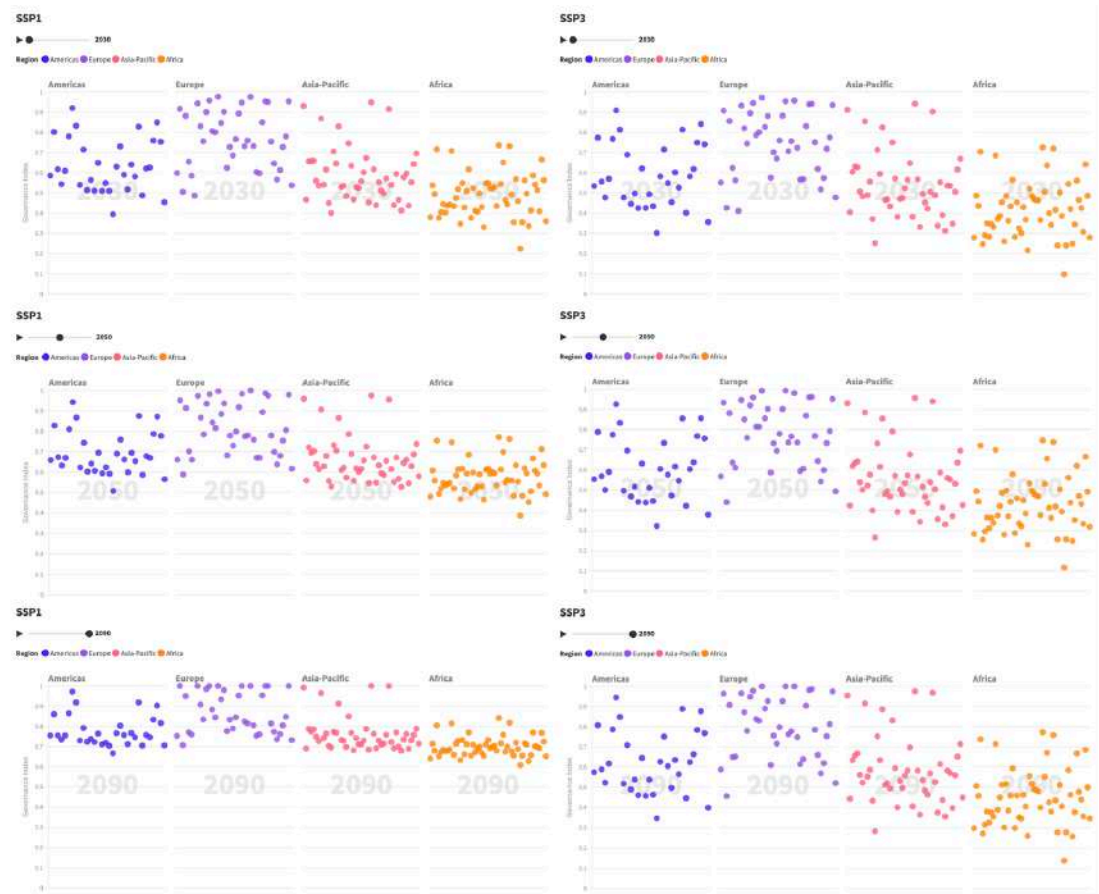


Figure 8: Governance outlook under SSP1 and SSP3 emissions scenarios. Source: Andrijevic et al., 2020 (Andrijevic, Crespo Cuaresma, Muttarak, et al.)

system or structure, or substantive over several structures and systems, known as transformational adaptation.[18]

In human systems, adaptation is defined as the process of adjustment to actual or expected climate and its effects, to moderate harm or exploit beneficial opportunities (Ara Begum et al., 2022). However, in natural systems, adaptation is the process of adjustment to actual climate and its effects, and this includes autonomous adjustments through ecological and evolutionary processes.

Adaptation action has increased over the last years in response to increasing climate impacts. However, current levels of adaptation are unequal to the scale of the challenge. Adaptation is also unequally distributed between world regions and sectors (IPCC, 2022a). Tracking adaptation progress and determining adaptation effectiveness are critical yet challenging tasks, due to the contextual nature of adaptation measures, the complexities of effectiveness at various scales and in different contexts, and the strong overlap of adaptation measures with development interventions. These challenges notwithstanding, the series of indicators on the current status of adaptation presented here provide an overview of the current state of adaptation in various sectors, the hazards being addressed, the types of adaptation responses considered, and the limits to adaptation, providing insight into adaptation effectiveness and action globally.

The Current State of Adaptation

Adaptation Occurs Unevenly Across Different Sectors

Sectors are adapting unevenly to climate change, with the majority of adaptation documented in the economic and infrastructure sectors. Adaptation in the areas of education, health, and environment, though important areas of climate impacts, are less documented (Figure 10).

Adaptation Responds to Different Climate Hazards

The majority of adaptation currently responds to water-related hazards such as extreme precipitation, precipitation variability, sea-level rise, and drought (Figure 10). Almost one third of documented adaptation responds to a combination of different hazards. While regionally specific literature on adaptation to sea-level rise is present in varying degrees in the Americas, Asia-Pacific, and Europe, there is little to no regionally specific literature on adaptation to sea-level rise for Africa.

Adaptation Response Types

To address the ways in which countries, regions, and communities adapt to climate change, adaptation response types are categorized into four broad categories, including behavioral or cultural responses; ecosystem-based adaptation; institutional responses; and technological or infrastructural measures.

In Africa and the Asia-Pacific region,

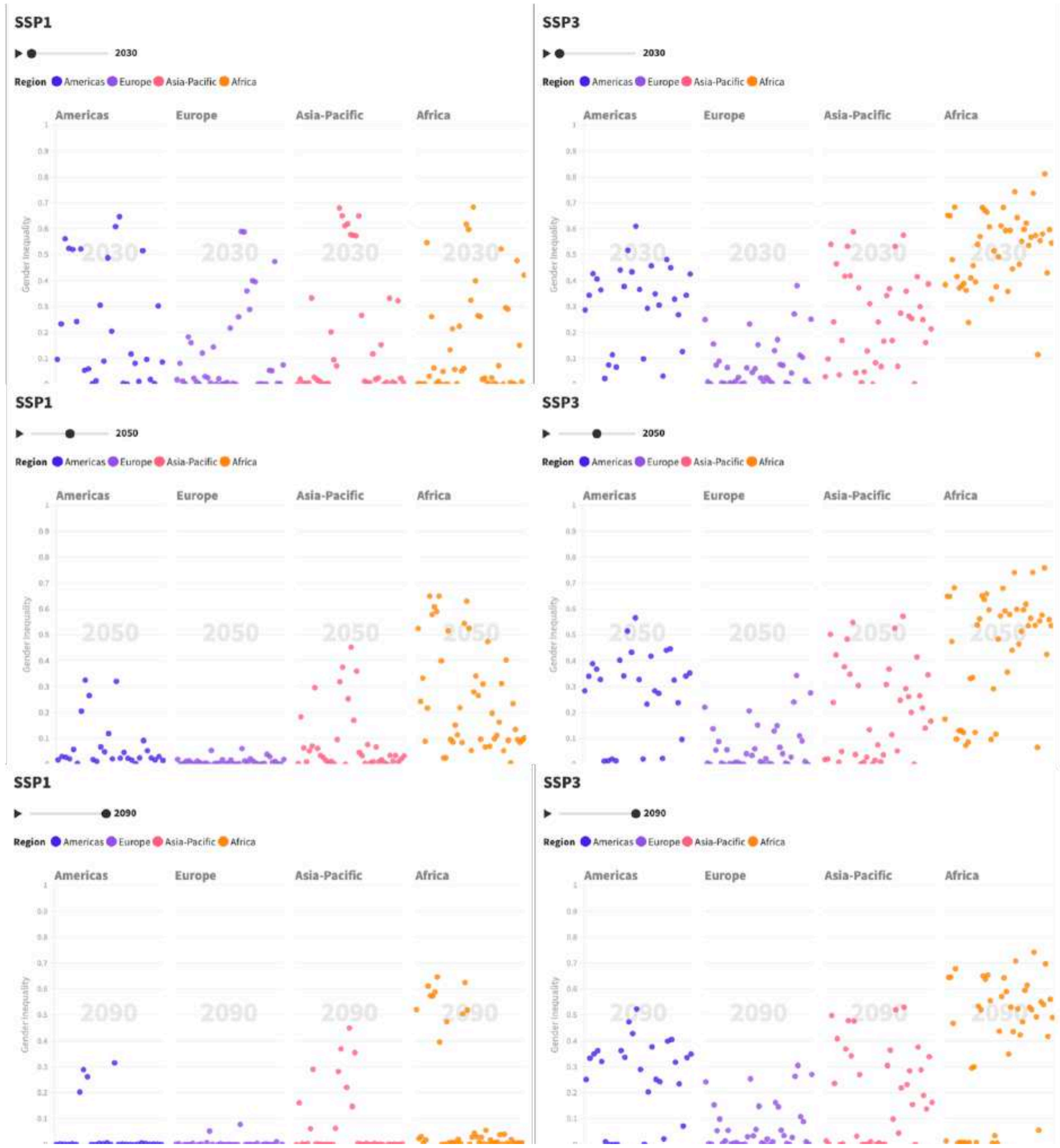


Figure 9: Gender equality outlook under SSP1 and SSP3 emissions scenarios. Source: Andrijevic et al., 2020 (Andrijevic, Crespo Cuaresma, Lissner, et al.)

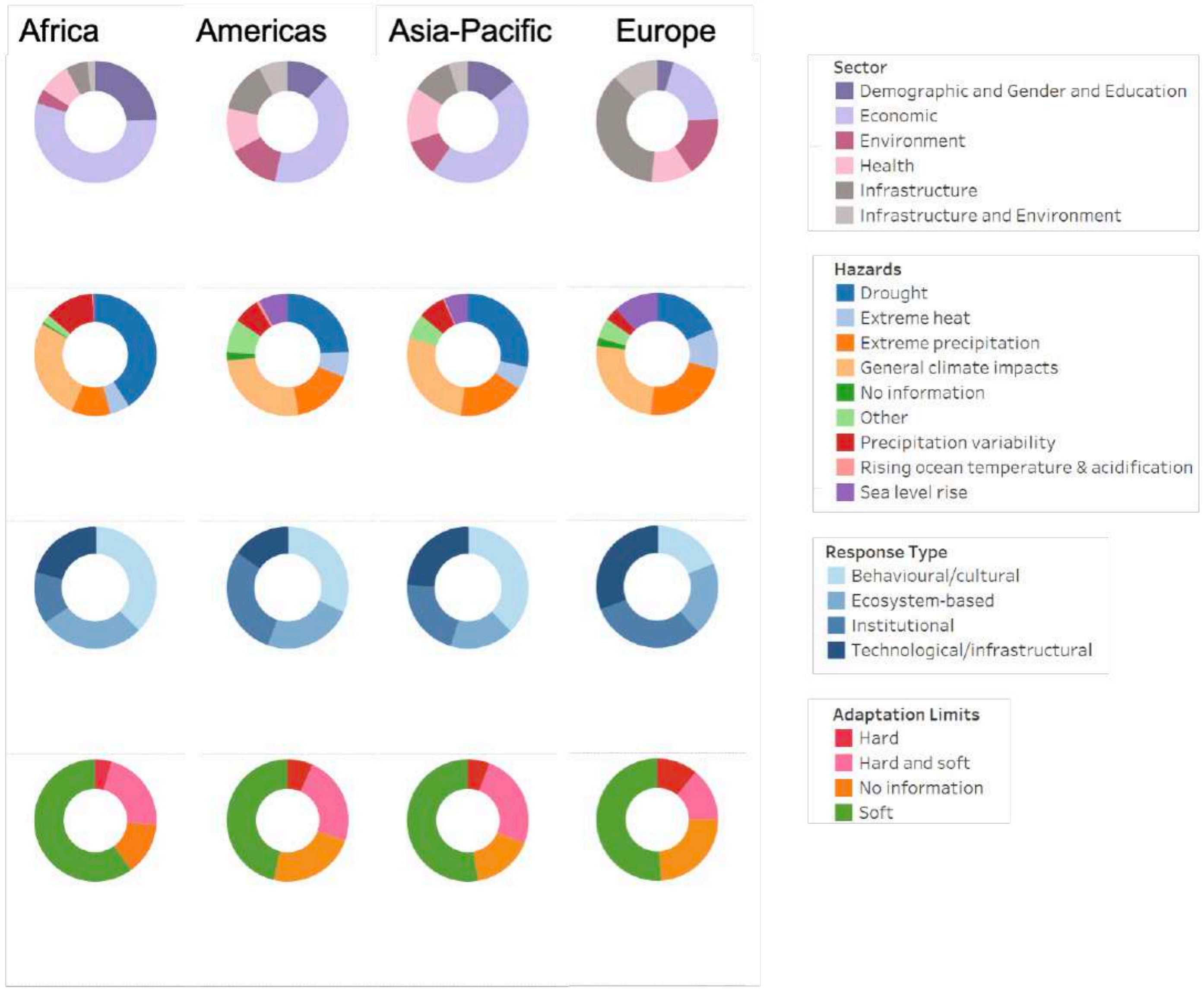


Figure 10: Scientific literature stocktake documenting the current state of adaptation in human and natural systems

behavioral/cultural adaptation methods account for the largest response types. In Europe, technological/ infrastructural adaptation responses were the most discussed in the scientific literature, in line with the sector that is most addressed in this region (Figure 10). Ecosystem-based adaptation has been gaining prominence in the adaptation community, and is reflected in the scientific literature, particularly in Africa and the Americas. Institutional adaptation responses are addressed relatively more frequently in the Americas and Europe, and less in Africa and the Asia-Pacific region.

Limits to Adaptation

The effectiveness of adaptation efforts depends on the constraints and limits that human and natural systems face when confronted with increasingly higher levels of climate risks. Adaptation limits refer to "the point at which system's needs cannot be secured from intolerable risks through adaptive actions. Adaptation limits can be soft, occurring when options may exist but are currently not available to avoid intolerable risks through adaptive actions. Adaptation limits can also be hard, and occur when no adaptive actions are possible to avoid intolerable risks" (Pörtner et al., 2022). Literature on limits to adaptation reveals that approximately half of literature at the regional level covers soft limits to adaptation, while there is limited evidence of hard limits being reached (Figure 10).

Biophysical

CLIMATE ANALYTICS

IV. Biophysical: Biophysical Impacts of Climate Change

A. Introduction

As is evidenced by the information presented in this Monitor report, every fraction of additional global warming is projected to have further adverse impacts on nature and people. Possible climate futures are estimated using emissions scenarios that drive climate model projections of change.

Physical climate system conditions, sometimes called climatic impact drivers (CIDs), are means, events, and extremes of the physical climate that are relevant to an element of society or an ecosystem. Information on changes in the physical climate and CIDs addresses how the physical climate has responded to greenhouse gas emissions at global, regional, and local scales. Climate impact research extends the value of these indicators by providing information on how these changes in the physical climate impact the human and natural sectors. In this section, information is provided on projections of 19 indicators describing the climatic conditions of *Temperature*, *Water*, and *Winds*, and sectoral impacts in *Agriculture* (Table 3). Further details on the indicators are provided in the Methodology. Median values for each indicator are provided for each continental region. The continental mean is computed using individual countries as opposed to geographical area, thus giving each country equal weight in the continental mean. National median values as well as ranges (13th and 87th percentiles) are provided through the CVM3 data explorer.

Temperature

Near-surface air temperature gives one of the clearest and most consistent signals of global and regional climate change. When both warmer and colder temperatures go above or below those norms rapidly, scientific evidence shows that natural and managed systems, such as biota and crop productivity, as well as human health and wellbeing, are negatively impacted by those extremes. Studies suggest that climate change will greatly increase the severity and frequency of extreme temperature conditions, leading to increases in temperature-related illness and death.

It is unequivocal that human influence has warmed the atmosphere, ocean, and land (IPCC, 2021b). The likely range of temperature increase from climate change is approximately 1.1°C relative to pre-industrial times. Greenhouse gas emissions from human activities are the main driver of warming.

Each of the last four decades has been successively warmer than the previous. Global surface temperature has risen faster since 1970 than any other period over the last 2,000 years. Hot extremes and heatwaves have become more frequent and more intense across the world, over land and in the ocean. In some cases, hot extremes occurred that would have been extremely unlikely without human-induced climate change. Marine heatwaves have doubled since the 1980s, and are projected to increase in frequency in the tropical ocean and Arctic with additional global

Temperature	Water	Winds	Agriculture
Daily maximum near-surface air temperature	Precipitation (Rainfall + snowfall)	Horizontal wind speed	Total soil moisture content
Daily minimum near-surface air temperature	Snow fall		Maize yields
Daily mean near-surface air temperature	Surface runoff		Rice yields (first growing period)
	Discharge		Rice yields (second growing period)
	Maximum of daily discharge		Soy yields
	Minimum of daily discharge		Winter wheat yields
	Drought Index		Spring wheat yields
	Extreme precipitation		

Table 3: Overview of all variables assessed with regard to biophysical impacts of climate change.

warming.

Water

The majority of climate impacts and consequent adaptation are related to water, including extremes, insufficient quality of water, or issues of accessibility through impacts on infrastructure. Water-related hazards drive most of the severe impacts that have been documented worldwide. Projections show increases in the duration, frequency, and intensity of many of the most severe water-related hazards as average temperatures have risen because of climate change, speeding up the Earth's water cycle through an increase in the rate of evaporation from soil and transpiration from plants.

Global average precipitation has likely increased since 1950 due to climate change (IPCC, 2020, IPCC 2021b). Global retreat of glaciers is attributable to climate change, along with the decrease in Arctic sea ice and melting of the Greenland and Antarctic ice sheets. The global mean sea level has risen faster since 1900 than in any preceding century in the last 3,000 years. It has risen by 0.20 m since the beginning of the 20th century, and has been rising faster since the 1970s.

Extremes in precipitation have also been affected by climate change. Heavy precipitation has become more frequent and more intense since the 1950s, and there has been an increase in droughts due to increased land evapotranspiration. It is likely that major tropical cyclones occur more frequently due to climate change, and human-induced climate change has increased heavy precipitation associated with tropical cyclones.

Winds

Changes in the speed and direction of prevailing winds can affect ecosystems and agricultural activities, such as altering the profile of seed dispersal and the distribution of pollen. Latest IPCC findings indicate that while mean near-surface winds over land have decreased within the last decades, the global proportion of major tropical cyclones (categories 3 to 5 of extreme winds) has increased over the last four decades. Intense tropical cyclones (categories 4 and 5) will increase as a proportion of all tropical cyclones, and peak winds of the most intense tropical cyclones are also projected to increase with increasing global warming (IPCC, 2021b). The proportion of intense tropical cyclonevs is projected to increase by 10% in a 1.5°C warmer world, by 13% in a 2°C warmer world, and by 20% in a 4°C warmer world.[19]

Agriculture

Climate change is anticipated to significantly impact the resilience of agricultural systems around the globe. While results shown here focus on crop yields and soil moisture content, agricultural resilience is impacted by several climate and no-climate factors, both local and global. Climate-related extremes have negatively affected the productivity of agricultural activities, increasingly hindering efforts to meet human needs. Human-induced global warming has slowed the growth of agricultural productivity over the past 50 years in mid and low latitudes. Methane emissions have negatively impacted crop yields by increasing temperatures and surface ozone concentrations (IPCC, 2022c). Warming is negatively affecting crop and grassland quality and harvest stability. Warming has altered the distribution, growing area suitability, and timing of key biological events, such as flowering and insect emergence, impacting food quality and harvest stability. At higher latitudes, warming has expanded the available area but has also altered phenology, potentially causing plant–pollinator and pest mismatches. At low latitudes, temperatures have crossed upper tolerance thresholds, more frequently leading to heat stress and/or shifts in distribution and losses for crop yields. The frequency of sudden food production losses has increased since at least the mid-20th century and the impacts of climate-related extremes on food security, nutrition, and livelihoods are particularly acute and severe for people living in Sub-Saharan Africa, Asia, small islands, Central and South America, and the Arctic. Local food production and consumption, while quite relevant for local markets, were beyond the scope of analysis for this report.

B. Climate and Impact Models

All the biophysical indicators presented in this report are meant to provide information on projected changes for the end-of-century no climate action scenario (SSP370) and the below 2°C (SSP126) scenario. The information is derived from an ensemble of climate and climate impact models (IMs) used in the latest Intersectoral Impact Model Intercomparison Project 3 (ISIMIP3).[20] All those IMs are forced with the latest generations of five global climate models (GCMs) from the Coupled Model Intercomparison 6 (CMIP6) initiative.

For both of the above scenarios, the time series is divided into following time slices:

- Baseline (1995–2014)
- Near term (2021–2040)
- Mid term (2041–2060)
- Long term (2081–2100).

ISIMIP3 does not have a 1.5°C-compatible scenario; therefore, a 1.5°C-compatible scenario is estimated by assuming that the temperatures stay at approximately 1.5°C throughout the century. The near-term time slice out of SSP126, which reaches 1.5°C by 2030, is thus also used to represent the medium- and long-term projections for the 1.5°C assessment. The IPCC has assessed many more pathways in its Working Group III report on mitigation, which shows that accelerated action to reduce emissions and energy demand in the next 10 years can hold temperature rise to 1.5°C with low or no overshoot this century.

C. Results

1. Temperature

a. Mean Near-Surface Air Temperature

Theoretical Background

Climate change and its magnitude is commonly measured using the mean temperature of the planet. Further, mean daily temperatures determine the climate condition humans, animals, and plants are exposed to on local and regional scales. The indicator assesses changes to the average, or mean, near-surface air temperature, which is a key factor in a wide range of applications and is used in various disciplines for assessment; for example, the suitability of specific crop types in the agricultural sector.

Indicator Methodology

The daily near-surface mean air temperature is measured in Kelvin (K) and provided globally with a resolution of 0.5°x0.5°. The data used for this variable has undergone a ISIMIP3 bias-adjustment procedure to correct for deviations between modeled and observed values over the time period where they overlap. The results are presented for this variable as absolute differences in °C for each future time period compared with the baseline period of 1995–2014.

Key Findings

The results are given in changes in degree relative to mean surface temperature in the baseline (1995–2014). Since pre-industrial times (1850–1900) and up until the baseline, global mean surface temperature has already increased by 1.1°C and is projected to further increase under any scenario. Projected changes show high variability, especially for the mid and long term, but overall only temperature increases are projected for all scenarios, timeframes, and countries (Figure 11). For all scenarios and timeframes, more extreme increases in temperature are projected for the northern hemisphere.

In a 1.5°C scenario, mean near-surface air temperature is projected to increase by an additional 0.74°C in Africa, 0.63°C in the Americas, 0.75°C in Asia-Pacific, and 0.82°C in Europe relative to the baseline. Stabilized temperatures at 1.5°C would greatly reduce risks posed by extreme heat compared to both other scenarios assessed.

In the near term (2030), mean near-surface air temperature is projected to increase relative to the baseline by an additional 0.74°C in Africa, 0.63°C in the Americas, 0.75°C in Asia-Pacific, and 0.82°C in Europe for a 2.0°C scenario and by 0.78°C, 0.68°C, 0.76°C, and 0.92°C, respectively, for the no climate action scenario.

In the medium term (2050), mean near-surface air temperature is projected to increase relative to the baseline by an additional 1.03°C in Africa, 0.88°C in the Americas, 1.08°C in Asia-Pacific, and 1.20°C in Europe for a 2.0°C scenario and by 1.61°C, 1.34°C, 1.49°C, and 1.68°C, respectively, for the no climate

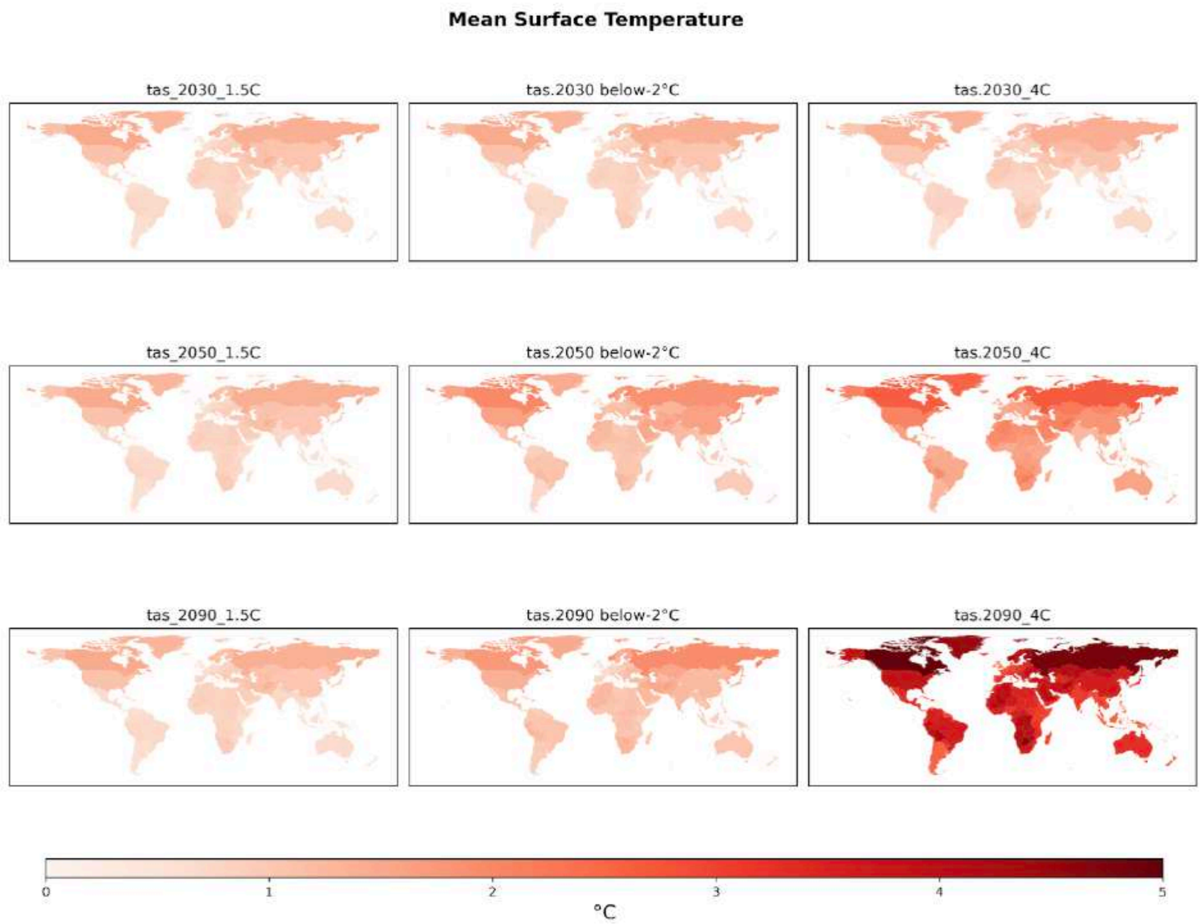


Figure 11: Mean near-surface air temperature at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle), and end-of-the-century no climate action scenario (SSP 370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

action scenario.

In the long term (2090), mean near-surface air temperature is projected to increase relative to the baseline by an additional 1.05°C in Africa, by 0.90°C in the Americas, 1.05°C in Asia-Pacific, and 0.98°C in Europe for a 2.0°C scenario, and by 3.41°C, 2.77°C, 2.95°C, and 3.31°C, respectively, for the no climate action scenario.

b. Maximum Near-Surface Air Temperature

Theoretical Background

The daily maximum near-surface air temperature is defined as the peak air temperature reached in a day and influenced by natural factors such as solar radiation, cloud cover, and wind, most commonly occurring during the day.[21]

Compared to mean surface temperature, this indicator helps to comprehend the increase in extreme events such as heatwaves. Observations show warming trends in temperature extremes over land within the past decades (*IPCC, 2021b*). Even small increases in maximum temperature may have impacts on ecosystems and, for example, the species distribution. Extreme high temperatures affect ecosystems and agriculture as high temperatures across certain thresholds can limit growth and lead to failure of crops, decreasing agricultural yields and causing substantial economic losses. Hot extremes pose a risk to infrastructure, as extreme temperatures may lead to damage to roads and train tracks and, moreover, trigger blackouts due to high cooling demand.

The number of days with maximum temperature above a threshold can be critical for human health and wellbeing, whereas the individual risk is highly dependent on geographic location and socioeconomic factors. Urban and poor populations are more exposed due to urban heat-island effects and lack of air conditioning. Therefore, the daily maximum temperature is also relevant to assess losses in labor productivity due to climate change, which can be an important factor for economic output and growth.

Indicator Methodology

Daily maximum air temperature is defined as the peak air temperature reached in a day is measured in Kelvin (K) and provided globally with a resolution of 0.5°x0.5°. The data used for this variable has undergone a ISIMIP3 bias-adjustment procedure to correct for deviations between modeled and observed values over the time period where they overlap. The results are presented for this variable as absolute differences for each future time period from the baseline period of 1995–2014.

Key Findings

The results are given in changes in degree relative to mean maximum surface temperature in the baseline (1995–2014). Projected changes show high variability, especially in the long term (2090) for the Conflicts and Challenges scenario (Figure 12). Overall, only temperature increases are projected for all scenarios, timeframes, and countries.

In a 1.5°C scenario, mean maximum surface air temperature is projected to increase relative to the baseline by an additional 0.75°C in Africa, by 0.65°C in the Americas, by 0.77°C in Asia-Pacific, and by 0.92°C in Europe. Stabilized temperatures at 1.5°C would greatly reduce risks posed by extreme heat compared to both other scenarios assessed.

In the near term (2030), mean maximum surface air temperature is projected to increase relative to the baseline by 0.75°C in Africa, by 0.65°C in the Americas, 0.77°C in Asia-Pacific, and 0.92°C in Europe for a 2.0°C scenario and by 0.74°C, 0.70°C, 0.74°C, and 1.01°C, respectively, for the no climate action scenario.

In the medium term (2050), mean maximum surface air temperature is projected to increase relative to the baseline by an additional 1.02°C in Africa, 0.91°C in the Americas, 1.07°C in Asia-Pacific, and 1.33°C in Europe for a 2.0°C scenario and by 1.57°C, 1.39°C, 1.48°C, and 1.77°C, respectively, for the no climate action scenario.

In the long term (2090), mean maximum surface air temperature is projected to increase relative to the baseline by an additional 1.06°C in Africa, 0.93°C in the Americas, 1.08°C in Asia-Pacific, and 1.05°C in Europe for a 2.0°C scenario and by 3.4°C, 2.92°C, 3.01°C, and 3.52°C, respectively, for the no climate action scenario.

c. Daily Minimum Near-Surface Air Temperature

Theoretical Background

Daily minimum near-surface air temperature is defined as the lowest air temperature reached in a day, in this case at 2 meters above the ground. The indicator describes the lowest temperature recorded per day, mostly occurring at night time. Compared to mean temperature, minimum temperature can be indicative of and helps to comprehend the increase in extreme events (for example, night time heat). Increases in minimum temperatures will have a variety of impacts, for example, warmer night temperatures can increase heat stress in livestock and affect crop growth.

Indicator Methodology

The daily minimum near-surface air temperature is measured in Kelvin (K) and provided globally with a resolution of 0.5°x0.5°. The data used for this variable has undergone a ISIMIP3 bias-adjustment procedure to correct for deviations between modeled and observed values over the time period where they overlap. The results are presented for this variable as absolute differences for each future time period from the baseline period of 1995–2014.

Key Findings

The results are given in changes in degree relative to daily minimum near-surface air temperature in the baseline (1995–2014). Projected changes show high variability, especially in the long term (2090) for the no climate action scenario (Figure 13). Overall, only temperature increases are projected for all scenarios, timeframes, and countries and no temperature reductions.

In a 1.5°C scenario, daily minimum near-surface air temperature is projected to increase relative to the baseline by an additional 0.77°C in Africa, 0.61°C in the Americas, 0.75°C in Asia-Pacific, and 0.75 °C in Europe.

In the near term (2030), daily minimum surface air temperature is projected to increase relative to the baseline by an additional 0.77°C in Africa, 0.61°C in the Americas, 0.75°C in Asia-Pacific, and 0.75°C in Europe

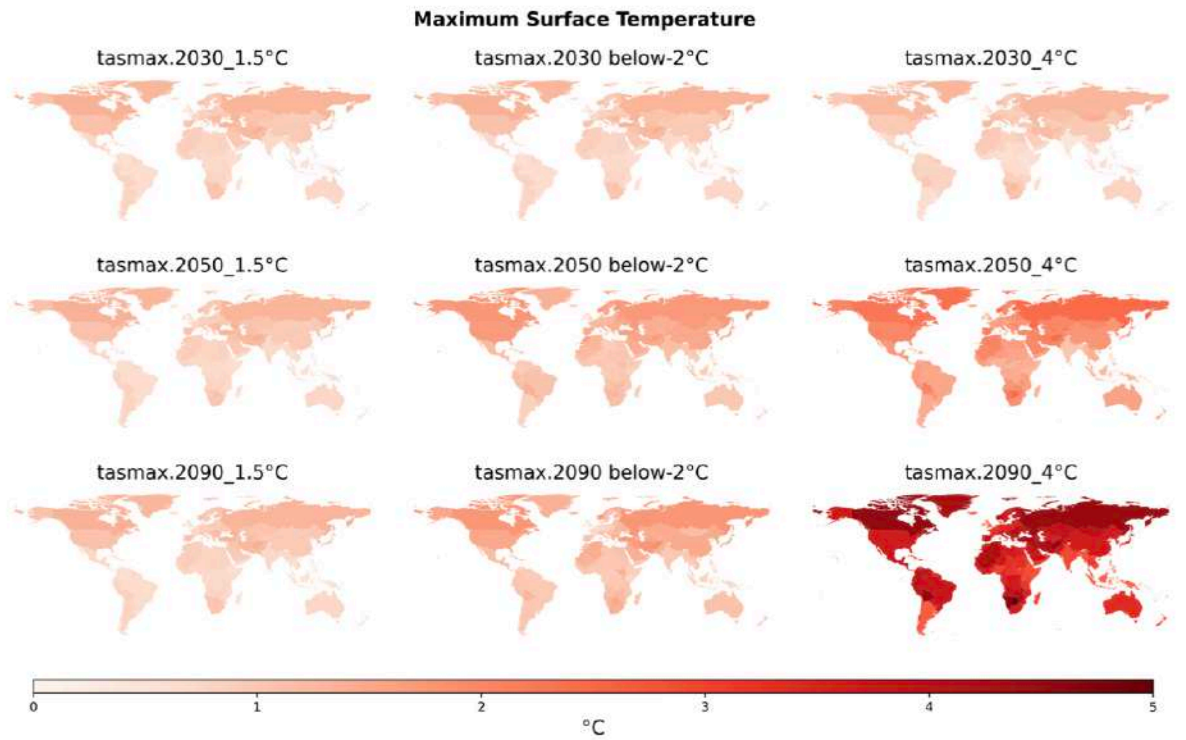


Figure 12: Maximum near-surface air temperature at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle), and end-of-the-century no climate action scenario (SSP370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

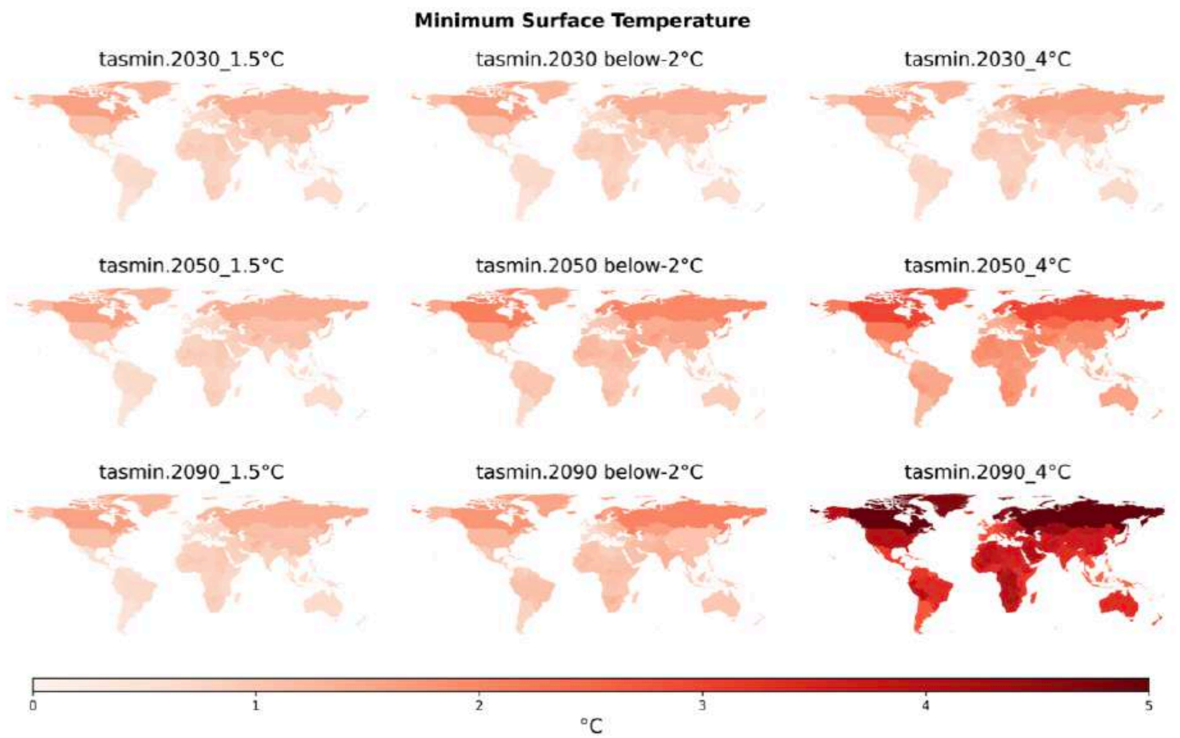


Figure 13: Daily minimum near-surface air temperature at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle), and end-of-the-century no climate action scenario (SSP370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

for a 2.0°C scenario and by 0.83°C, 0.67°C, 0.80°C, and 0.87°C, respectively, for the no climate action scenario.

In the medium term (2050), daily minimum near-surface air temperature is projected to increase relative to the baseline by an additional 1.04°C in Africa, 0.86°C in the Americas, 1.08°C in Asia-Pacific, and 1.13°C in Europe for a 2.0°C scenario and by 1.65°C, 1.33°C, 1.51°C, and 1.66°C, respectively, for the no climate action scenario.

In the long term (2090), daily minimum near-surface air temperature is projected to increase relative to the baseline by an additional 1.06°C in Africa, 0.86°C in the Americas, 1.00°C in Asia-Pacific, and 0.99°C in Europe for a 2.0°C scenario and by 3.47°C, 2.70°C, 3.02°C, and 3.32°C, respectively, for the no climate action scenario.

2. Water

a. Precipitation (rainfall+snowfall)

Theoretical Background

Precipitation is defined as the mass of water (both rainfall and snowfall) falling on the Earth's surface, per unit area, and time. Precipitation plays an important role in all environmental systems and social sectors, including agriculture, natural ecosystems, water supply, energy production, and tourism. Changes in global circulation patterns (synoptic atmospheric circulation) play a crucial role in the observed changes in precipitation (Fleig et al., 2014). Latest findings by the IPCC conclude that the globally averaged precipitation over land has likely increased since 1950 and in addition, people worldwide are increasingly experiencing unfamiliar precipitation patterns, including extreme precipitation events and droughts (Caretta et al., 2022).

Indicator Methodology

Data used for this indicator consists of monthly values for rainfall and snowfall data, in which precipitation (rainfall + snowfall = total precipitation) per 0.5° x 0.5° global grid resolution is measured in the unit of kilograms per square meter ($kg/m^2 s^{-1}$). The data used for this variable has undergone a ISIMIP3 bias-adjustment procedure to correct for deviations between modeled and observed values over the time period where they overlap. The results are presented for this variable as percentage differences for each future time period from baseline period of 1995–2014.

Key Findings

The results are given as changes in precipitation in % relative to the baseline (1995–2014). The range of projections is quite wide – ranging from negative values indicating decreased future precipitation to positive values projecting increased precipitation – for every continent and also for several countries. These opposing results are generated by the significant variability contained within underlying model results (Figure 14).

In a 1.5°C scenario, projected median changes range from -7 to +25% for Africa, -4 to +13% for the Americas, -6 to +33% for Asia-Pacific, and from -5 to +5% for Europe.

In the short term (2030), projected median changes range from -7 to +25% for Africa, -4 to +13% for the Americas, -6 to +33% for Asia-Pacific, and from -5 to +5% for Europe in the below 2°C scenario, and projected changes in the no climate action scenario range from -10 to +31%, -7 to +11%, -5 to +32%, and -12 to +8%, respectively.

In the medium term (2050), projected median changes range from -10 to +30% for Africa, -4 to +12% for the Americas, -10 to +28% for Asia-Pacific, -14 to +7% for Europe

Country Spotlight: Saint Lucia

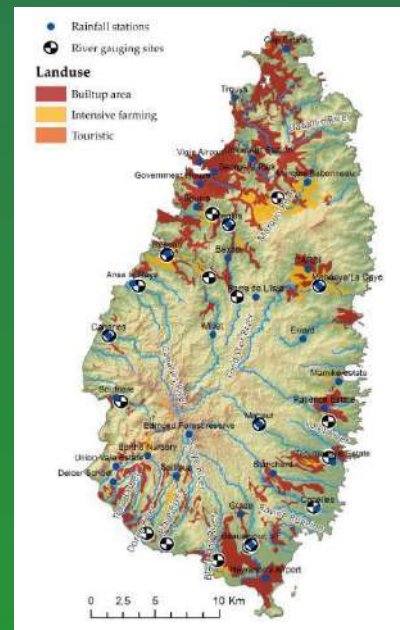
Situated in the eastern Caribbean Sea, Saint Lucia is an independent island nation of diverse geography. The island is of volcanic origin and while its northern region is shaped by eroded ridges and broad flat valleys, the central and south regions are formed of steep valleys and mountain peaks. A range of rainforests, dry forest, scrub, and mangroves shape the country's vegetation. The climate is tropical but moderated by northeast trade winds, with seasons typically shaped by a dry period from December to May and a rainy period from June to November. The island receives an average of 2000 mm annual precipitation, unevenly distributed across the two seasons. Tropical storms and hurricanes are a threat to the island from June to November.

The majority of the 184,401 (World Bank, 2021) inhabitants reside in rural towns and villages along the coastal areas. Approximately one fifth of the island's population lives in urban settings. The northwest of the island is more densely populated, and includes the capital Castries. The tourism industry contributes ca. 65% to Saint Lucia's GDP and accounts for the majority of the country's workforce (CIA, 2019). In recent years, a financial services industry has developed on the island, while agricultural production (bananas, mangoes, avocados) has declined and now only contributes just under 3% to the total GDP. 99.4 % of the urban population has access to drinking water, while 98.5% of the rural population has access to drinking water.

The geological conditions and the topography of the island make precipitation the primary source of fresh water, and rainfall runoff discharges into the ocean radially from the centre of the island to the ocean. Municipal freshwater supply is almost exclusively provided through overland rivers, stemming from one of the seven main inland watersheds (Figure 15). The northern half of the island is serviced by a dam that contributes to the stability of the water supply of the densely populated region and its tourism and commercial areas. However, the water supply is increasingly put under pressure by the expanding tourism industry as cruise ships mainly arrive during the dry season, thus causing a significant increase in water consumption. In addition, prioritization of hotels for limited water supply has led to residents outside the sphere of tourism experiencing more frequent water disruptions. Residents in the southern half of the island are more frequently exposed to water disruptions as the water supply is serviced through direct water intakes from watersheds, making it more reliant on rainfall. In addition, lack of access to pipe-borne water remains a challenge in parts of the island and in particular for poor and rural communities due to their relatively high reliance on rivers and streams for water supply. Attempts to mitigate disruption effects and increasing pressure on Saint Lucia's water supply include rainwater harvesting at the household level, as well as household storage of municipal water in tanks.

Saint Lucia in particular and the Caribbean more generally are projected to experience hotter, more arid climates in the future due to human-induced climate change, thus reducing water availability in rivers and streams. Climate projections of precipitation show a decrease in Saint Lucia's average precipitation, becoming more noticeable in the second half of the 21st century (Figure 16). For the near term (2030), the country is projected to experience a median decrease of 5% under a high warming scenario, while relatively no change is estimated in a below 2°C scenario.

By the mid century (2050), the difference between a higher emissions scenario and a lower emissions scenario becomes more apparent, with a 21% projected decrease in precipitation under a high warming scenario. Keeping global warming below 2°C would restrict precipitation decreases on the island to 4% by mid century. By the end of the 21st century (2090), both scenarios show noticeable decreases in precipitation, from 15% in a below 2°C scenario to 48% reduction in a high warming scenario. These long-term projections exceed the estimated precipitation changes under a 1.5°C scenario, in which there is relatively no change in precipitation by the end of the century. The decrease in precipitation and related river discharge will affect water availability and increasingly put groups at risk that are already vulnerable to climate change. In particular, residents in the southern half of the island and poor residents of rural communities who heavily rely on discharge from rivers and streams will increasingly be at risk of water shortages.



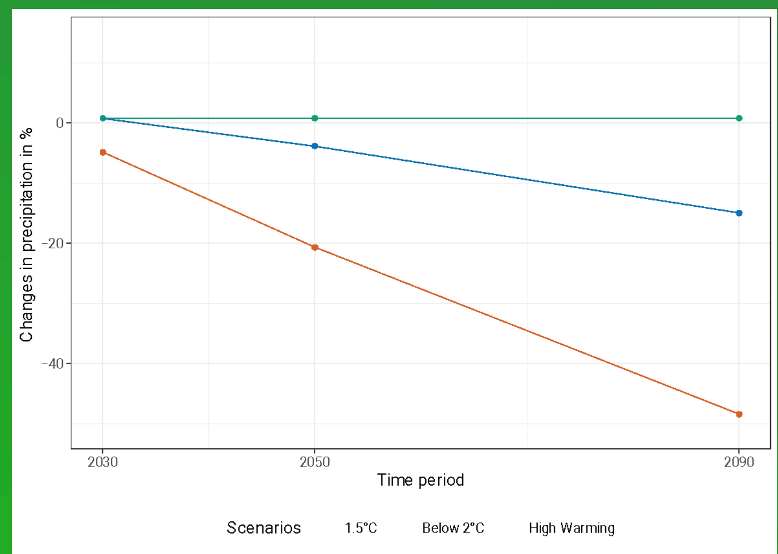


Figure 2: CVM3 precipitation projection for Saint Lucia. Changes in % are given relative to the baseline (1995–2014).

in the below 2°C scenario, and projected changes in the no climate action scenario range from -14 to +36%, -19 to +16%, -8 to +33%, and -13 to +9%, respectively.

In the long term (2090), projected median changes range from -13 to +19% for Africa, -15 to +10% for the Americas, -10 to +31% for Asia-Pacific, and from -9 to +8% for Europe in the below 2°C scenario, and projected changes in the no climate action scenario range from -40 to +69%, -47 to +29%, -17 to +79%, and -24 to +15%, respectively.

The results illustrate clearly the additional challenges posed by climate change for water management, with the increasing model range posing severe challenges not only from an impacts point of view, but also in terms of uncertainty for planning. Limiting warming to 1.5°C not only reduces the potential impacts substantially, but also provides more clarity for planning responses.

b. Snowfall

Theoretical Background

Snowfall is defined as the mass of water falling on the Earth's surface in the form of snow, per unit area and time. Snowfall is an important component of precipitation in high-latitude and mountain watersheds and contributes to building up glacier mass, acting as a protective cover for glaciers. Many people depend on snowmelt water for their water supply and many communities economically rely on snow for winter recreation activities. In addition, certain animals and vegetation depend on snow and snowmelt.

Climate change–induced warming has already led to a significant decrease in snowfall over the last decades on the global scale as precipitation increasingly falls in the form of rain instead of snow, although snowfall trends vary by region. In the northern hemisphere, significant reductions in annual mean potential snowfall areas by 0.52 million km2 per decade have been observed. Findings of the IPCC's fifth assessment report show that an increase in high-latitude precipitation may lead to an increase in snowfall in the coldest regions and a decrease in snowfall in warmer regions due to a decreased number of freezing days (*IPCC, 2014*).

Reduced snowfall negatively impacts the balance of the glacier mass and accelerates melting. For people whose livelihoods depend on glacier melt for the water supply – for example, for irrigation – changes in snow regimes can have severe impacts (Qin et al., 2020), with potential limits to adaptation at higher level warming (Caretta, Mukherji et al., 2022). Moreover, changes in timing and the amount of snowfall impose negative impacts on fish spawning in spring and water availability in spring and summer.

Indicator Methodology

Data for this indicator consists of monthly values and is measured in kilograms per square meter per second ($kg\ m^2\ s^{-1}$) with a global grid resolution of 0.5° x 0.5°. The data used for this variable has undergone a ISIMIP3 bias-adjustment procedure to correct for deviations between modeled and observed values over the time period where they overlap. The results are presented as absolute differences for each future time period from the baseline period of 1995–2014. It is well established that climate models as well as re-analysis datasets have a tendency to show spurious precipitation, which results in snowfall over the countries where it does not snow. Hence, a mask has been applied over the grid boxes where it snows less than 0.2 mm/day according to Boisvert et al. (Boisvert et al. 2020).

Key Findings

The results are given as changes in snowfall in % relative to the baseline (1995–2014) (Figure 15).

In a 1.5°C scenario, snowfall is projected to change relative to the baseline by -5% in Africa, by -5% in the Americas, -5% in Asia-Pacific, and -4% in Europe.

In the near term (2030), snowfall is projected to change relative to the baseline by -5% in Africa, by -5% in the Americas, -5% in Asia-Pacific, and -4% in Europe for a below 2.0°C scenario, and by -6%, -4%, -5%, and -6%, respectively, for the no climate action scenario.

In the medium term (2050), snowfall is projected to change relative to the baseline by -15% in Africa, by -3% in the Americas, -5% in Asia-Pacific, and -7% in Europe for a below 2.0°C scenario, and by -19%, -9%, -8%, and -10%, respectively, for the no climate action scenario.

In the long term (2090), snowfall is projected to change relative to the baseline by
-15% in Africa, by -4% in the Americas, -5% in Asia-Pacific, and -7% in Europe for a below 2.0°C scenario, and by -28%, -17%, -18%, and -25%, respectively, for the no climate action scenario.

c. Surface Runoff

Theoretical Background

Surface runoff is defined as the flow of water over the surface, which typically originates from the part of liquid precipitation and/or snow/ice melt that does not evaporate, transpire, or refreeze, and returns to water bodies (IPCC AR6 WG2, Ch 2, Ch 4). Surface runoff is a highly non-linear process, depending for instance on rainfall intensity, soil infiltration capacity, vertical profile of soil moisture, and water table depth. Hydroclimate variables like surface runoff are influenced by climate change via changes in precipitation, glacier runoff, and snowmelt. As a result, less frequent but more intense rainfall will increase the proportion of rainfall leading to surface runoff and potentially intensify severe flooding. In addition, increased sealing of soil as part of the urbanisation process, as well as deforestation, reduces permeability of the surface, leading to an increased surface runoff, adding to erosion and flooding.

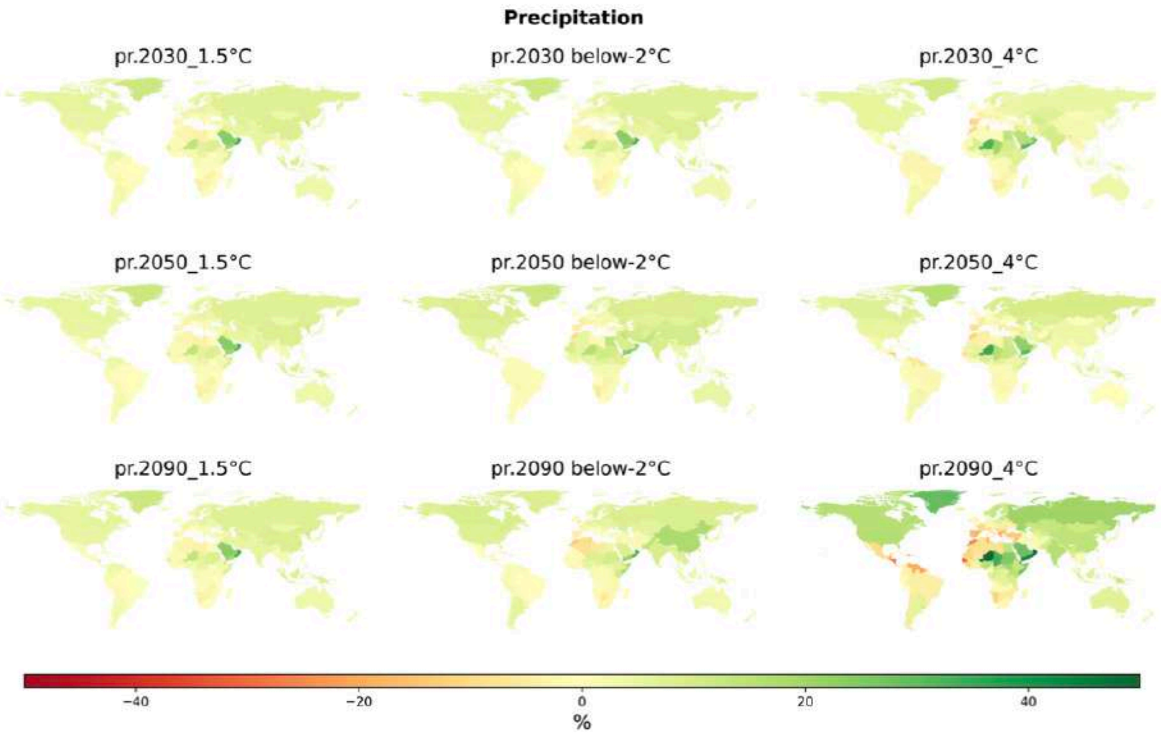


Figure 14: Daily mean precipitation at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle) and end-of-the-century no climate action scenario (SSP 370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

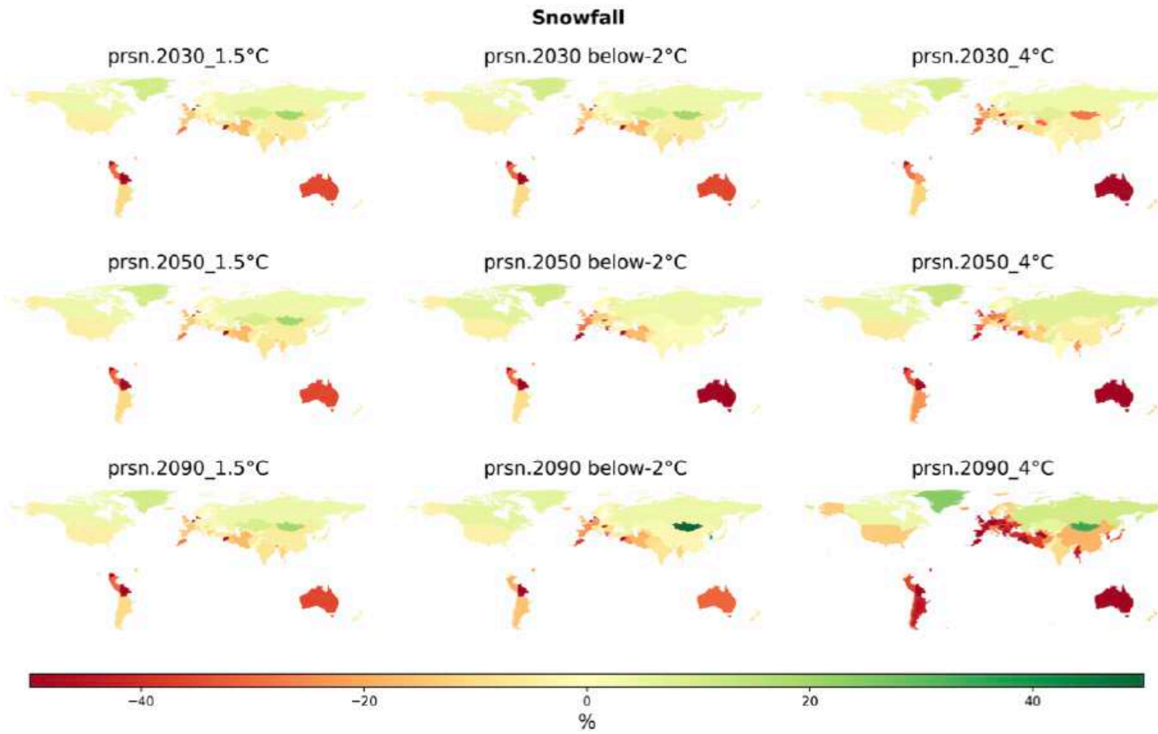


Figure 15: Snowfall at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle), and end-of-the-century no climate action scenario (SSP370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

Indicator Methodology

Data assessed for surface runoff consists of monthly values measured in kilogram per square meter ($kg\ m^2\ s^{-1}$) with a global grid resolution of 0.5° x 0.5°. The data used for this variable has undergone a ISIMIP3 bias-adjustment procedure to correct for deviations between modeled and observed values over the time period where they overlap. The results are presented for this variable as absolute differences for each future time period from the baseline period of 1995–2014.

It is important to note here that the following results were obtained with established land surface or hydrological models, which nevertheless depict a simplified, hence imperfect, representation of the evolution of surface runoff under climate change. They were forced with a limited number of climate model simulations; therefore, despite efforts to account for this while pre-processing the data, short-term fluctuations can reflect the influence of natural climate variability rather than the response to anthropogenic climate change. Confidence in the results decreases for high warming levels, which have been attained in a smaller number of the climate model simulations underlying these results.

Key Findings

The results are given as changes in surface runoff in % relative to the baseline (1995–2014). The range of projections is quite wide across all countries, timeframes, and scenarios, indicating significant variability within model results (Figure 16).

In a 1.5°C scenario, surface runoff is projected to change relative to the baseline by +3% in Africa, by +4% in the Americas, +6% in Asia-Pacific, and +1% in Europe.

In the near term (2030), surface runoff is projected to change relative to the baseline by +3% in Africa, by +4% in the Americas, +6% in Asia-Pacific, and +1% in Europe for a below 2.0°C scenario, and by +5%, -1%, +3%, and -4%, respectively, for the no climate action scenario (Figure 16).

In the medium term (2050), surface runoff is projected to change relative to the baseline by +7% in Africa, by 0% in the Americas, +7% in Asia-Pacific, and -3% in Europe for a below 2.0°C scenario, and by +2%, -4%, +4%, and -2%, respectively, for the no climate action scenario.

In the long term (2090), surface runoff is projected to change relative to the baseline by +4% in Africa, by +1% in the Americas, +7% in Asia-Pacific, and 0% in Europe for a below 2.0°C scenario, and by +3%, -17%, +12%, and -7%, respectively, for the no climate action scenario.

Overall, the changes in 1.5°C scenarios remain positive for all assessed regions; however, a decrease in runoff is observed for Americas and Europe for a no climate action scenario for each time period.

d. Discharge

Theoretical Background

Discharge or streamflow refers to the average amount of water flowing in a river or stream. River flow is a main source of freshwater both in mountain regions and downstream areas. Various sources contribute to it, including rainfall, snow and glacier melt, and groundwater. Changes in river discharge have several environmental implications. For example, changes in river flows in coastal rivers can lead to changes in phytoplankton structure and other aspects of coastal ecosystems, having implications for fisheries and aquaculture (Cooley et al., 2022, Caretta et al., 2022).

In addition to environmental implications, freshwater availability is impacted by sectoral water supply and water demand, with the latter being determined by sectors such as agriculture, energy, industry, or domestic use, as well as by competition among these sectors. Formal and informal water extraction and use prevail, and competition includes issues of inequality, power relations, and asymmetry. Consequently, the effects of climate change on water resources, people, and ecosystems are strongly modulated and often exacerbated by socioeconomic development and related water resource management (*Caretta et al., 2022*).

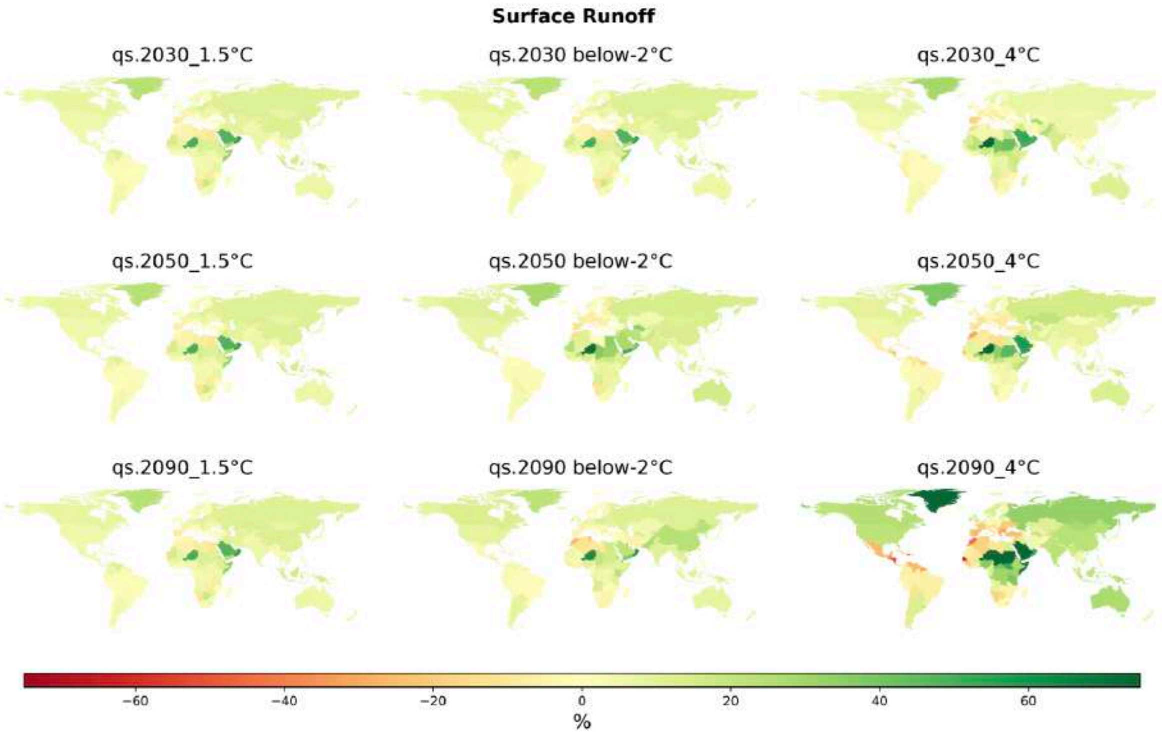


Figure 16: Surface runoff at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle) and end-of-the-century no climate action scenario (SSP370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

Indicator Methodology

Streamflow, or discharge, is the mean water flow within a river channel and is expressed in, for example, $m^3\ s^{-1}$. For this analysis, river discharge indicators consist of monthly values measured in cubic meter per second ($m^3\ s^{-1}$) with a global grid resolution of 0.5° x 0.5°. The data used for this variable has undergone a ISIMIP3 bias-adjustment procedure to correct for deviations between modeled and observed values over the time period where they overlap. The results are presented for this variable as absolute differences for each future time period from the baseline period of 1995–2014.

Key Findings

Both climate change and human activities influence the magnitude and direction of change in runoff and streamflow. Overall, there is medium confidence that anthropogenic climate change is a driver of the global pattern of change in streamflow. There are no clear trends of changing streamflow on the global level; however, trends emerge on a regional level.

The results are given as changes in discharge in % relative to the baseline (1995–2014).
The range of projections is wide across all countries, timeframes, and scenarios, indicating significant variability within model results.

In a 1.5°C scenario, discharge is projected to change relative to the baseline by +1% in Africa, by +1% in the Americas, +3% in Asia-Pacific, and 0% in Europe.

In the near term (2030), discharge is projected to change relative to the baseline by +1% in Africa, by +1% in the Americas, +3% in Asia-Pacific, and 0% in Europe for a below 2.0°C scenario, and by +5%, -2%, +3% and -5%, respectively, for the no climate action scenario (Figure 17).

In the medium term (2050), discharge is projected to change relative to the baseline by +5% in Africa, by 0% in the Americas, +6% in Asia-Pacific, and -7% in Europe for a below 2.0°C scenario, and by +4%, -4%, +3%, and -4%, respectively, for the no climate action scenario.

In the long term (2090), discharge is projected to change relative to the baseline by +3% in Africa, by +1% in

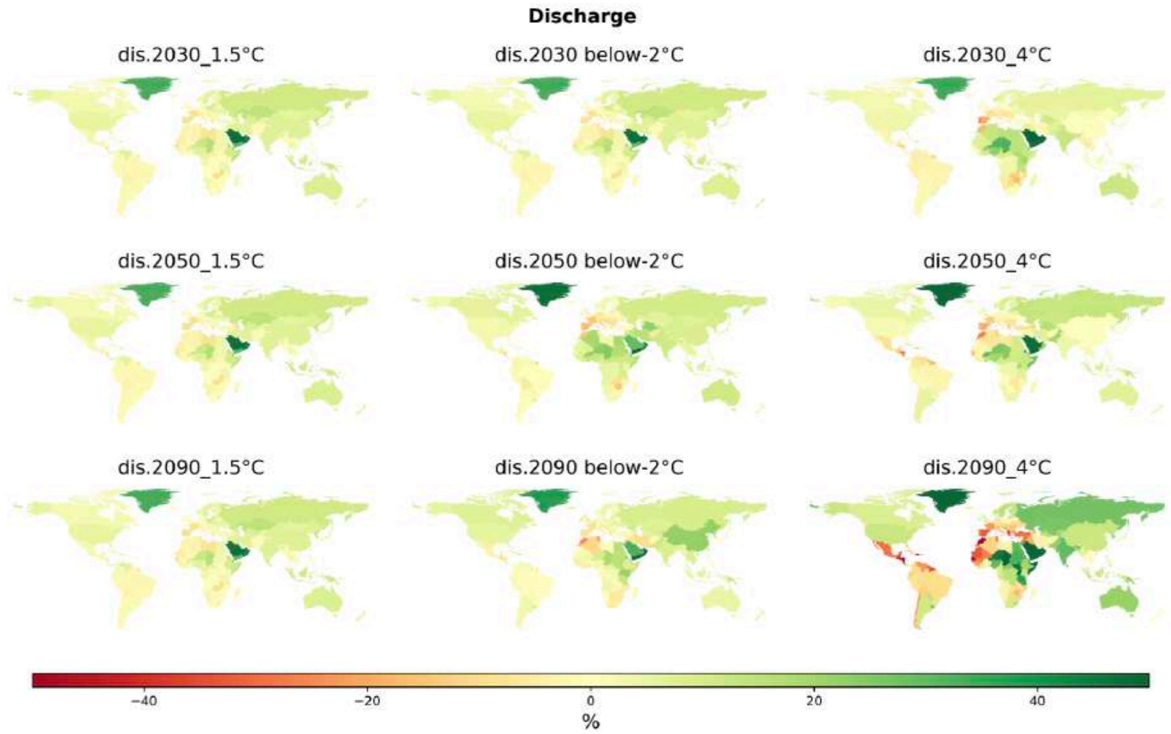


Figure 17: Discharge (streamflow) at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle) and end-of-the-century no climate action scenario (SSP370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

the Americas, +7% in Asia-Pacific, and +1% in Europe for a below 2.0°C scenario, and by +7%, -10%, +9%, and -10%, respectively, for the no climate action scenario.

A gradual decrease in discharge is observed for Americas and Europe in all time periods for no climate action scenarios, which gradually intensifies as we move towards the end of the century.

e. Maximum of Daily Discharge

Theoretical Background

Maximum river discharge refers to the amount of water flowing in a river or stream. In contrast to the discharge indicator that describes the mean river flow during a given period of time, this indicator describes the highest river flow in a given period of time. Maximum river discharges and related river depths indicate a river's propensity to flooding. The IPCC's *Sixth Assessment Report* has assessed with high confidence an increase in present-day extreme precipitation and an associated increase in the frequency and magnitude of river floods (Caretta et al., 2022). The IPCC's *Special Report on the Ocean and Cryosphere in a Changing Climate* concluded that changes in the cryosphere have led to changes in frequency, magnitude, and location of rain-on-snow floods, snowmelt floods, and glacier-related floods (Cooley et al., 2022).

Indicator Methodology

Maximum streamflow, or maximum discharge, is the maximum water flow within a river channel, expressed in $m^3 s^{-1}$. Within the CVM3 data, river discharge indicators consist of monthly values measured in cubic meter per second ($m^3 s^{-1}$), with a global grid resolution of 0.5° x 0.5°.

Key Findings

The range of projections is quite wide across all countries, timeframes, and scenarios, indicating significant variability within model results (Figure 18).

In a 1.5°C scenario, maximum daily discharge is projected to change relative to the baseline by +5% in Africa, by +5% in the Americas, +6% in Asia-Pacific, and +2% in Europe.

In the near term (2030), maximum daily discharge is projected to change relative to the baseline by +5% in Africa, by +5% in the Americas, +6% in Asia-Pacific, and +2% in Europe for a below 2.0°C scenario, and by +11%, +3%, +6%, and -2%, respectively, for the no climate action scenario.

In the medium term (2050), maximum daily discharge is projected to change relative to the baseline by +13% in Africa, by +4% in the Americas, +9% in Asia-Pacific, and 0% in Europe for a below 2.0°C scenario, and by +11%, +1%, +8%, and -1%, respectively, for the no climate action scenario.

In the long term (2090), maximum daily discharge is projected to change relative to the baseline by +8% in Africa, by +6% in the Americas, +9% in Asia-Pacific, and +4% in Europe for a below 2.0°C scenario, and by +17%, -1%, +16%, and -1%, respectively, for the no climate action scenario.

f. Minimum of Daily Discharge

Theoretical Background

Minimum river discharge refers to the amount of water flowing in a river or stream. In contrast to the discharge indicator that describes the mean river flow during a given period of time, this indicator describes the lowest river flow in a given period of time. Lower river and groundwater levels can also damage ecosystems more broadly, harming plants and animals and increasing the risk of wildfires. There is an interconnection between minimum river discharges and droughts. Droughts over time lead to deficits in streamflow, leading to a reduction in water supply. A river's minimum discharge has ecological implications for sustenance of aquatic species and ecosystems, as well as infrastructure implications; for example, support of water-based transportation.

Indicator Methodology

Minimum streamflow, or minimum discharge, is the minimum water flow within a river channel, expressed in $m^3 s^{-1}$. Within the CVM3 data, river discharge indicators consist of monthly values measured in cubic meter per second ($m^3 s^{-1}$), with a global grid resolution of 0.5° x 0.5°. The results are given as changes in minimum of daily discharge in % relative to the baseline (1995–2014).

Key Findings

The range of projections is quite wide across all countries, timeframes, and scenarios, indicating significant variability within model results. Nonetheless, trends in minimum of daily discharge can still be determined (Figure 19).

In a 1.5°C scenario, minimum daily discharge is projected to change relative to the baseline by 0% in Africa, by -3% in the Americas, +1% in Asia-Pacific, and -1% in Europe.

In the near term (2030), minimum daily discharge is projected to change relative to the baseline by 0% in Africa, by -3% in the Americas, +1% in Asia-Pacific, and -1% in Europe for a below 2.0°C scenario, and by +2%, -5%, +1% and -6%, respectively, for the no climate action scenario.

In the medium term (2050), minimum daily discharge is projected to change relative to the baseline by +1% in Africa, by -3% in the Americas, +3% in Asia-Pacific, and -10% in Europe for a below 2.0°C scenario, and by 0%, -7%, -1%, and -8%, respectively, for the no climate action scenario.

In the long term (2090), minimum daily discharge is projected to change relative to the baseline by -1% in Africa, by -1% in the Americas, +4% in Asia-Pacific, and -1% in Europe for a below 2.0°C scenario, and by -6%, -15%, +2%, and -17%, respectively, for the no climate action scenario.

a. Drought Index

Theoretical Background

There are different types of droughts for which different definitions exist. Drought in general can be defined as an exceptional period of water shortage for existing ecosystems and the human population (due to low rainfall, high temperature, and/or wind). Within this, hydrological droughts describe a period with large runoff and water deficits in rivers, lakes, and reservoirs, whereas a meteorological drought is defined as a period with an abnormal precipitation deficit. Agricultural and ecological droughts describe a period with abnormal soil moisture deficit, caused by a combined shortage of precipitation and excess

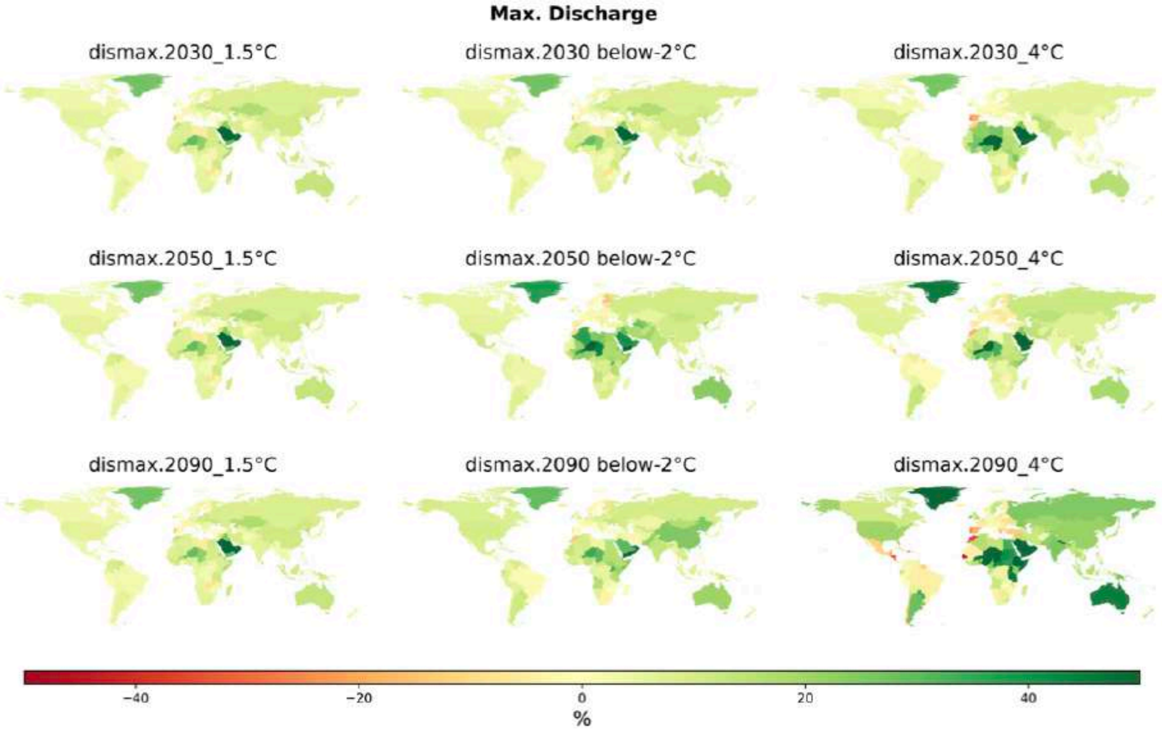


Figure 18: Maximum of daily discharge at: 1.5°C compatible scenario (left), below-2°C (SSP126) scenario (middle) and end-of-the-century no-climate-action (SSP 370) scenario (right). Rows indicate the reference year from the time slices: upper - 2021-2040 (2030), middle - 2041-2060 (2050) and lower - 2081-2100 (2090).

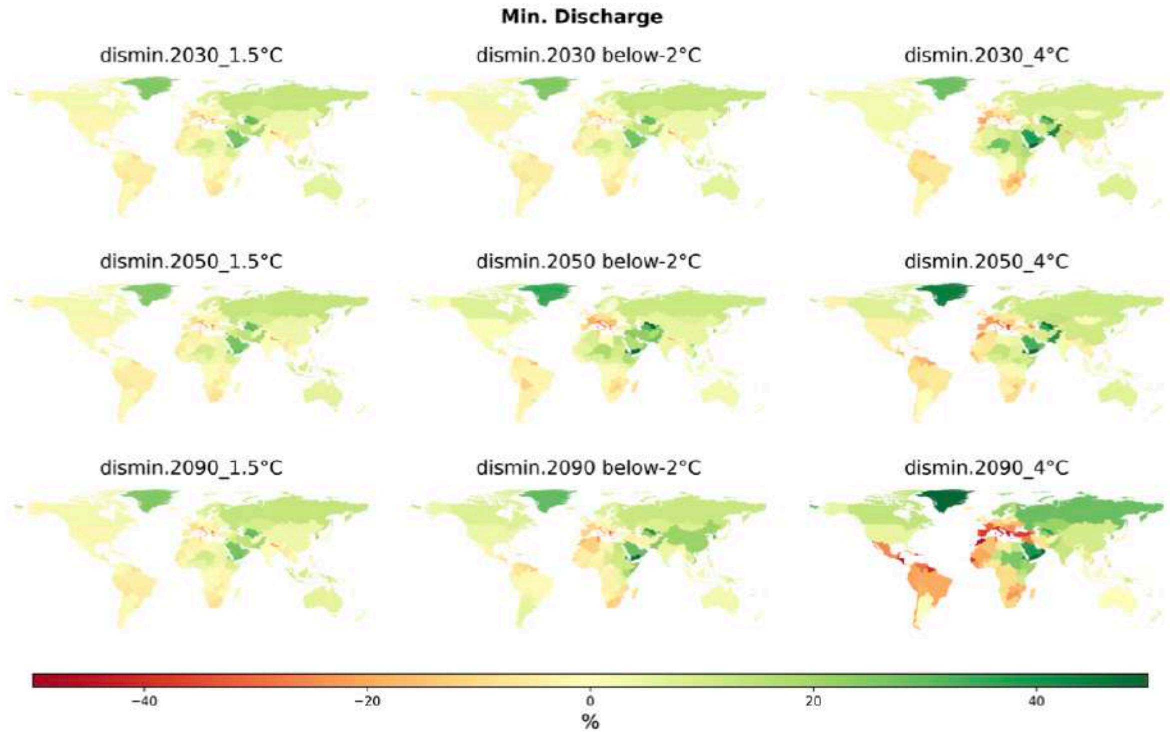


Figure 19: Minimum of daily discharge at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle) and end-of-the-century no climate action scenario (SSP370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

evapotranspiration (IPCC, 2021).

Drought conditions pose a risk to agriculture, water supply, energy production, human health, and many other aspects of society. The impacts thereby depend on the type, location, intensity, and duration of the drought. Impacts on water supplies can range from decreased water levels in reservoirs and dried-up streams to greater water shortages, whereas impacts on the agricultural sector can range from slowed crop growth to severe crop failures. Prolonged droughts pose a particular threat to vulnerable groups who are economically and culturally dependent on land and water. Warming and drought can threaten medicinally and culturally important plants and animals, and reduce water quality and availability, leaving vulnerable people particularly exposed to waterborne diseases.

Human influence has likely increased the chance of compound extreme events since the 1950s, including increases in the frequency of concurrent heatwaves and droughts on the global scale (*Chapter 12: Climate Change Information for Regional Impact and for Risk Assessment*).

Indicator Methodology

The Standardized Precipitation-Evapotranspiration Index (SPEI) is used to characterize drought conditions for this analysis. The SPEI is a multiscalar drought index based on climatic data and measures drought severity. For each GCM, the parameters required to calculate the SPEI are derived using the 1995–2014 baseline simulation data at each grid point using gamma fitting. The fitted parameters are then utilized to calculate the projected drought indices in the future time period. Though SPEI can be calculated at various lengths of interest, only results for a length of 12 months are presented for brevity. Furthermore, the droughts are classified according to the levels of severity. SPEI value of -1.5 is considered severe drought, hence this value is used to define the threshold. Therefore, occurrence of drought as the total number of drought events in the entire study period (that is, baseline and future periods) are

Country Spotlight: Kenya

Situated in the East African Greater Horn of Africa, Kenya is a country of diverse geography, ranging from rift valleys and grasslands to forests and a coastline on the Indian Ocean. Its name stems from the centrally located Mount Kenya, which is surrounded by the Kenyan Highlands, a fertile region with significant agricultural production. Of the estimated current population of 47.6 million, around 70% remain in rural areas, though a trend for rapid urbanization continues.

The country's climate varies from humid tropical conditions along the coast to semi-arid and arid further inside. In total, 85% of the country is arid and semi-arid lands (ASALs), which are host to 4.4 million pastoralists raising domestic animals in grassland environments, using herd and household mobility. Livestock contributes 43% to Kenya's agricultural sector GDP and accounts for more than 12% of the country's total GDP (World Bank, 2018). In rural areas such as the ASALs, the agricultural sector employs 70% of the total population and moreover it is a part of cultural identity, including prestige and wealth. Pastoralists have adapted to the natural variability of extreme climatic conditions and erratic water supply and rely on livestock for their survival and livelihood, hence also on the stability of seasonal patterns.

Droughts are among the most important climate extremes experienced in Kenya and have had significant impacts, especially for the most vulnerable groups. Pastoralists often rely on traditional forecasting, which is getting increasingly unreliable as a result of climate change. The increasingly unpredictable variations in climate and recurring extreme events such as droughts pose great threats to the wellbeing of agricultural and pastoralist livelihoods, further increasing the vulnerability of these rural livelihoods and also affecting Kenya's national economy at large. Other relevant hazards that have a major effect on Kenya include sea-level rise, tropical cyclones, and flooding.

Kenya has recently suffered from one of the most severe droughts in history, with millions of Kenyans at risk for food insecurity between in 2021 and 2022 (Figure 1). In the particularly affected ASALs, an estimated 2.1 million people experienced high levels of acute food insecurity, mainly resulting from poor performances of seasonal rainfall and increasing staple food prices due to high demand for maize for human and livestock food.

CVM data indicates that the likelihood for droughts will dramatically increase within the next decades. By stabilizing warming at 1.5°C, the global mean surface temperature in Kenya could be stabilized at a significantly lower level with strong implications for the occurrence of drought events. In 2100, in a below 2.0°C scenario, global mean surface temperature in Kenya would be 0.26°C warmer than in a 1.5°C scenario. Under a no climate policy scenario, global mean surface temperature would be 2.44°C warmer in 2090 than under a 1.5°C scenario (Figure 2). Already by 2050, significant differences in drought occurrence are projected between a below 1.5°C and below 2.0°C scenario to a no climate policy scenario. The number of drought events under a below 1.5°C scenario, is projected to occur 3-fold compared to the baseline. Under a below 2.0°C, the number of drought events per 20 years is projected to increase by 5-fold and by 7-fold in a no climate policy scenario relative to the baseline. By the end of the century, the occurrence of drought events in Kenya is projected to further increase in a below 2.0°C scenario and no climate policy scenario. In 2090, the number of projected drought events per 20 years is projected to increase by 4-fold under a below 2.0°C scenario and by 11-fold in a no climate policy scenario compared to the baseline (Figure 3).

The increased probability for droughts, along with increasing maximum temperatures and heatwaves, in turn will have implications for the country's food security, potentially reducing agricultural and livestock production.

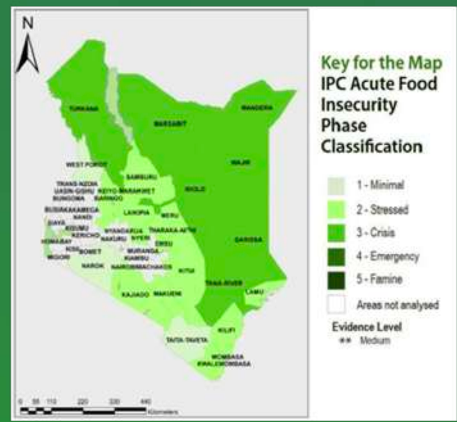


Figure 1: Food Insecurity in Kenya July - October 2021. Source IPC 2021

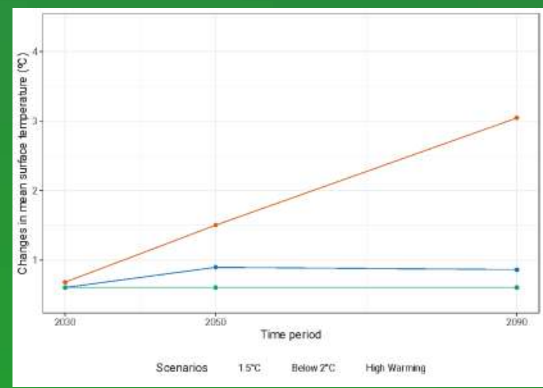


Figure 3: CVM3 projection for changes in number of drought events per 20 years according to projections of the SPEI indicator.

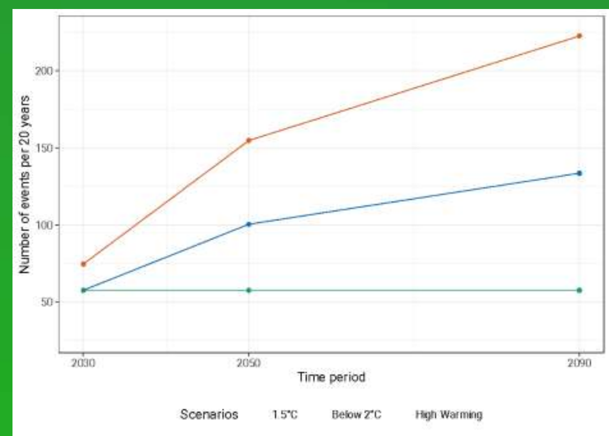


Figure 2: CVM3 projection for changes in mean surface temperature relative to baseline (1995-2014). Global mean surface temperature has already increased from 1850–1900 to 1995–2014 by 0.86 according to our assessment.

calculated. Results are presented as the difference of drought occurrence from future and the baseline periods. The results are given as changes in the number of events per 20 years relative to the baseline (1995–2014), in which drought conditions prevail according to the Standardized Precipitation Index.

Key Findings

Several regions in Africa, South America, and Europe are projected to experience an increase in frequency and/or severity of agricultural and ecological droughts with medium to high confidence; increases are also projected in Australasia, Central and North America, and the Caribbean with medium confidence (*IPCC, 2021b*).

The results are given in changes in events per 20 years, in which drought conditions prevail according to the Standardized Precipitation Index relative to the baseline (1995–2014).

In a 1.5°C scenario, the number of drought events per 20 years is projected to increase relative to the baseline by 8-fold in Africa, by 8-fold in the Americas, 6-fold in Asia-Pacific, and 4-fold in Europe (Figure 20).

In the near term (2030), the number of drought events per 20 years is projected to change relative to the baseline by 8-fold in Africa, by 8-fold in the Americas, 6-fold in Asia-Pacific, and 4-fold in Europe for a below 2.0°C scenario, and by 9-, 8-, 6-, and 4-fold, respectively, for the no climate action scenario.

In the medium term (2050), the number of drought events per 20 years is projected to change relative to the baseline by 11-fold in Africa, by 11-fold in the Americas, 9-fold in Asia-Pacific, and 5-fold in Europe for a below 2.0°C scenario, and by 13-, 12-, 11-, and 8-fold, respectively, for the no climate action scenario.

In the long term (2090), the number of drought events per 20 years is projected to change relative to the baseline by 12-fold in Africa, by 11-fold in the Americas, 10-fold in Asia-Pacific, and 8-fold in Europe for a below 2.0°C scenario, and by 14-, 13-, 13-, and 12-fold, respectively, for the no climate action scenario.

h. Extreme Precipitation

Theoretical Background

Extreme precipitation events are defined as the daily precipitation amount over land that was exceeded on average once a decade during the 1850–1900 reference period (IPCC, 2022a). Besides the risk of flooding, potential direct impacts of extreme precipitation include crop damage or soil erosion. The increased flooding risk poses a threat to human and animal life, as well as extensive infrastructure damage.

While the total amount of yearly precipitation may remain the same in a particular place, changes in timing, frequency, and intensity have led to an increase in extreme precipitation events since the 1950s over most land areas, exposing people to unfamiliar precipitation patterns (IPCC 2021) (*IPCC_AR6_WGI_SPM.Pdf*).

Indicator Methodology

The data basis for this indicator is a climate index measuring heavy precipitation over a five-day period (RX5day), with high values corresponding to a high chance of flooding. An increase in this index with time means that the chance of flood conditions will increase.

The intensity of extreme precipitation events may be defined with block maxima approach, such as annual maxima, or with peak over threshold approach, such as rainfall above 95th or 99th percentile at a particular space.

The results are given as changes in five-day maximum precipitation in % relative to the baseline (1995–2014).

Key Findings

The range of projections is quite wide across all countries, timeframes, and scenarios, indicating significant variability within model results. Nonetheless, trends in mean five-day maximum precipitation can still be determined (Figure 21).

In a 1.5°C scenario, five-day maximum precipitation is projected to change relative to the baseline by +8% in Africa, by +7% in the Americas, +4% in Asia-Pacific, and +5% in Europe.

In the near term (2030), five-day maximum precipitation is projected to change relative to the baseline by +8% in Africa, by +7% in the Americas, +4% in Asia-Pacific, and +5% in Europe for a below 2.0°C scenario, and by +5%, +3%, +4%, and +4%, respectively, for the no climate action scenario.

In the medium term (2050), five-day maximum precipitation is projected to change relative to the baseline by +7% in Africa, by +5% in the Americas, +5% in Asia-Pacific, and +5% in Europe for a below 2.0°C scenario, and by +8%, +2%, +5%, and +7%, respectively, for the no climate action scenario.

In the long term (2090), five-day maximum precipitation is projected to change relative to the baseline by +8% in Africa, by +3% in the Americas, +5% in Asia-Pacific, and +6% in Europe for a below 2.0°C scenario, and by +22%, +4%, +9%, and +13%, respectively, for the no climate action scenario.

3. Winds

a. Horizontal Wind Speed

Theoretical Background

Wind describes the natural movement of air relative to the Earth's surface. Wind occurs across spatial scales and time, from local gusts induced by heating of surfaces up to global-scale wind systems created by differences in solar energy absorption of the Earth's surface. Wind speed quantifies the velocity of these air masses. Wind transfers heat and moisture across the Earth's surface and the atmosphere and is therefore an important factor of many components of the water cycle, such as evaporation rates of plants in agricultural areas and general precipitation patterns. Seasonal winds influence the bloom of algae and affect lake and ocean currents. Moreover, wind speed is an important indicator for wind farm planning, as average wind speeds indicate the potential for wind farms at particular locations.

Changes in the speed and direction of prevailing winds can affect ecosystems and agricultural activities such as altering the profile of seed dispersal and the distribution of pollen. Windblown pest and disease vectors are affected by potential changes, affecting human health. While increasing wind speed may boost soil erosion, in turn generating more severe dust storms, decreases in wind speed negatively impact electricity production of wind farms.

Indicator Methodology

Wind speed is measured in meters per second (m s^{-1}). Here we consider

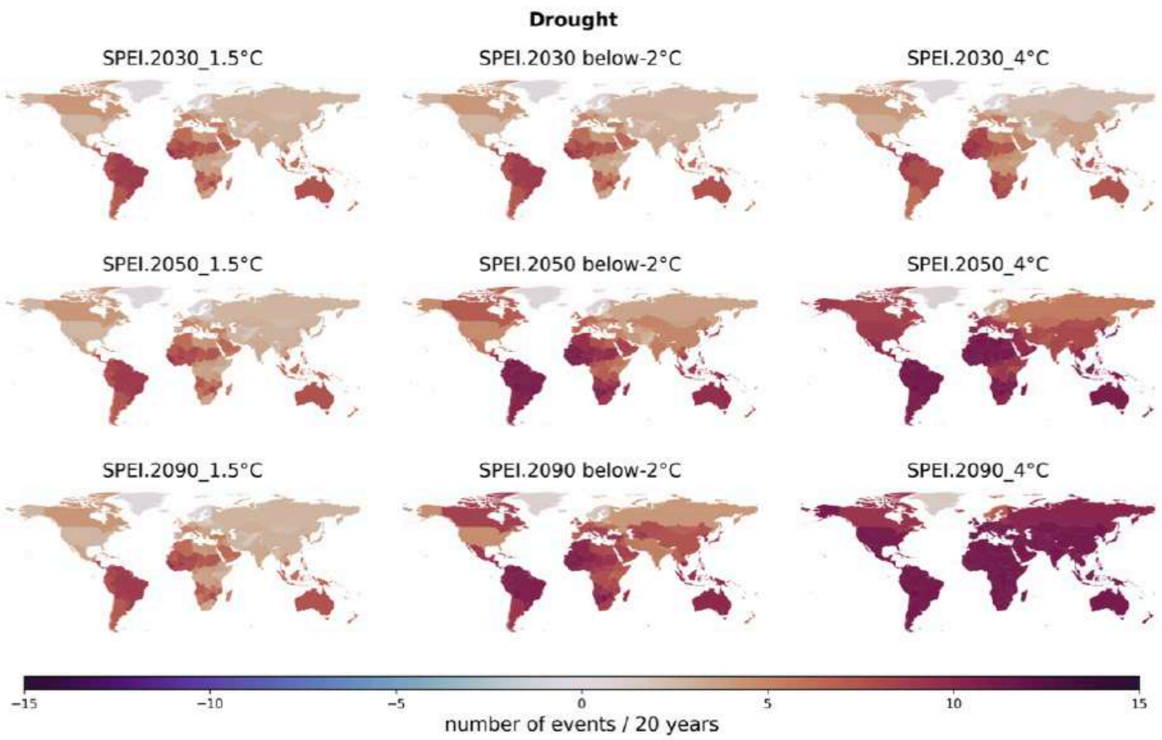


Figure 20: Number of drought events per 20 years at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle) and end-of-the-century no climate action scenario (SSP370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

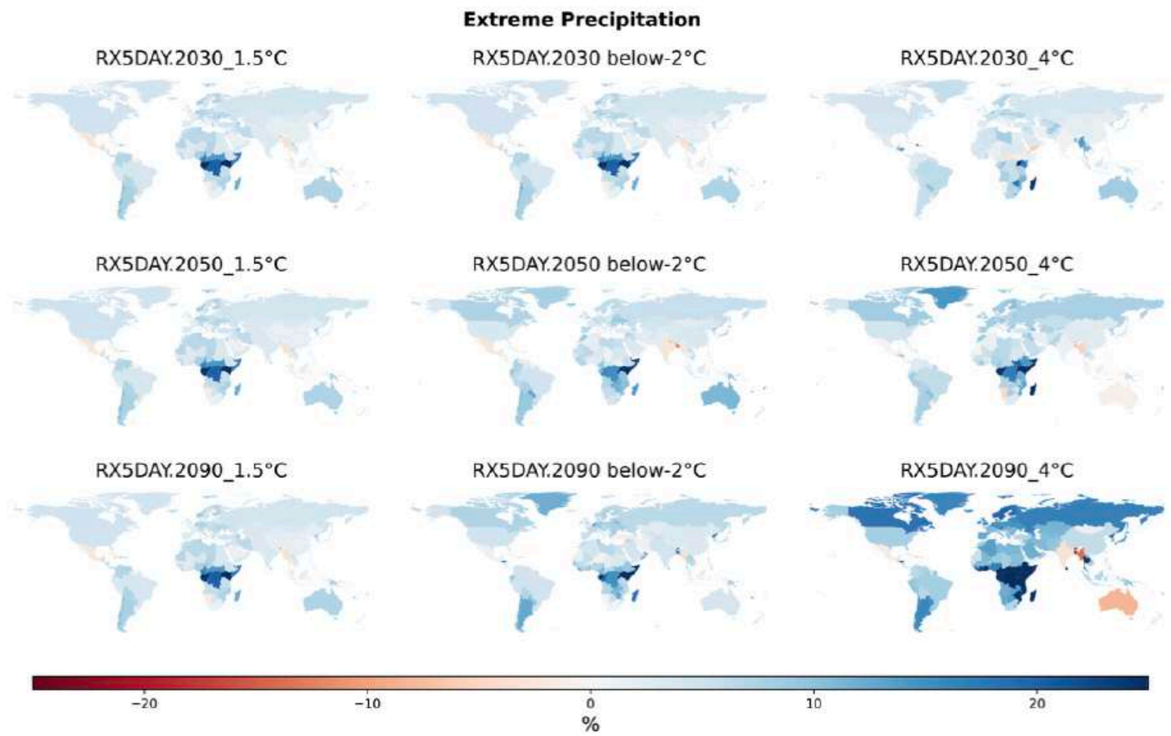


Figure 21: Extreme precipitation at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle), and end-of-the-century no climate action scenario (SSP370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

Country Spotlight: Philippines

The Philippines is a country situated in the western Pacific Ocean with more than 7,600 islands forming an archipelago of around 300,000 km², making it the fifth-largest island country in the world. The archipelago stretches over three main island groups of which the northern island of Luzon and the southern island of Mindanao make up a third of the country's total land area. The islands are of volcanic origin and their topography is characterized by mountainous terrain bordered by narrow coastal plains. The country's location along the pacific "ring of fire" exposes its population to natural hazards such as frequent volcanic eruptions and earthquakes. The vegetation is diverse and shaped by different types of forests and considered one of the most biologically rich and diverse countries in the world.

The climate of the Philippines is tropical marine, characterized by relatively high temperatures, high humidity, and rainfall influenced by summer and the winter monsoon season. The distribution of the annual average precipitation is also highly dependent on geographic and orographic location across the archipelago, resulting in variations of annual rainfall from 1,000 to 4,000 mm. Tropical cyclones pose a major threat to the Philippines from June till October as the country lies within the "typhoon belt" and receives an average of 20 typhoons every year.

The total population of ca. 109 million is distributed over the 2,000 inhabited islands. Around a third of the population lives on the island of Luzon within the metropolitan area of the capital Manila and its surrounding regions, making it the fifth most populous region in the world. The Philippines has a high rate of urban growth; however, ca. 52 % still reside in rural areas (World Bank, 2022). The country has rapidly transitioned towards a services- and industry-based economy, which account for 90% of GDP, overall, with over 50% of people employed in the service sector. Agricultural output has declined over the past decades and adds up to 10% of GDP. However, the agricultural sector still employs 23% of the population, with key agricultural products including sugar cane, coconuts, and rice.

Key Risks

The Philippines is exposed to flooding as a result of tropical cyclones and heavy rainfall, which are exacerbated by land-use change such as urbanization and logging. The estimated population annually affected by flooding is 176,000 and estimated damages is US$625 million, assuming up to a 1-in-25-year-event (2010).[22] On average, between 1951 and 2013, nine tropical cyclones crossed the country per year (Cinco et al., 2016). While tropical cyclones (typhoons), associated with extreme precipitation and coastal flooding, play a key role in driving flood damages in the Philippines, and have led to staggering losses and damage, extreme rainfall alone also has severe effects on all sectors. Over the last 10 years (2012–2022), flooding and related impacts such as landslides, have caused over 16,000 fatalities and economic damages are estimated at almost US$50 billion (Emergency Events database, EM-DAT).[23]

Floods can have direct impacts on infrastructure, and lead to the loss of agricultural crops and livestocks, and loss of productivity in industry, commerce, and trade, as well as human lives through forced displacement, emotional stress, diseases, or death. Indirect impacts are also destructive after a period of heavy rainfall, including the lack of basic utilities, such as sanitary facilities, health facilities, and educational facilities; food and potable water; and contamination of water supply, which results in gastro-intestinal diseases.[24]

Sustained rainfall also results in the accumulation of debris and stagnant water, which become breeding grounds for mosquitos, leading to higher risk of dengue and other vector-borne diseases (Aumentado et al., 2015). While about 90% of the population has registered for the public health insurance under the government-organized Philippine Health Insurance Corporation (PhilHealth)[25] statistics show that out-of-pocket health expenditures are still about 50% of the total health expenditure (2019).[26 27]

Projected Risks

Under a high GHG emissions scenario, no or small reductions in the frequency of tropical cyclones (TCs) can be expected with no or small increases in TC intensity (Gallo et al., 2018). It has been shown that indicators of extreme precipitation can be used to proxy the occurrence of TCs (Kitoh et Endo, 2019). The study used a one-day extreme precipitation indicator (RX1-day); however, with the CVM3 projections, our analysis relies on five-day extreme precipitation (RX5-day), which can also indicate pluvial floods.

CVM3 projections indicate a significant increase in flood risk for the Philippines under all scenarios, with the combined changes in runoff, precipitation, and wind speeds showing an upward trend. Differences between scenarios become increasingly pronounced, with risks of flooding significantly less severe if warming is limited to 1.5°C. In a below 1.5°C, five-day extreme precipitation is projected to not change significantly compared to the baseline with a change of +1% (-3 to 2%), whereas by 2090 projected changes under a below 2.0°C would amount to +5 (-3 to +6%), and +5% (-13 to +11%) in a no climate policy scenario (Figure 1).

Changes in precipitation consequently lead to changes in surface runoff and river discharge. In a below 1.5°C, surface runoff is projected to increase by 20% (+4 to +47%), whereas by 2090 surface runoff is projected to increase by 20% (-20 to +72%) in a below 2.0°C, and by 26% (-8 to +137%) in a no climate policy scenario (Figure 2).

In a below 1.5°C, discharge is projected to increase by 9% (+0% to +21%), whereas by 2090 surface runoff is projected to increase by 14% (-22 to +46%) in a below 2.0°C, and by 19% (-9 to +105%) (Figure3).

For extreme precipitation, discharge, and surface runoff, higher risks are projected under the upper and lower ranges of the projections, which also need to be considered.

Surface wind speeds are projected to stay relatively constant in a below 1.5°C scenario +1% (range -2% to +3%). By 2090, surface wind speed is projected to increase by 1% (-0 to +5%) in a below 2.0°C, and by 1% (-1 to +14%) in a no climate policy scenario, with high risks projected at the upper range of no climate policy projections (Figure 4).

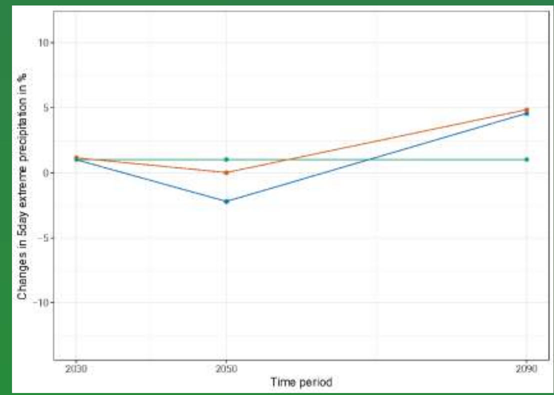


Figure 1: CVM3 projection for changes in extreme 5 day precipitation relative to the baseline (1995-2014) in the Philippines.

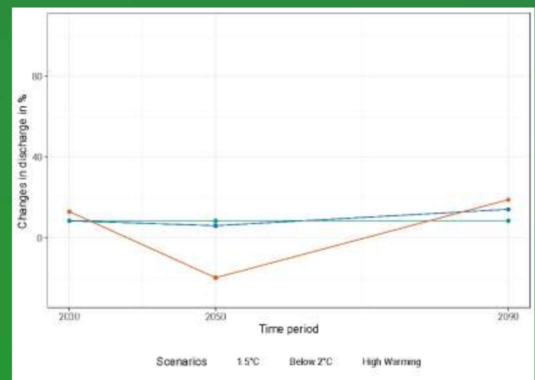


Figure 2: CVM3 projection for changes in discharge relative to the baseline (1995-2014) in the Philippines.

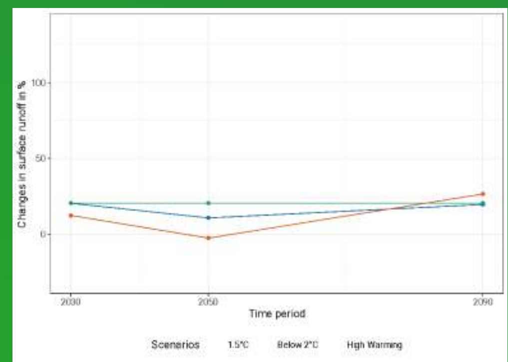


Figure 3: CVM3 projection for changes in surface runoff relative to the baseline (1995-2014) in the Philippines.

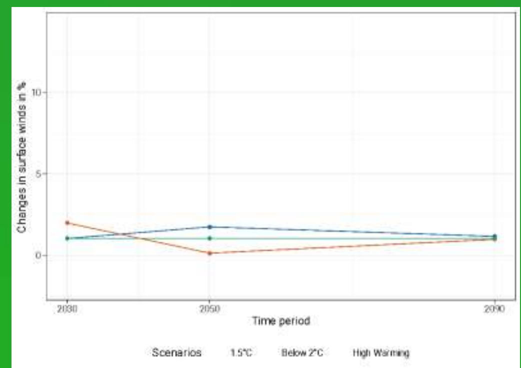


Figure 4: CVM3 projection for changes in surface wind speeds relative to the baseline (1995-2014) in the Philippines

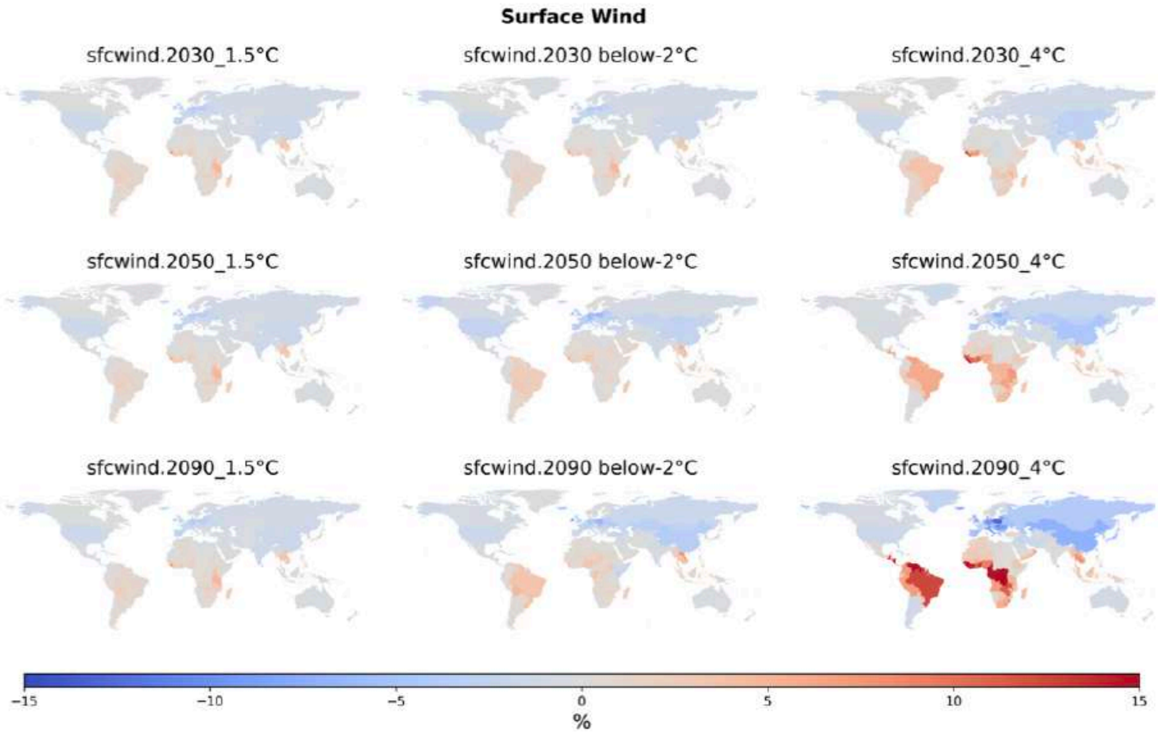


Figure 22: Surface wind at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle) and end-of-the-century no climate action scenario (SSP370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

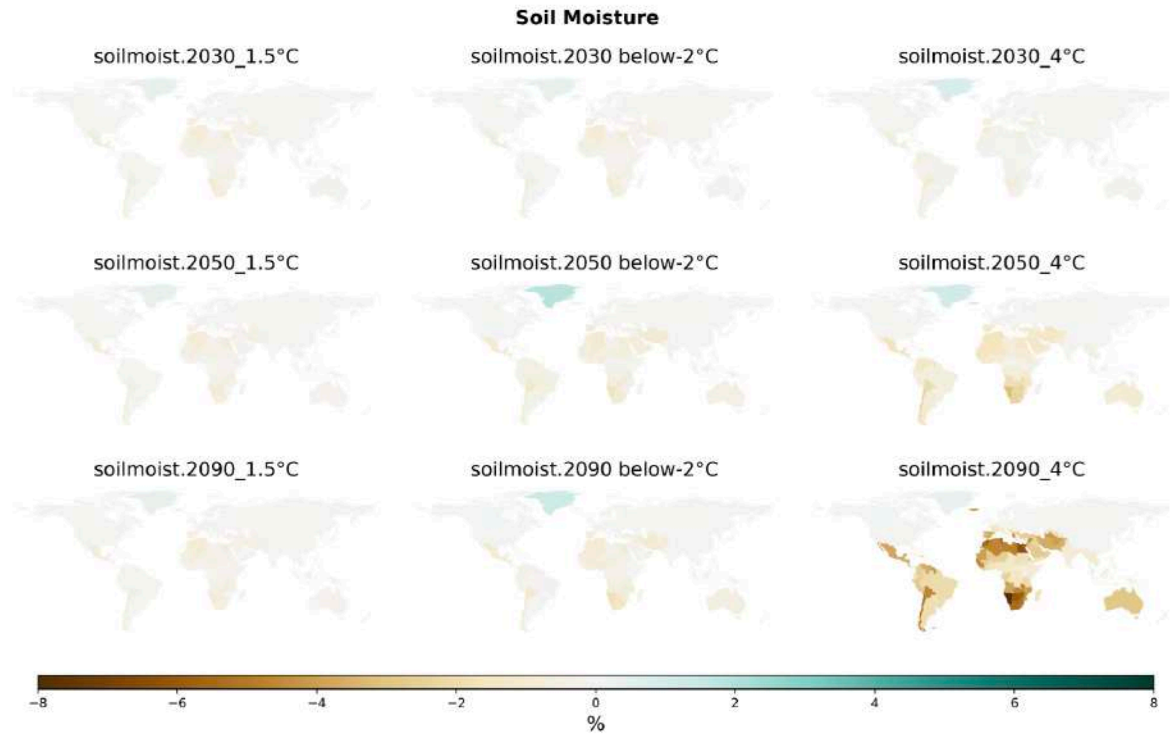


Figure 23: Soil moisture at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle) and end-of-the-century no climate action scenario (SSP370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

the wind speed 10 m above ground. The data used for this variable has undergone a bias-adjustment procedure to correct for deviations between modeled and observed values over the time period where they overlap.[28]

Key Findings

The results are given as changes in surface wind speed in % relative to the baseline (1995–2014). The range of projections is quite wide across African countries, indicating significant variability within model results. Nonetheless, trends in median surface winds can still be determined (Figure 22).

In a 1.5°C scenario, surface wind speed is projected to change relative to the baseline by +1% in Africa, by -1% in the Americas, 0% in Asia-Pacific, and -2% in Europe.

In the near term (2030), surface wind speed is projected to change relative to the baseline by +1% in Africa, by -1% in the Americas, 0% in Asia-Pacific, and -2% in Europe for a below 2.0°C scenario, and by +1%, 0%, 0%, and -1%, respectively, for the no climate action scenario.

In the medium term (2050), surface wind speed is projected to change relative to the baseline by 0% in Africa, by 0% in the Americas, 0% in Asia-Pacific, and -3% in Europe for a below 2.0°C scenario, and by +3%, 0%, -1%, and -3%, respectively, for the no climate action scenario.

In the long term (2090), surface wind speed is projected to change relative to the baseline by +1% in Africa, by 0% in the Americas, 0% in Asia-Pacific, and -2% in Europe for a below 2.0°C scenario, and by +4%, +2%, -1%, and -5%, respectively, for the no climate action scenario.

4. Agriculture

Total Soil Moisture Content

Theoretical Background

Soil moisture refers to the quantity of water stored within the unsaturated soil zone (Seneviratne et al., 2010). Soil moisture provides water to plants, a crucial requirement for plant growth. Soil moisture can be categorized into four types: gravitational moisture, capillary moisture, hygroscopic moisture, and combined moisture. All types of soil moisture start off as free water that is added to the soil through precipitation. Their final forms (or types) rely upon the moisture conditions of the soil.

Climate change and the associated increase in the frequency of extreme weather events have a strong impact on the hydrological processes in soils. Research based on modelling of long-term changes in soil moisture found that precipitation and temperature variability have a pronounced effect on soil moisture.

Indicator Methodology

Total soil moisture content quantifies water stored in soil, per unit area. Here soil moisture contained at a consistent depth of approximately 1 meter is considered, which is taken for multiple crop types from established crop models. The unit is kilograms per square metre (kg/m2). The temporal resolution and aggregation are monthly and mean, respectively.

Key Findings

The results are given as changes in soil moisture content in % relative to the baseline (1995–2014) (Figure 23).

No changes are detected for any region across all the time periods for the 1.5°C and below 2.0°C scenarios. The main reason is that besides small changes, the results are aggregated over multiple countries for each region, hence canceling out the direction of change. For example, while changes in the below 2°C scenario are negligible for Africa, even by the end of the century, Namibia will still see changes of -2%.

Detectable changes at a continental scale appear only for the no climate action scenario in the medium term (2050), which shows a change relative to the baseline by -1% in Africa and by -1% in the Americas.

In the long term (2090), soil moisture is projected to change relative to the baseline by -2% in Africa, by -3% in the Americas, -1% in Asia-Pacific, and -1% in Europe for a no climate action scenario. By that time, Spain would see a change of -4%.

Change in Crop Yields

Crops such as cereals, vegetables, fruit, oilseeds, and sugar account for about 80% of the global dietary energy supply (Bezner et al., 2022). Major staple crops, including maize, rice, soy, and wheat, are critically relevant in assessing global food security. Changes in crop production and yields affect both food supply and income for about 600 million farms globally, 90% of which are operated by smallholder and subsistence farmers (IPCC AR6 WG1 Ch5, 2021) (*Gurney-Smith et al. - SPM5 Food, Fibre and Other Ecosystem Products.Pdf*). Climate-related hazards that cause crop losses are increasing, leading to decreased global average yields of major crops. Presented here are the main staple crops for food security including maize, rice, soy, and wheat. In many countries, there are other additional staple crops as well as crops for trade and export; for example, tea and coffee, which are not assessed here.

Indicator Methodology to Assess Changes in Crop Yields

The methodological approach to assess climate impacts on crop yields is the same across all assessed crops and therefore summarized here for all remaining indicators.

All results on crop yields were obtained using established global gridded crop models, which depict a representation of the evolution of crop systems under climate change. They were forced with a limited number of climate model simulations and CO_2 fertilization is accounted for in the models. Yield projections accounting for CO_2 fertilization indicate lower losses or yield increases, but do not account for other potential impacts of increased CO_2, such less nutritional value of crops or higher susceptibility to pests and diseases. Impacts on yields may therefore be higher than represented (Caretta et al., 2022).

Worthy of note is that these models

have not been calibrated for every country. Maize yields were calculated by assuming that the cultivated areas of both rain-fed and irrigated maize will remain constant throughout the 21st century. Their projected changes hence only reflect the future evolution of climate, and not that of agricultural management practices. Maize yields are measured in tons of dry matter per hectare (t ha^{-1} (dry matter)) and the temporal resolution is per growing season.

i. Maize Yields

Theoretical Background

Maize (*Zea mays*) originates in the Andean region of Central America and is one of the most important cereals both for human and animal consumption. Maize is grown for grain, forage, and biofuels. Present world production is about 594 million tons of grain from about 139 million ha (LavagnedOrtigue). Maize provides at least 20% of the food calories for more than 4.5 billion people in 94 developing countries, including 900 million poor consumers for whom maize is the preferred staple. Maize is also an important ingredient in animal feed and is used extensively in industrial products, including the production of biofuels. Increasing demand and production shortfalls in global maize supplies have worsened market volatility and contributed to surging global maize prices. Climatic variability and change, and the consequent rise in abiotic and biotic stresses further confound the problem.

Several studies have predicted a decline in maize yields due to increased rainfall variability and elevated temperatures (Choruma et al., 2022; Kucharik et al., 2008; Shiferaw et al., 2011) (Choruma et al.; Sacks and Kucharik; Shiferaw et al.). This decline can be attributed to an increased temperature that would shorten the growing stages of the maize crop. Elevated temperature increases the rate of accumulation of growing degree days, thereby influencing growth duration. Several studies have shown that temperature increases lead to early crop maturing, allowing less time to accumulate biomass and form grain yield (Choruma et al., 2022; Kucharik et al., 2008; Shiferaw et al., 2011)

Country Spotlight: Ghana

Ghana is a west African country of 238,533 km² in size located on the Gulf of Guinea, sharing borders with Ivory Coast in the west, Burkina Faso in the north, and Togo in the east. The northern part of the country features high plains, while a forested plateau characterizes the southwest and central south. The artificial Lake Volta, as part of the Volta basin, shapes the central part of Ghana, covering some 8,482 km². Its location just north of the equator makes Ghana's climate tropical, with two main seasons influenced by west African monsoon winds. The north of the country experiences one rainy season from May until September, while two rainy seasons are typical for the south, lasting from April to July and September to November, respectively.

The majority of the 31.7 million (World Bank, 2021) inhabitants live in the southern part of the country, with its largest cities Kumasi and the capital Accra. The urbanization trend continues and as of 2021, 58% of the total population lived in urban areas. While less than 10% of the population live in extreme poverty, it is still comparably high in rural savannah in the north of the country, a significant area of agricultural production. Agriculture remains the largest sector of Ghana's economy, accounting for 20% of GDP and employing 45% of the country's workforce. Ghana's agriculture produces mainly cocoa, cassava, yam, bananas, and maize. The sector is shaped by smallholder farmers, cultivating 1–2 hectares of land, thereby accounting for 80% of the total agricultural output.

Dependence on agriculture adversely impacts livelihoods in Ghana, with increasing severity from the coast to the northern savannah. Rural communities often depend on agriculture as it contributes to income, employment, food security, and export earnings and thus, the agricultural sector has also been an important factor in reducing poverty. In particular, maize production plays a vital role in food security for many poor households in Ghana, additionally serving as an important food source for livestock and cash crops. Agricultural production in Ghana mainly relies on stable precipitation patterns and only 2% of the country's agricultural area is irrigated. Compound farming is a traditional agricultural practice of combining food crops such as maize with animal husbandry to minimize risk of crop failure from drought or flooding.

Erratic rainfall as well as related flooding and droughts are among the most predominant climate extremes experienced in Ghana, which vulnerable groups such as farmers of the savannah regions are exposed to. Climate change has already impacted these vulnerable communities and traditional agricultural practices, such as compound farming, because of altered rainfall patterns. Traditionally, farmers would dry their harvest under the sun during the dry period, with its arrival becoming less predictable in recent years, resulting in crop losses and food insecurity. In addition, increases in temperature and extreme weather events are putting crops and livestock at higher risk as they accelerate degradation of land and increase desertification and erosion. Research has shown that increasing temperatures lead to shortened growing stages of maize crop, resulting in reduced accumulation of biomass and formation of grain yield.

Climate Change is projected to further exacerbate the observed impacts on Ghana's agricultural sector. CVM3 data indicates that the direct impacts of climate change will lead to an overall decrease in maize yield for the median in all assessed scenarios. The high warming scenario for 2050 and 2090 show a projected median decrease of 4% and 5%, respectively, yet upper and lower bounds show potential decreases of up to 38%. Under a below 2°C scenario, median yield loss remains around 4%, with worst case projections at 14% and 17% in 2050 and 2090, respectively. Limiting warming to 1.5°C would reduce these risks to maize yields to median yield loss of 1%, with the risk range extending to a 10% yield decrease, thereby greatly reducing risks to food security and loss of income through yield reductions in Ghana.

Global agricultural models often underestimate extremes, thereby also not fully representing the potential impacts of increasing drought risks. The three scenarios assessed show a potentially large increase in drought severity risk, especially under the scenarios that are not able to stabilize temperatures at 1.5°C.
The projected risks to maize yields have the potential to lead to food insecurity due to higher risk of crop losses and damage. Moreover, socioeconomic factors such as poverty and economic growth in Ghana are closely interlinked with agricultural production and food security, adding to people's vulnerability to future climate change impacts.

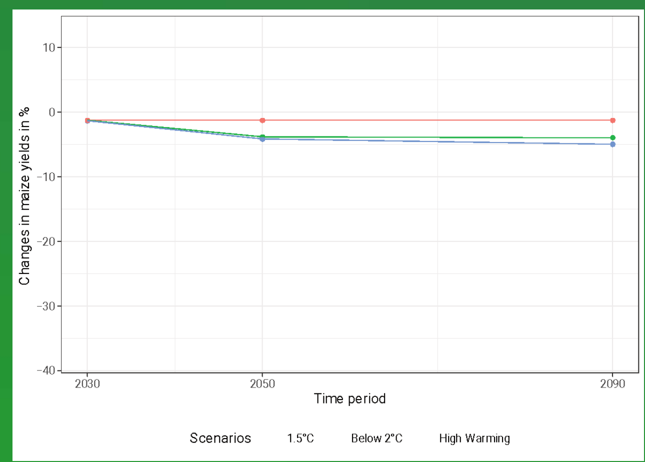


Figure 1: CVM3 maize yields projection for Ghana. Changes in % are given relative to the baseline (1995-2014).

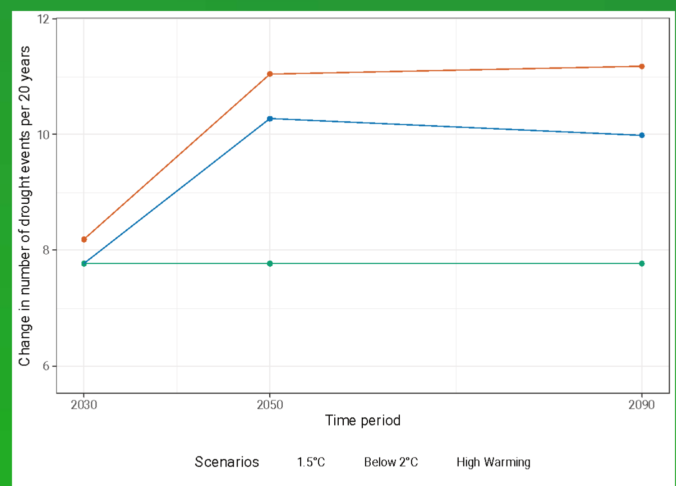


Figure 2: CVM3 projection for changes in number of drought events per 20 years according to projections of the SPEI indicator.

(Choruma et al.; Sacks and Kucharik; Shiferaw et al.). Furthermore, research has shown that maize requires the right amount and distribution of rainfall. A shift in precipitation would affect yield as studies have shown maize to be sensitive to the distribution and amount of moisture.

Key Findings

The results are given as changes in maize yield in % relative to the baseline (1995–2014).
The range of projections is quite wide for several countries, indicating significant variability within model results (Figure 24).

In a 1.5°C scenario, maize yield is projected to change relative to the baseline by -1% in Africa, by -2% in the Americas, -1% in Asia-Pacific, and 0% in Europe.

In the near term (2030), maize yield is projected to change relative to the baseline by -1% in Africa, by -2% in the Americas, -1% in Asia-Pacific, and 0% in Europe for a below 2.0°C scenario, and by -1%, -1%, -1%, and 0%, respectively, for the no climate action scenario.

In the medium term (2050), maize yield is projected to change relative to the baseline by -1% in Africa, by 0% in the Americas, -1% in Asia-Pacific, and 0% in Europe for a below 2.0°C scenario, and by 0%, -1%, 0%, and 0%, respectively, for the no climate action scenario.

In the long term (2090), maize yield is projected to change relative to the baseline by -1% in Africa, by -2% in the Americas, -1% in Asia-Pacific, and 0% in Europe for a below 2.0°C scenario, and by -1%, -1%, -1%, and 0%, respectively, for the no climate action scenario.

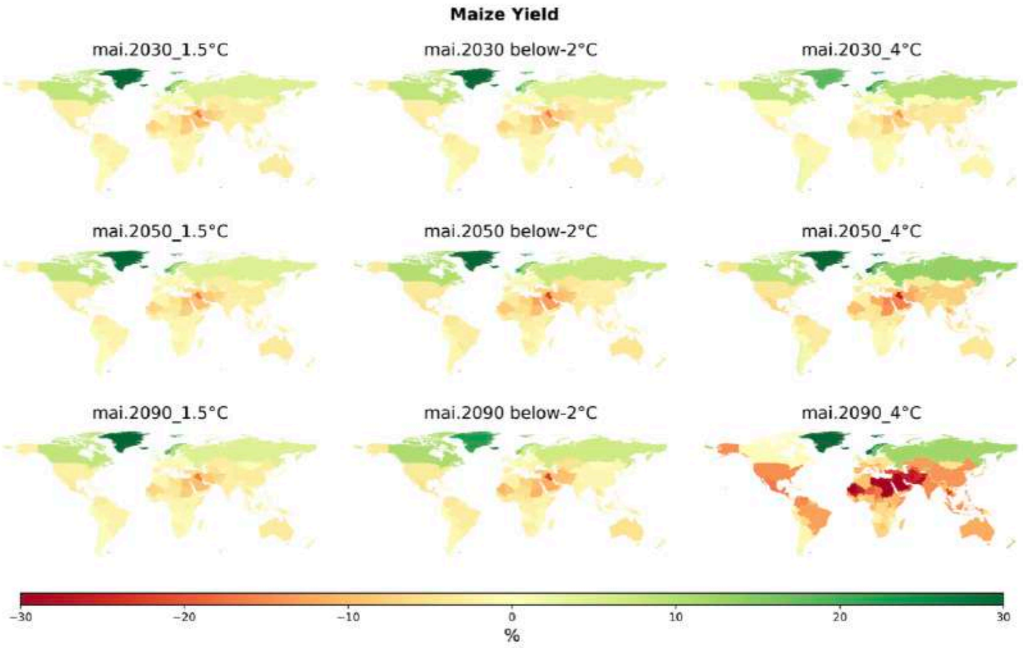


Figure 24: Maize yield at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle) and end-of-the-century no climate action scenario (SSP370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

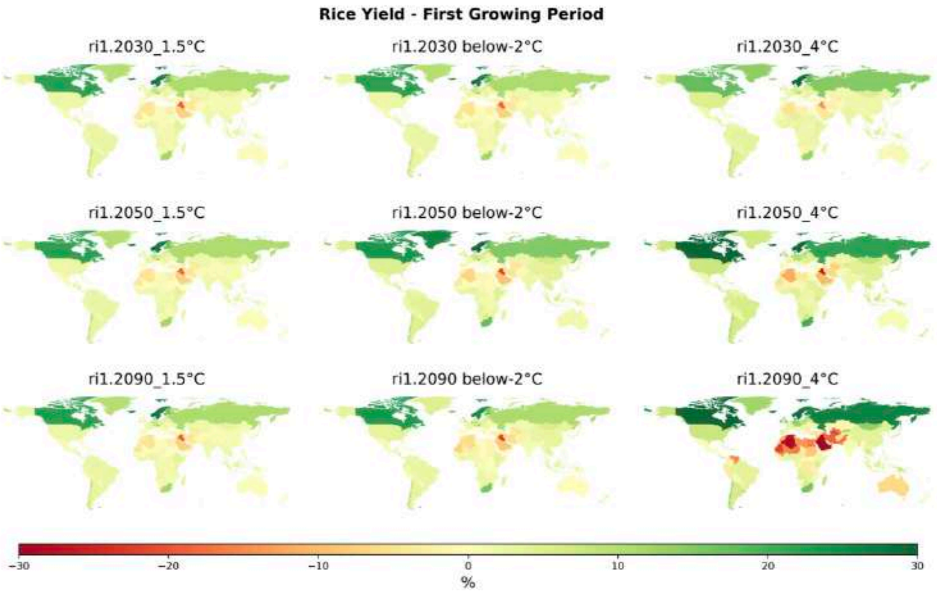


Figure 25: Rice y –first growing period at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle) and end-of-the-century no climate action scenario (SSP370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

ii. Rice Yields: First Growing Season

Theoretical Background

Nearly half of the world's population regard rice as the main source of calorie intake, and the high water consumption of rice growth is more susceptible to the effects of climate change, causing widespread concern for rice production.

Due to the influence of climatic factors, climate change has had a negative impact on rice yields in some countries such as China in recent decades. Higher temperatures have a negative impact on yields for some rice varieties as this shortens the growing period. The main cause of this decline was reduced photosynthesis at extremely high temperatures. Tropospheric (that is, the lowest 6–10 km of the atmosphere) ozone exacerbates negative impacts of climate change (Mattos et al., 2014; Chuwah et al., 2015; McGrath et al., 2015; Bisbis et al., 2018) (Mattos et al.; Chuwah et al.; McGrath et al.; Bisbis et al.). Ozone is an air pollutant and shortlived GHG that affects air quality and global climate. It is a strong oxidant that reduces physiological functions, yield and quality of crops and animals (IPCC, 2022) (Bezner et al., 2022). Ozone-induced yield losses in 2010–2012 averaged 4.4% for rice. The estimated yield loss does not account for interactions with other climatic factors. Temperatures enhance not only ozone production but also ozone uptake by plants, exacerbating yield and quality damage (IPCC, 2022) (Gurney-Smith et al.). Burney (2014) estimated current yield losses due to the combined effects of ozone and heat in India at 20% for rice (*Recent Climate and Air Pollution Impacts on Indian Agriculture | PNAS*).

Key Findings

The results are given as changes in rice yield in the first growing season in % relative to the baseline (1995–2014). The range of projections is quite wide for several countries, indicating significant variability within model results (Figure 25).

In a 1.5°C scenario, rice yield in the first growing season is projected to change relative to the baseline by +1% in Africa, by +2% in the Americas, 0% in Asia-Pacific, and +2% in Europe.

In the near term (2030), rice yield in the first growing season is projected to change relative to the baseline by +1% in Africa, by +2% in the Americas, 0% in Asia-Pacific, and +2% in Europe for a below 2.0°C scenario, and by +2%, +3%, +1%, and +4%, respectively, for the no climate action scenario.

In the medium term (2050), rice yield in the first growing season is projected to change relative to the baseline by +2% in Africa, by +3% in the Americas, +1% in Asia-Pacific, and +4% in Europe for a below 2.0°C scenario, and by +3%, +5%, +2%, and +8%, respectively, for the no climate action scenario.

In the long term (2090), rice yield in the first growing season is projected to change relative to the baseline by +1% in Africa, by +2% in the Americas, 0% in Asia-Pacific, and +3% in Europe for a below 2.0°C scenario, and by 0%, +3%, -2%, and +9%, respectively, for the no climate action scenario.

iii. Rice Yields: Second Growing Period

Theoretical Background

Ratooning is a practice of harvesting a second crop from the stubble of a first crop. Ratoon (second) crop production is one of the advantages of rice production (Nakano et al., 2020) (Nakano et al.). After harvest, the rice plant produces new shoots and panicles. About 1–2 t/ha of rice can be harvested within 60 days after harvest. Ratooning is considered to be an effective, low-input management strategy that possesses higher yield potential compared to conventional rice-growing methods and can increase

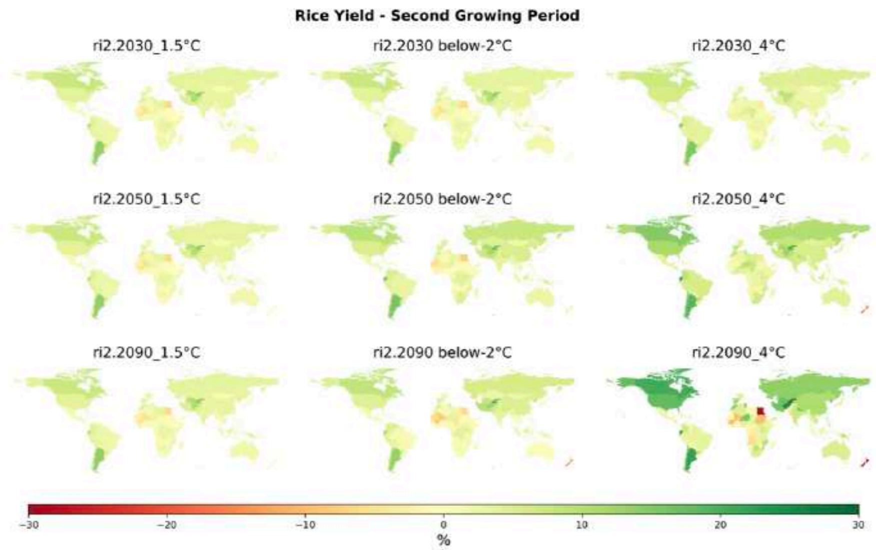


Figure 26: Rice yield – second growing period at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle) and end-of-the-century no climate action scenario (SSP370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

rice yields by 50% (Zhou et al., 2022) (Zhou et al.).

Climatic stressors such as drought, flood, saltwater, and extreme temperatures devastate rice crops and risk the livelihoods of 144 million smallholder rice farmers each growing season.[29] The length of the frost-free season is a limiting factor for ratooning.

Key Findings

The results are given as changes in rice yield in the second growing season in % relative to the baseline (1995–2014). The range of projections is quite wide for several countries, indicating significant variability within model results (Figure 26).

In a 1.5°C scenario, rice yield in the second growing season is projected to change relative to the baseline by +1% in Africa, by +2% in the Americas, +2% in Asia-Pacific, and +1% in Europe.

In the near term (2030), rice yield in the second growing season is projected to change relative to the baseline by+1% in Africa, by +2% in the Americas, +2% in Asia-Pacific, and +1% in Europe for a below 2.0°C scenario, and by +2%, +4%, +3%, and +1%, respectively, for the no climate action scenario.

In the medium term (2050), rice yield in the second growing season is projected to change relative to the

Country Spotlight: Bangladesh

Situated in South Asia, Bangladesh is a low-lying country on the Bay of Bengal. Its topography is shaped by mostly flat floodplain land as it is located at the confluence of one of the world's largest river deltas, formed by the rivers Ganges, Brahmaputra, and Meghna. The country stretches over an area of 148,000 km² and borders India to the west, north and east, as well as Myanmar in the south-east. Bangladesh has a tropical humid and warm climate, which is primarily marked by distinct seasonal variations under the influence of monsoon and the effects of the Himalayan mountain chain north of Bangladesh. The monsoon season from June to October, with heavy rain, makes up around 80% of the annual total precipitation in the country. Large parts of Bangladesh constitute natural floodplains and partial flooding constitutes a natural phenomenon that is also key to restoring soils for agriculture and for sustainable fisheries. However, development of settlements in these areas as well as flood protection measures and ill-planned infrastructure have contributed to increasingly disastrous flooding events. Coupled with changes in climate, including shifts in monsoon precipitation, droughts as well as tropical cyclones, Bangladesh is particularly vulnerable to further increases in these climatic stressors (Rahman and Salehin, 2013).

A total of 166 million inhabitants are sharing Bangladesh's land area, making it one of the most densely populated countries in the world. An increasing share of 39% of the total population is living in urban areas and despite economic growth, 13.5% of the population are living in extreme poverty. Bangladesh's industrial sector continues to grow, contributing 29.3% of GDP and garments remain the backbone of Bangladesh's industrial sector, accounting for more than 80% of total exports. The agricultural sector makes up 11.6% of GDP and is crucial for the country's economy as it employs about 38% of the total workforce and supports many people indirectly via processing and servicing of goods. In addition, three quarters of the rural population derive their livelihood from the agricultural sector. Followed by wheat, rice is the single most important agricultural product and is grown on the agricultural land that makes up 70% of the land area.

The country already suffers greatly from flooding, drought, cyclones, and erosion, and it lacks financial resources, which identifies Bangladesh as highly vulnerable to the effects of climate change. In addition, societal exposure to such risks is further increased by the country's high population and population density. Current climate change issues are having a considerable effect on the food security of millions of people in Bangladesh. Every year, natural hazards cause extensive damage to crops, livestock, and community assets, leading to decreases in livelihood opportunities for vulnerable groups and posing a threat to health and nourishment.

In particular, coastal and riverine communities in Bangladesh are highly vulnerable because of their low adaptive capacity and direct exposure to natural disasters such as regularly occurring floods and erosion. Many people have resettled their families and most of the climate-induced internally displaced people are being relocated to char lands – hundreds of islands surrounded by ambient rivers. Several studies have revealed that communities living in the char lands are at high risk to climate change due to the combination of natural hazards they're exposed to as well as being highly dependent on the agricultural fertility of these flooding areas.

It is anticipated that food and water security in Bangladesh will be under increasing pressure due to socioeconomic growth and the effects of climate change. CVM3 projections indicate increases in surface runoff of +38 % (range from -13 to +124%) by 2050 in a no climate policy scenario and decreases by -6% (range from -24% to +170%) in a below 2.0°C scenario, with the upper range of the projections showing significant increases in surface runoff. In a 1.5°C scenario, changes in surface runoff would only amount to +2%, with the lower (-27%) and upper (+95%) range of these projections also projecting significant changes relative to the baseline.
These changes in surface runoff will lead to increases in river discharge with the maximum daily discharge projected to increase under any scenario and timeframe relative to the baseline. In a 1.5°C scenario, drought events are projected to occur 1.4 (-0.7 to 13.4) times more often compared to the baseline, whereas by 2050 under a below 2.0°C scenario, drought events are projected to occur 3.2 (1.2 to 23.4) times more often and 5.0 (4.5 to 28.1) more often under a no climate action scenario.

An additional challenge to food security for Bangladesh is posed by projected changes in rice yields in the two rice growing seasons. The median rice projections show minor changes; however, the lower ranges show very strong potential decreases for rice yields in the second growing season. As agricultural models often underestimate extremes, the lower ranges in particular should be carefully considered. For example, in a 1.5°C scenario, the lower range amounts to -4%, whereas in 2090 under a below 2.0°C scenario, the lower range amounts to changes of -4% and -32% in a no climate action scenario.

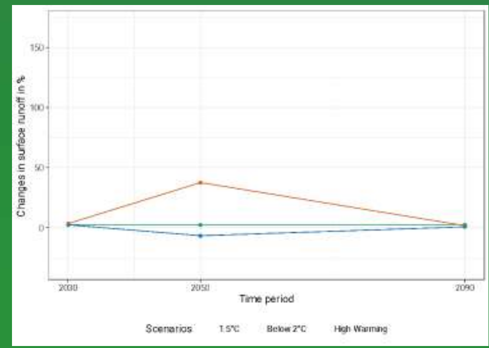


Figure 1: CVM3 projection for surface runoff changes relative to baseline (1995–2014) in Bangladesh

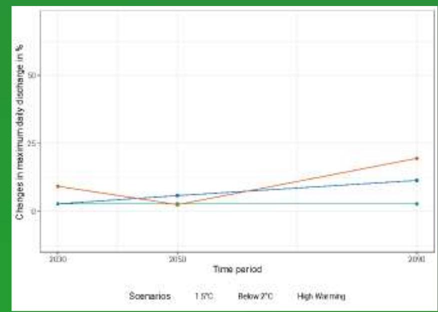


Figure 2: CVM3 projection for maximum daily discharge relative to the baseline (1995–2014) in Bangladesh.

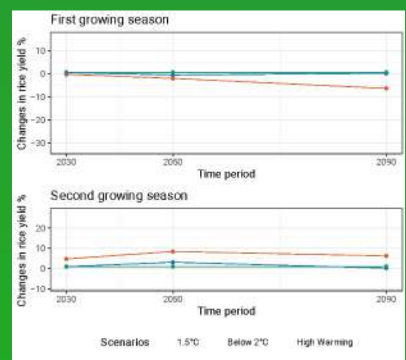


Figure 3: CVM3 projection for changes in rice yields in both growing seasons relative to baseline (1995–2014) in Bangladesh

baseline by +2% in Africa, by +3% in the Americas, +3% in Asia-Pacific, and +1% in Europe for a below 2.0°C scenario, and by +2%, +6%, +5%, and +3%, respectively, for the no climate action scenario.

In the long term (2090), rice yield in the second growing season is projected to change relative to the baseline by +1% in Africa, by +2% in the Americas, +2% in Asia-Pacific, and +1% in Europe for a below 2.0°C scenario, and by +1%, +6%, +7%, and +2%, respectively, for the no climate action scenario.

iv. Soy Yields

Theoretical Background

Soybean (*Glycine max*) is one of the most important world crops that is grown for oil and protein. Present world production is about 176.6 million tons of beans over 75.5 million ha. The crop is mainly grown under rainfed conditions but irrigation, specifically supplemental irrigation, is increasingly used (LavagnedOrtigue). Soybean is a major source of protein for humans, has the highest protein content (40–42%) of all other food crops among food legumes, and is a high-quality animal feed.[30] Moreover, soybean is also used for aquaculture and biofuel.

Soybean is grown under warm conditions in the tropics, subtropics,

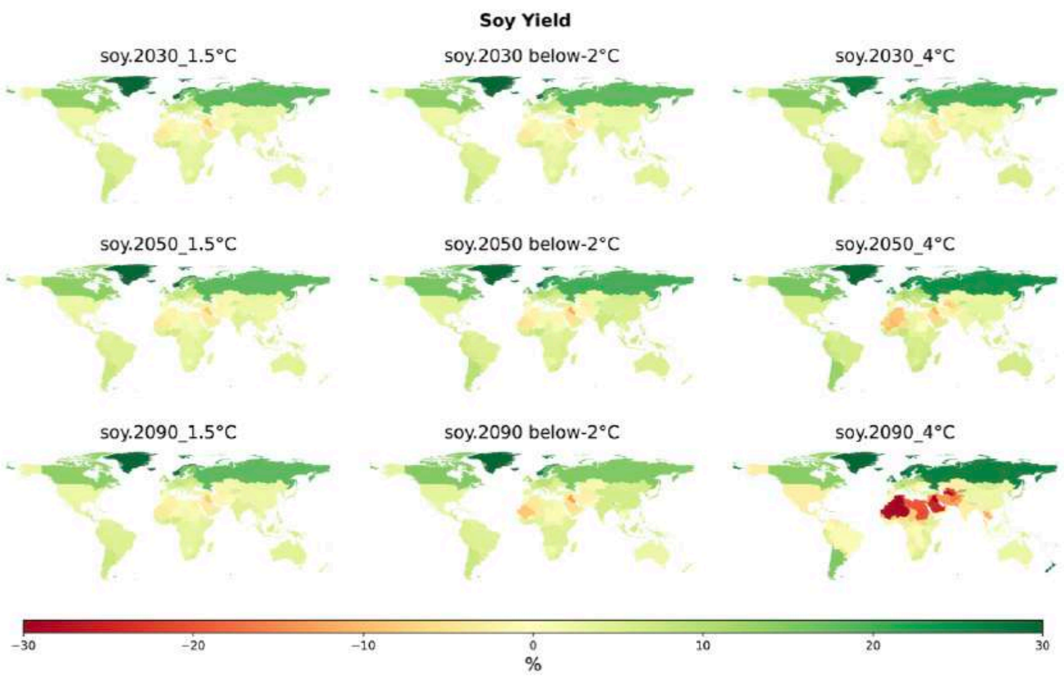


Figure 27: Soy yield at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle) and end-of-the-century no climate action scenario (SSP370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

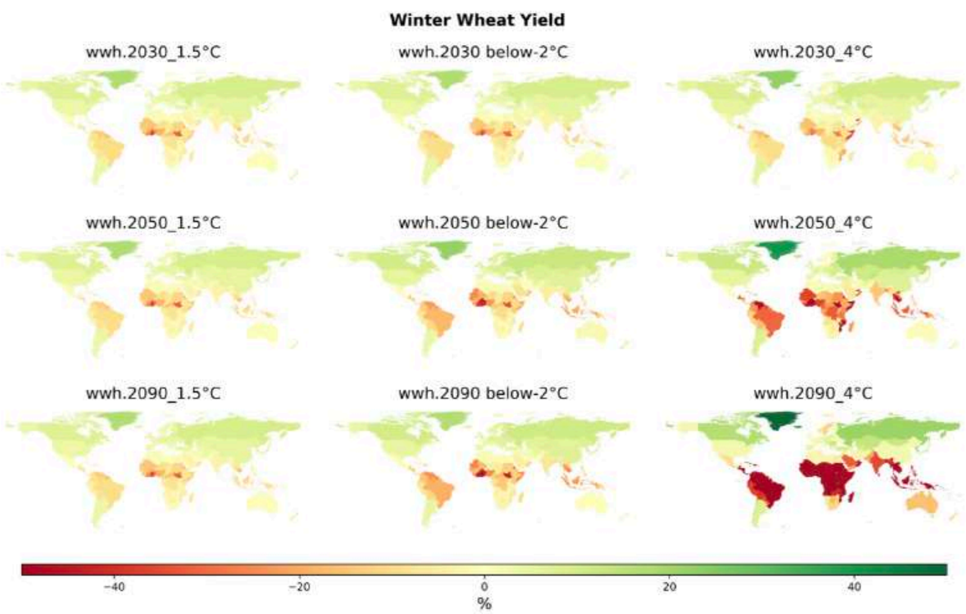


Figure 28: Winter wheat yield at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle) and end-of-the-century no climate action scenario (SSP370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

and temperate climates. Soybean is relatively resistant to low and very high temperatures but growth rates decrease above 35°C and below 18°C. In some varieties, flowering may be delayed at temperatures below 24°C. Minimum temperatures for growth are about 10°C and for crop production about 15°C.

Key Findings

The results are given as changes in soy yield in % relative to the baseline (1995–2014).
The range of projections is quite wide for several countries, indicating significant variability within model results (Figure 27).

In a 1.5°C scenario, soy yield is projected to change relative to the baseline by +3% in Africa, by +3% in the Americas, +2% in Asia-Pacific, and +5% in Europe.

In the near term (2030), soy yield is projected to change relative to the baseline by +3% in Africa, by +3% in the Americas, +2% in Asia-Pacific, and +5% in Europe for a below 2.0°C scenario, and by +4%, +4%, +3%, and +6%, respectively, for the no climate action scenario.

In the medium term (2050), soy yield is projected to change relative to the baseline by +4% in Africa, by +4% in the Americas, +3% in Asia-Pacific, and +7% in Europe for a below 2.0°C scenario, and by +4%, +5%, +3%, and +9%, respectively, for the no climate action scenario.

In the long term (2090), soy yield is projected to change relative to the baseline by +3% in Africa, by +3% in the Americas, +2% in Asia-Pacific, and +6% in Europe for a below 2.0°C scenario, and by -1%, +2%, -1%, and +7%, respectively, for the no climate action scenario.

v. Winter Wheat Yields

Theoretical Background

Bread and durum wheat (*Triticum aestivum* and *T. turgidum*) are grown for food in major parts of the world (LavagnedOrtigue). In China, winter wheat accounts for approximately 90% of total wheat yields. Wheat is grown as a rainfed crop in temperate climates, in the subtropics with winter rainfall, in the tropics near the equator, in the highlands with altitudes of more than 1,500 m and in the tropics away from the equator where the rainy season is long and where it is grown as a winter crop. The length of the total growing period of winter wheat needs about 180 to 250 days to mature. Winter wheat requires a cold period or chilling (vernalization) during early growth for normal heading under long days. For winter wheat, the minimum daily temperature for measurable growth is about 5°C. Mean daily temperature for optimum growth and tillering is between 15°C and 20°C.[31] Research has shown that warming trends during the winter wheat growing season have a negative effect on wheat yield, whereas the increasing trend of precipitation has a positive effect on yields.

Key Findings

The results are given as changes in winter wheat yield in % relative to the baseline (1995–2014). The range of projections is quite wide for several countries, indicating significant variability within model results (Figure 28).

In a 1.5°C scenario, winter wheat yield is projected to change relative to the baseline by -1% in Africa, by -1% in the Americas, +2% in Asia-Pacific, and +4% in Europe.

In the near term (2030), winter wheat yield is projected to change relative to the baseline by -1% in Africa, by -1% in the Americas, +2% in Asia-Pacific, and +4% in Europe for a below 2.0°C scenario, and by 0%, +1%, +2%, and +4%, respectively, for the no climate action scenario.

In the medium term (2050), winter wheat yield is projected to change relative to the baseline by -1% in Africa, by 0% in the Americas, +3% in Asia-Pacific, and 6% in Europe for a below 2.0°C scenario, and by -1%, +1%, +3%, and +6%, respectively, for the no climate action scenario.

In the long term (2090), winter wheat yield is projected to change relative to the baseline by -1% in Africa, by 0% in the Americas, +2% in Asia-Pacific, and 6% in Europe for a below 2.0°C scenario, and by -4%, 0%, +2%, and +3%, respectively, for the no climate action scenario.

vi. Spring Wheat Yields

Theoretical Background

Spring wheat is normally grown from May until September in Eurasia and from mid April to late August in North America. The length of the total growing period of spring wheat ranges from 100 to 130 days. The yields of spring wheat are relatively low (1.5–3.0 t/ha) due to the limited growing season, moisture availability, and the impact of abiotic and biotic stresses. Climate change is expected to have large effects on global wheat production: for every 1˚C increase in temperature, global wheat yields are predicted to decline by 4.1–6.4% (Morgounov et al., 2018). Wheat grown in warmer regions is likely to experience greater yield losses than that grown in cooler regions, though there is also general agreement that high-latitude spring wheat production will benefit from a warmer climate through an extension of the growing period.

Key Findings

The results are given as changes in spring wheat yield in % relative to the baseline (1995–2014). The range of projections is quite wide for several countries, indicating significant variability within model results (Figure 29).

In a 1.5°C scenario, spring wheat yield is projected to change relative to the baseline by 0% in Africa, by 0% in the Americas, +1% in Asia-Pacific, and +3% in Europe.

In the near term (2030), spring wheat yield is projected to change relative to the baseline by 0% in Africa, by 0% in the Americas, +1% in Asia-Pacific, and +3% in Europe for a below 2.0°C scenario, and by -5%, -3%, +2%, and +4%, respectively, for the no climate action scenario.

In the medium term (2050), spring wheat yield is projected to change relative to the baseline by 0% in Africa, by 0% in the Americas, +1% in Asia-Pacific, and +4% in Europe for a below 2.0°C scenario, and by +2%, +1%, +3%, and +6%, respectively, for the no climate action scenario.

In the long term (2090), spring wheat yield is projected to change relative to the baseline by -1% in Africa, by 0% in the Americas, +1% in Asia-Pacific, and +4% in Europe for a below 2.0°C scenario, and by -15%, -10%, -2%, and +6%, respectively, for the no climate action scenario.

5. Conclusion

Climate Change Has and Will Further Impact Biophysical Conditions Globally

Observed changes in the climate system are evident in mean and extreme conditions, across dimensions of temperature, water, and storms, and across sectors, including agriculture, economics, and health. These impacts have caused loss and damage globally, with the most vulnerable regions and population groups most affected. Future global warming, likely reaching 1.5℃ in the near term, will cause unavoidable increases in climate hazards and negative impacts on ecosystems and humans (IPCC, 2022a).

Projections of the biophysical conditions of temperature, water, storms, and agriculture presented in CVM3 have revealed the following:

- Global mean surface temperature has already increased by over 1°C since pre- industrial times and is projected to further increase under any scenario. Temperature increases are projected for all scenarios, timeframes, and countries.
- Several regions of the world are projected to experience an increase in frequency and/or severity of droughts for all scenarios and timeframes, with intensity increasing with higher global warming pathways.
- There is a trend (despite high variability) toward increasing extreme precipitation for many parts of the world, particularly across Central Africa, for all scenarios and timeframes. The notable exception is Australasia.
- Soil moisture is projected to decrease for all the assessed regions under a no policy action scenario in the long term.
- Climate projections show increasing agricultural yields in northern latitudes and decreasing agricultural yields near the equator.
- Stabilizing temperature rise at 1.5°C would greatly reduce the additional impacts caused by further warming for all regions and across all indicators.

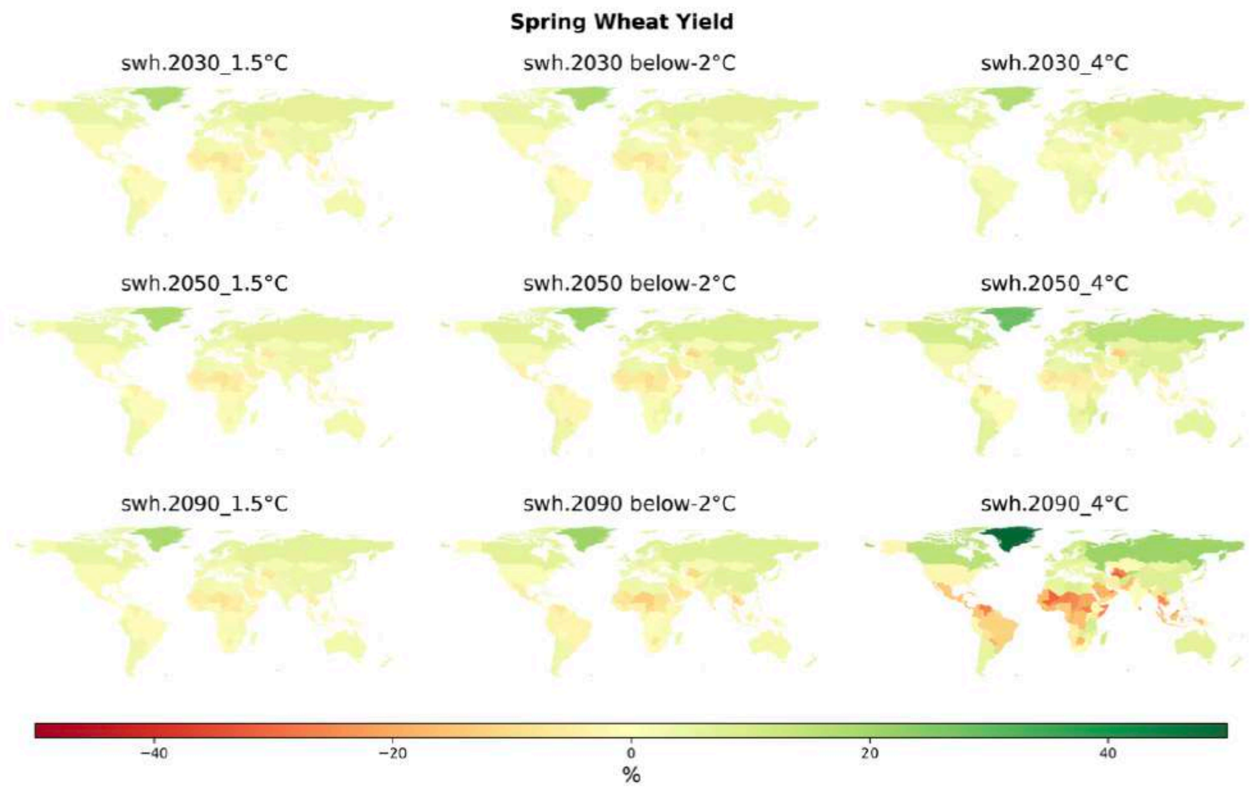


Figure 29: Spring wheat yield at: 1.5°C compatible scenario (left), below 2°C scenario (SSP126) (middle) and end-of-the-century no climate action scenario (SSP370) (right). Rows indicate the reference year from the time slices: upper – 2021–2040 (2030), middle – 2041–2060 (2050), and lower – 2081–2100 (2090)

The Urgent Need for Climate Action

Limiting warming to below 1.5°C is essential to reduce risks and allow for adaptation and climate-resilient development. While negative impacts exist under all scenarios, projections of biophysical indicators show the lowest additional impacts under 1.5°C for all indicators compared to present conditions. Increasing temperatures in the near term, along with rises in frequency and severity of extreme events, will place many ecosystems at high risk of biodiversity loss, and the number of people at risk of climate change will increase (IPCC, 2022a). Mid- and long-term impacts would be up to multiple times higher than currently observed. 1.5℃ is a key warming threshold, over which risks to unique and threatened systems are crossed with high risks of extinction, drastically increased risk of direct flooding damage, as well as risks to food crops and food security. A scenario with no climate action would have extremely devastating impacts across all biophysical dimensions, especially related to heat, drought, and agricultural yields. Near-term actions that limit global warming to close to 1.5℃ would substantially reduce projected losses and damage.

Adaptation and Adaptation Finance are Imperative

Adaptation and adaptation finance are essential to reduce climate risks, even at present day levels. Progress is being made in adaptation planning and implementation globally. However, adaptation gaps still exist between current levels of adaptation and levels needed to respond to climate impacts (IPCC, 2022a). Adaptation finance remains a key barrier to effective adaptation and climate finance needs to be made available urgently to enable adaptation. Access to sufficient finance is also key to address social inequities and improve education and institutional effectiveness, which are all shown to reduce the impacts of climate change and improve adaptation effectiveness. Finance access therefore needs to be flexible to also address underlying drivers of vulnerability along with the physical risks from climate hazards.

Losses and Damage and the World's Most Vulnerable

Adaptation, even when effective, does not prevent all losses and damage. Losses and damage occurring today will continue to increase. Losses and damage are often felt most acutely by the vulnerable, whose underlying socioeconomic conditions exacerbate increasing climate hazards (Martyr-Koller et al., 2021; Thomas et al., 2020). The most vulnerable need support to cope with these effects to enable resources to be put into adaptation and resilience. Recent examples of compound and sequential extreme events reveal vicious cycles of damage to recovery to damage, which need to be broken by adequate support as increasing damage limits the resources that are available to build resilience. This is a global responsibility that needs to be addressed by wealthy countries to support the most vulnerable.

AERIAL TOP DOWN FOOTAGE OF MALAYSIA AFTERMATH BIGGEST FLOOD COVERING MAJOR AREA IN SELANGOR AND KLANG VALLEY. IT SIDE IMPACT FROM THE RAI TYPHOON.

by MuhammadSyafiq

Link : https://stock.adobe.com/fr/images/aerial-top-down-footage-of-malaysia-aftermath-biggest-flood-covering-major-area-in-selangor-and-klang-valley-it-side-impact-from-the-rai-typhoon/479745078

Health

LANCET COUNTDOWN: TRACKING PROGRESS ON HEALTH AND CLIMATE CHANGE

IV. Health: Climate Change and Health

Introduction

The previous section described the many ways in which Earth systems are changing. All of these changes impact human health as well, making climate change the greatest threat to global health of this century (Costello et al., 2009) (Romanello et al., 2022). The physical, social, and economic environments that health and wellbeing depend on are already being undermined through interconnected pathways by the direct and indirect impacts of climate change (Romanello et al., 2021).

Even at current global mean heating of 1.1°C above pre-industrial levels, the frequency and intensity of extreme weather and weather-related events, including extreme rainfall, drought, cyclones, and wildfires are increasing (IPCC; 2021). Extreme events can cause immediate harm to people and infrastructure while leaving a trail of long-lasting side effects, often causing injury, impacts on mental health (Box 1), damage to health centers, supply chain disruption, and economic losses that ultimately affect the socioeconomic determinants of health (Landeg, 2022; Lenzen et al., 2019; Park, 2022; Salamati Nia and Kulatunga, 2017; Tasdik Hasan et al., 2022).

Rising global temperatures and the associated increased humidity in the atmosphere puts people at risk of heat stress and potentially lethal heat stroke, adverse pregnancy outcomes, and negative mental health impacts. Indeed, about one third of all current heat-related deaths are attributable to anthropogenic climate change (Vicedo-Cabrera et al., 2021). Beyond these clinical health impacts, heat exposure also undermines health indirectly, by reducing labor capacity, disrupting services and infrastructure, and contributing to overwhelmed power grids as the demand for cooling with air conditioning peaks (Ebi et al., 2021). As the planet continues to heat, these impacts are set to increase.

Alterations in rainfall patterns are increasing the frequency of flood events, which increase the risk of infectious disease transmission, loss of assets, and death; while in parallel, the frequency and intensity of drought is rising, putting food and water security at risk. These and other extreme weather events, increased temperatures, soil salinification through sea water intrusion and sea level rise, and spatiotemporal changes in the incidence of crop pests and disease associated with climate change are all undermining food production. Meanwhile, reduced productivity and economic losses associated with climate change also undermine food access, while carbon dioxide reduces the nutritional content of crops – all of which act in conjunction to exacerbate the risk of food insecurity.

As climate change and its drivers cause shifts in environmental conditions, the environmental suitability for the transmission of infectious diseases is also changing. Indeed, about half of known human pathogenic diseases are thought to be at risk of being aggravated by climate change (Mora et al., 2022). Modeling indicates that rising temperatures, changing rainfall patterns, and humidity are making new locations more suitable for the spread of vector-borne infectious diseases such as dengue, malaria, tick-borne encephalitis, Lyme disease, and West Nile Virus (Semenza and Suk; 2012). Similarly, changing climatic conditions are increasing the likelihood for the transmission of waterborne, food-borne, and air-borne diseases across new areas, exposing populations to emerging and re-emerging infectious diseases.

While climate change–related health impacts affect populations in every part of the world, the impacts are felt most strongly by the most disadvantaged populations, including those with underlying and predisposing health conditions, and those with limited resources to cope with and recover from health impacts. Populations with limited access to healthcare and protective mechanisms, living in places where essential service infrastructure and provision are frail, and the material resources to rebuild and recover are limited, are particularly at risk. Indeed, countries that are placed low or medium on the UNDP-defined Human Development Index are often the hardest hit, despite contributing modestly to the emissions that cause global heating (Romanello et al., 2022). Older adults, infants and children, workers in heavy labor jobs (both outdoors and indoors in buildings without cooling systems), and Indigenous peoples are particularly vulnerable as temperatures rise, and people living in poverty have reduced capacity to adapt to changes (Ford, 2012; Nazrul Islam and John Winkel, 2017; Salm et al, 2021.; Hope, 2009; Habibi et al., 2021). With the most vulnerable populations more strongly affected, climate impacts therefore exacerbate inequities within and between countries (Nazrul Islam and John Winkel, 2017).

Increasing adaptation and resilience to climate hazards is therefore essential to minimize health impacts and reduce global health inequities (H.-O. Pörtner DCR et al., 2022). An essential first step to the development of adaptive measures is the identification of existing and emerging risks that populations might be exposed to in the future. As countries work to deliver the commitments made under the Paris Agreement, understanding potential future health impacts is also critical to inform comprehensive cost-benefit analysis.

This section presents indicators of selected future health risks that world populations will be exposed to under different climate change scenarios, assuming no changes in adaptation. These build on the Lancet Countdown indicators (Romanello et al., 2022), to provide different aspects of the relationship between climate change and health. Some of the indicators monitor emerging health-relevant hazards (for example, increased environmental suitability for the transmission of infectious diseases, or reduction in crop growth duration), while others estimate the exposure of vulnerable populations to emerging risks (such as, the exposure of populations over 65 years of age to life-threatening heatwaves, exposure of populations to days of very high wildfire risk, or exposure to temperatures that pose a risk of heat stress during physical activity). Others project the expected health impacts that will occur without increased adaptation to climate hazards (for example, heat-related mortality, reduced labor productivity, or increases in malnutrition and hunger due to heatwaves).

Indicators were processed for two future scenarios: the low-emissions scenario (SSP1-2.6), representative of a future in which temperatures are kept below 2°C above pre-industrial times, and the high-emissions scenario (SSP3-7.0), representative of a hypothetical future scenario in which no (further) climate action is taken, and in which temperature rise reaches 3.6°C by the end of the century (referred to in this text as a scenario compatible with no climate action). Indicator means were processed for a reference baseline period of 1995–2014, and for three future time slices representing the near-term (2021–2040), medium-term (2041–2060), and long-term (2081–2100) future. For the low-emissions scenario, the near-term period is assumed for the purposes of this report to be representative of a mean heating of 1.5°C above pre-industrial levels, the goal enshrined in the Paris Agreement. The near-term estimates under the low-emissions scenario can therefore provide an indication of the benefits of ambitious climate change mitigation. Findings in this report are presented as relative or absolute change with respect to the baseline period for each of the future time slices.

By exposing these risks, the indicators presented here help identify the health benefits of accelerated climate action, and the risks to which mitigation and adaptation measures must be tailored to minimize the impacts of climate change on people's health.

Heat and Health

As a result of human activities, global mean temperatures are increasing, with the frequency of extreme heat events on the rise worldwide (Perkins-Kirkpatrick and Lewis, 2020). Detection and attribution studies in recent years have quantified the influence of climate change on various extreme heatwave events, and established beyond reasonable doubt that climate change is the main driver of the extremes of heat that are increasingly putting people's health at risk.

Such studies have established, for example, that without human-caused climate change, the record temperatures reached in 2022 in the UK would have been "extremely unlikely" (Zachariah et al., 2022); that the 2020 Siberian heatwave, and the 2021 Western North American extreme heat would have been almost impossible (Philip et al., 2021; Ciavarella et al., 2021); and that anthropogenic climate change made the devastating heat in India and Pakistan in May 2022 30 times more likely (Coleman, 2022).

Exposure to extreme heat can result in direct and indirect adverse impacts on health, including heat stress and life-threatening heat stroke. It can also exacerbate underlying chronic conditions such as cardiovascular and respiratory disease, lead to acute kidney injury and adverse pregnancy outcomes, and affect mental health (Székely et al., 2015; McElroy et al., 2022; Syed et al., 2022; J. Liu et al., 2016). Extreme heat also limits people's capacity for physical activity, therefore undermining work productivity and the capacity to maintain active, healthy lifestyles (Obradovich and Fowler, 2017; Flouris et al., 2018; Heaney et al., 2019; An et al., 2020; Nazarian et al., 2021).

Indicators in this section estimate various aspects of the potential health impact of heat exposure under the low-emissions scenario (compatible with global mean heating under 2°C by the end of the century) and the high-emissions scenario (compatible with global mean heating of approximately 3.6°C by the end of the century), including the increase in the exposure of vulnerable populations to life-threatening heatwaves, deaths attributable to heat, and loss of labor capacity.

Exposure of Vulnerable Populations to Heatwaves

Climate change is driving an increase in the frequency, duration, and intensity of heatwaves, and resulting in an increased exposure of vulnerable populations to life-threatening extremes of heat (IPCC). The elderly, very young infants, and those living with underlying chronic health conditions are most vulnerable. Urban populations, which are growing and today make up 57% of the global world population according to the World Bank, are particularly at risk, as the urban fabric makes temperatures in cities higher than in neighbouring rural areas (a phenomenon known as the "urban heat island effect").

With further global mean temperature rise already inevitable, and the global population continuing to age, the number of vulnerable people exposed to extremes of heat and, consequently, at risk from associated illness and death, is set to increase even further (De Perez et al., 2018; Marx et al., 2021; Perkins-Kirkpatrick and Lewis, 2020). Estimating the potential increase in exposure to heatwaves is essential for countries to roll out mitigation and adaptation efforts, and to develop resilience mechanisms to manage the expected increase in the associated burden of disease.

Box 1: Climate Change and Mental Health

In addition to its numerous impacts on physical health, climate change is also affecting mental health and emotional wellbeing. Changes in temperature, precipitation, and extreme events can all have direct effects, while the physical, social, and economic effects of climate change can also indirectly result in adverse mental health outcomes.

High heat exposure can lead to worsened mental health and increased suicidality (J. Liu et al, 2021.; Mullins and White, 2019; Obradovich et al., 2018; Thompson et al., 2018). Exposure and proximity to wildfires and the smoke they generate is associated with anxiety, depression, paranoia, and post-traumatic stress disorder (PTSD) (Cianconi et al, 2020.; Rodney et al., 2021). Days of extreme precipitation have also been linked with worse mental health outcomes, while floods are associated with anxiety, depression, grief, substance use, and PTSD (Fernandez et al., 2015; Baylis et al., 2018; Stanke, Murray, et al., 2012).

In addition to immediate impacts, rapid events such as floods and cyclones can also destroy infrastructure, potentially damaging health systems, disrupting essential services, and undermining livelihoods, with cascading impacts on mental health (Hayes et al., 2018, Obradovich et al. 2018; Piguet et al., 2011). Droughts can devastate agricultural productions and threaten water availability, which, in turn, can endanger livelihoods and food security, and increase stress, anxiety, and trauma (OBrien et al.; Middleton et al.; Stanke, Kerac, et al.; Vins et al.). The associated economic strains of extreme weather events can also drive people to migrate, with often adverse mental health impacts to migrant populations if support mechanisms are not in place, and with particular impacts on those unable to migrate, due to the feeling of being trapped (Berry et al., 2014; Middleton et al., 2013; Piguet et al., 2011).

In addition, increased knowledge of climate change and its effects is leading to feelings of anxiety and fear, leading to eco-anxiety, climate grief, or solastalgia (distress over the adverse transformation of one's home environment) (Cunsolo and Ellis, 2018). Young people, in particular, are more prone to these impacts, as well as anxiety, depression, phobias, sleep disorder, substance abuse, and emotional and cognitive disorders (Hickman et al, 2021.; Burke et al. 2018).

Across the numerous paths through which climate change affects mental health, historically marginalized communities and otherwise vulnerable groups are often disproportionately affected. Those with a unique bond with the land, such as Indigenous peoples, rural farmers, and outdoor workers, are often greatly affected as climate change affects it (Cunsolo Willox et al., 2015; Hayes et al., 2018; Middleton et al., 2020; OBrien et al., 2014).

Women often experience higher rates of mental health impacts from wildfire smoke, floods, and changes in temperature and precipitation (Cruz et al., 2020; Hayes and Poland, 2018; Middleton et al., 2020; Baylis et al., 2018). People with pre-existing mental health conditions are also particularly vulnerable to extreme weather events (Berry et al., 2014; Hayes et al., 2018; Rodney et al., 2021; Stanke and Kerac, et al., 2012; Stanke and Murray, et al., 2012). Children are at greater risk of depression, anxiety, phobias, and attachment disorders due to climate change and its effects (Burke et al., 2018), and people with low income and those who live in low-resource countries or areas are at greater risk of serious mental health outcomes (Cianconi et al., 2020; Hayes et al., 2018; Obradovich et al., 2018).

Such health effects of climate change are all rapidly increasing, and are set to continue rising as the planet warms. However, monitoring the mental health impacts of climate change is challenging, not least because the stigma around mental illness and the varied attitudes to and valuation of mental health across cultures means that differing definitions and standards exist across the world. Moreover, the absence of robust data makes it difficult to assess the global burden of mental health conditions (Gopalkrishnan, 2018; Hayes and Poland, 2018). However, and while there is an undoubted need for additional study of the complicated relationships between climate change and mental health, there is already sufficient evidence of the linkages to drive action (Romanello et al., 2022).

As temperatures rise, precipitation patterns change, and extreme events become more common and intense, emotional wellbeing will continue to be affected, and adaptation measures must urgently be put in place to ease their burden. Climate change adaptation planning that includes mental health, expansion of green spaces, and additional future research can help to safeguard and bolster mental health in a changing world (Lawrance et al., 2021; Hayes and Poland, 2018; Fernandez et al., 2015).

This indicator estimates the future change in exposure to heatwave of one particularly vulnerable group: people over 65 years of age. It combines projections of daily minimum and maximum temperatures with estimates of the future number of people over 65 years of age under the two scenarios presented in this report, providing estimates of future exposure. For this purpose, heatwaves are defined as a period of two or more days where both the minimum and maximum temperatures are above the 95th percentile for 1995–2014. Data is presented as "person-days", which captures the total number of days of heatwave that people over 65 years of age were collectively exposed to (that is, one person-day is one person exposed to one day of heatwave). If 10 persons are simultaneously exposed to a heatwave day, this would translate to 10 person-days). It therefore reflects both the changes in the frequency of heatwave events, changes in their length, and changes in the size of the over-65 population exposed to them.

Exposure of people over the age of 65 to heatwaves is projected to increase significantly in both emissions scenarios (Figure 30). In the near term (2021–2040), a similar global increase in heatwave exposure is projected under both scenarios, with a 3.5-fold increase in the number of person-days under the low-emission scenario (SSP1-2.6) relative to the 1995–2014 baseline, which is compatible with 1.5°C of heating above pre-industrial levels. This highlights the need for rapid adaptation measures to be implemented, even under ambitious decarbonization. On the other hand, a 4.7-fold increase in person-days of exposure is projected in the near term under the high-emissions scenario (SSP3-7.0); results that reflect both an increase in heatwave exposure, and an increase in population size. Both scenarios significantly diverge with time; under SSP1-2.6 (compatible with 2°C of heating), exposure increases by 11.2-fold by 2041–2060 and 25.1 times by 2081–2100, while under SSP3-7.0, considerably larger increases of 16.7-fold by 2041–2060 and 63.1-fold by 2081–2100 are projected, with the latter compatible with 3.6°C of heating. These estimates expose the potential health gains of meeting the Paris Agreement goals: as compared with a no climate action scenario, 57% of the days of exposure of vulnerable populations to dangerous heatwaves could be avoided yearly by the end of the century if temperatures are kept below 2°C, and an estimated 93% could be avoided under a 1.5°C-compatible scenario.

In absolute terms, the largest number of person-days of exposure occur in the Asia-Pacific region (up to 78 billion person-days in 2081–2100 under SSP3-7.0), while the largest relative increases occur in the Africa region, reaching an astounding 550 times the present day in 2081–2100 in the same scenario (Figure 30).

Exposures increase faster under SSP3-7.0 than SSP1-2.6 in all regions except Europe. This is due to the differences in population projections between the different emission pathways. In Europe, SSP3-7.0 projects a significantly smaller size of the over-65 population

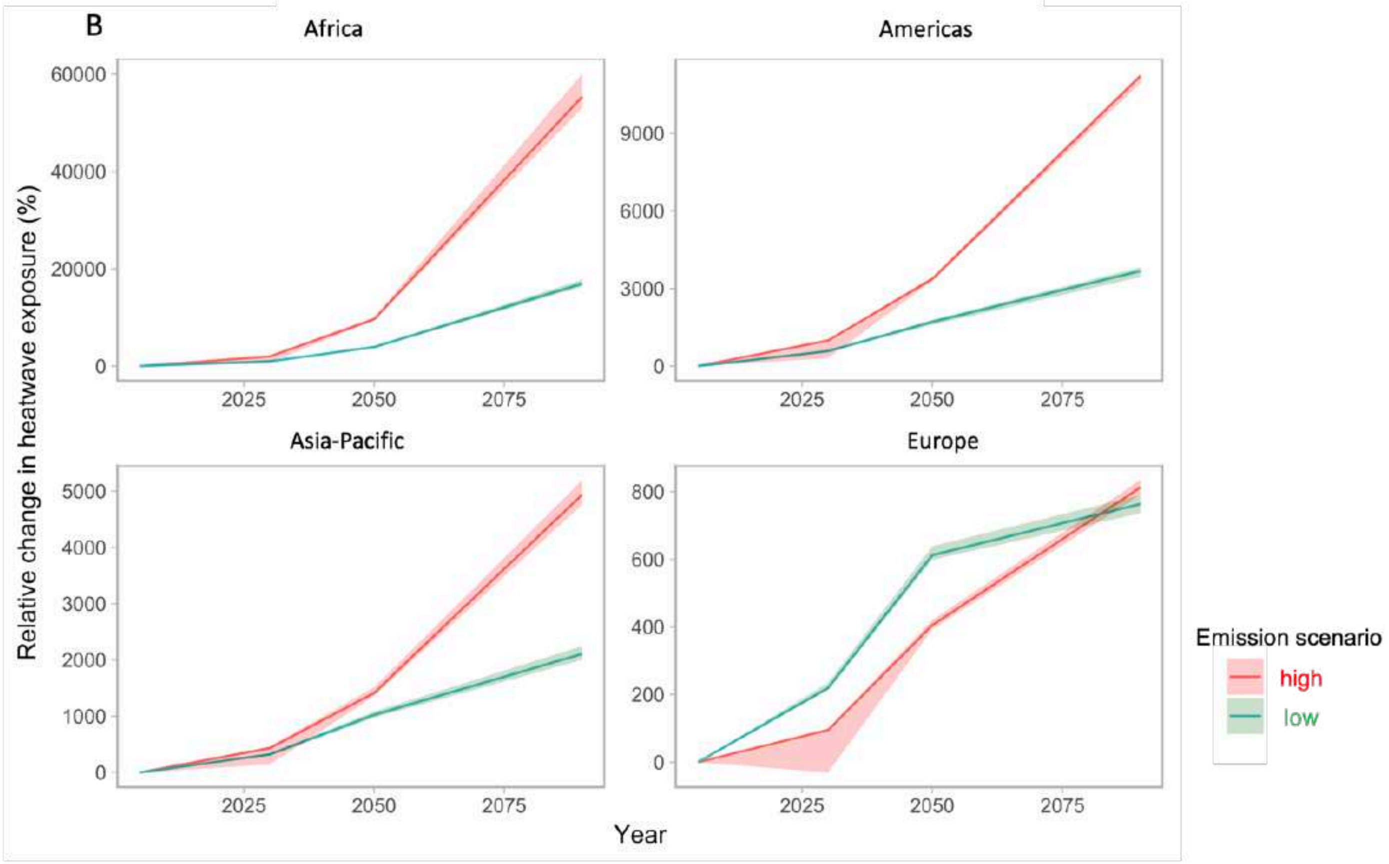


Figure 30: regional relative change, in the person-days of heatwave exposure of people over 65 years of age, with respect to a 1995–2014 baseline, for high- and low-emissions scenarios. The shaded areas represent the range between the maximum and minimum values obtained using the five GCMs.

relative to SSP1-2.6, due to both a lower population overall and lower life expectancy. For example, in the 2021–2041 period, SSP3-7.0 projects 80 million over-65s compared to 124 million in SSP1-2.6. In 2081–2100, however, the increase in heatwaves is so severe that there are again higher exposures in SSP3-7.0 than SSP1-2.6, even though SSP3-7.0 projects there to be only 78 million over-65s compared to 196 million in SSP1-2.6.

Heat and Physical Activity

Regular physical exercise is essential for good health. It can help reduce the risk of chronic diseases, improve mental health, and ultimately reduce demands on healthcare systems. However, high temperature and humidity can reduce a person's capacity and motivation to exercise (Périard et al., 2021). For those who continue to exercise despite high heat stress, their risk of heat-related illness is elevated due to the combination of environmental heat exposure and internal heat production generated from metabolic processes (Casanueva et al.; 2014). Data from the Lancet Countdown estimates that from 1991–2000 to 2012–2021, the number of annual hours in which meteorological conditions posed moderate risk and high risk of heat stress during light outdoor physical activity increased globally by an average of 281 (33% increase) and 238 (42%) hours per person, respectively (Romanello et al., 2022).

This indicator uses temperature and relative humidity data to estimate the number of hours people would be exposed to at least moderate risk of exertional heat stress when undertaking moderate intensity physical activity (for example, jogging or cycling). Heat stress risk is stratified into four categories – low, moderate, high, and extreme – in accordance with the 2021 Sports Medicine Australia Extreme Heat Policy. Sports and activities are further classified into five risk classification groups based on intensity of the activity and clothing worn (Chalmers and Jay, 2018). For the purposes of this analysis, the lowest sport risk classification, leisurely walking, was used, as this indicator is meant to reflect the risk to general populations rather than elite athletic populations.

Person-hours are calculated by determining the number of hours in a given day that the interpolated hourly combinations of temperature and relative humidity exceed at least the moderate heat stress risk threshold, multiplied by the number of people estimated to be within that same grid cell for that year per country. Thus, the person-hours at risk is the sum of total annual person-hours for each country.

Under the low-emissions scenario (SSP1-2.6, representative of a scenario in which temperatures remain below 2°C of heating above pre-industrial times), rising heat stress conditions are projected to result in 4.73 trillion more person-hours exceeding the moderate heat stress risk threshold for moderate intensity outdoor activity annually in the near term (2021–2040), than in the 1995–2014 baseline – a 45% increase (Figure 31).

These short-term estimates represent 1.5°C of heating, indicating the increased risk even under moderate temperature rise, and the need for rapid adaptation measures to be implemented. As heat stress keeps increasing in the medium term under the SSP1-2.6 scenario, the increase in the number of person-hours exceeding the moderate heat stress risk threshold is projected to increase to 65% above baseline (6.74 trillion more), falling back to 46% above baseline (4.77 trillion more) by 2081–2100.

In the high-emissions scenario (SSP3-7.0, representing no climate action), the person-hours of moderate or higher risk of heat stress increase substantially, with 112% more person-hours (11.6 trillion more person-hours) compared to baseline by 2041–2060 – resulting in 28% more person-hours in the 2°C representative scenario. Towards the end of the century, the high-emissions scenario would result in 218% more person-hours of at least moderate heat stress risk than in the 1995–2014 baseline (or 22.7 trillion extra), and in a 118% more person-hours than in the low-emission, scenario compatible with global temperature rise under 2°C.

The Asia-Pacific region would be the most affected under the high-emissions scenario by the end of the century (2081–2100), with the person-hour increase (11.1 trillion) 850% greater than the low-emissions scenario (1.30 trillion). In the case of Europe and the Americas, the estimated long-term person-hour increase will be relatively modest, even under the high-emissions scenario.

The countries set to benefit the most from keeping temperatures below 2°C are India, Nigeria, Pakistan, China, and Bangladesh (Figure 32). Estimated person-hour increases from baseline for India in 2081–2100 under SSP1-2.6 are less than one-sixth (912 billion) of those estimated with SSP3-7.0 (5,946 billion), while the increase in at least moderate heat stress risk person-hours in India in 2041–2060 under SSP3-7.0 will be approximately triple the value estimated in 2081–2100 under SSP1-2.6. Under SSP1-2.6, China is estimated to have a 281 billion reduction in at least moderate heat stress risk per person-hours in 2081–2100 compared to the present-day baseline, whereas a 437 billion person-hour increase is estimated under SSP3-7.0.

Loss of Labor Productivity

Heat stress poses physiological limits to physical work, forcing workers to reduce their work intensity or to take longer breaks to avoid serious health effects. This leads to loss of labor productivity. The associated loss in income and threats to livelihoods undermines the socioeconomic conditions that good health and wellbeing depend on and undermines sustainable development. The Lancet Countdown estimates that approximately 470 billion potential labor hours could have been lost globally in 2021, a 37% increase from the annual average in 1990–1999 (Romanello et al., 2022). Climate change–induced increases in temperature and humidity will further reduce productivity worldwide (Kjellstrom et al., 2018).

Low-income workers in agriculture

and construction are the most vulnerable to increasing heat as much of their daily work depends on labor unprotected from outdoor heat exposure. However, millions of indoor factory and workshop workers in low- and middle-income countries are also at risk of serious effects of excessive heat as their workplaces are seldom air conditioned. Climate change will increase heat exposure in most parts of the world and this will also undermine efforts for poverty reduction in vulnerable countries (UNDP, 2016). Heat stress is caused by a combination of ambient temperature, humidity, wind speed, solar heat radiation, work intensity (here, wattage W), and clothing (Parsons, 2014).

This indicator uses an exposure-response function (based on actual productivity loss) combined with temperature, dew point, and solar radiation data to estimate the impact of heat exposure on labor productivity (Kjellstrom et al., 2018). Results are presented as Percentage Work Hours Lost (PWHL) at three work intensities: light work (sitting or moving around slowly, equivalent to working in an office), medium (common manufacturing work), or heavy (typical agriculture or construction labor), corresponding to metabolic rates of 200 W, 300 W and 400 W, respectively. Because heat stress working in the sun is generally markedly greater than that in the shade, the work hours loss expected to occur when workers are exposed to the sun is presented separately (PWHL-400-sun).

Globally, the 1995–2014 baseline PWHL ranges from 1% to 7.6% for light work in the shade (200 W) to heavy work in the sun (400 W). In the near term, there will be a slight increase in the PWHL under both emissions scenarios; however, the difference between SSP1-2.6, which is compatible with 1.5°C of heating, and SSP3-7.0, is small. Despite this, these findings highlight the increased likelihood of health hazards under 1.5°C of warming and the need for rapid adaptation. In the medium and long term, the changes are far greater; by 2081–2100, the PWHL for work at 300 W is 5% and 11% under SSP1-2.6

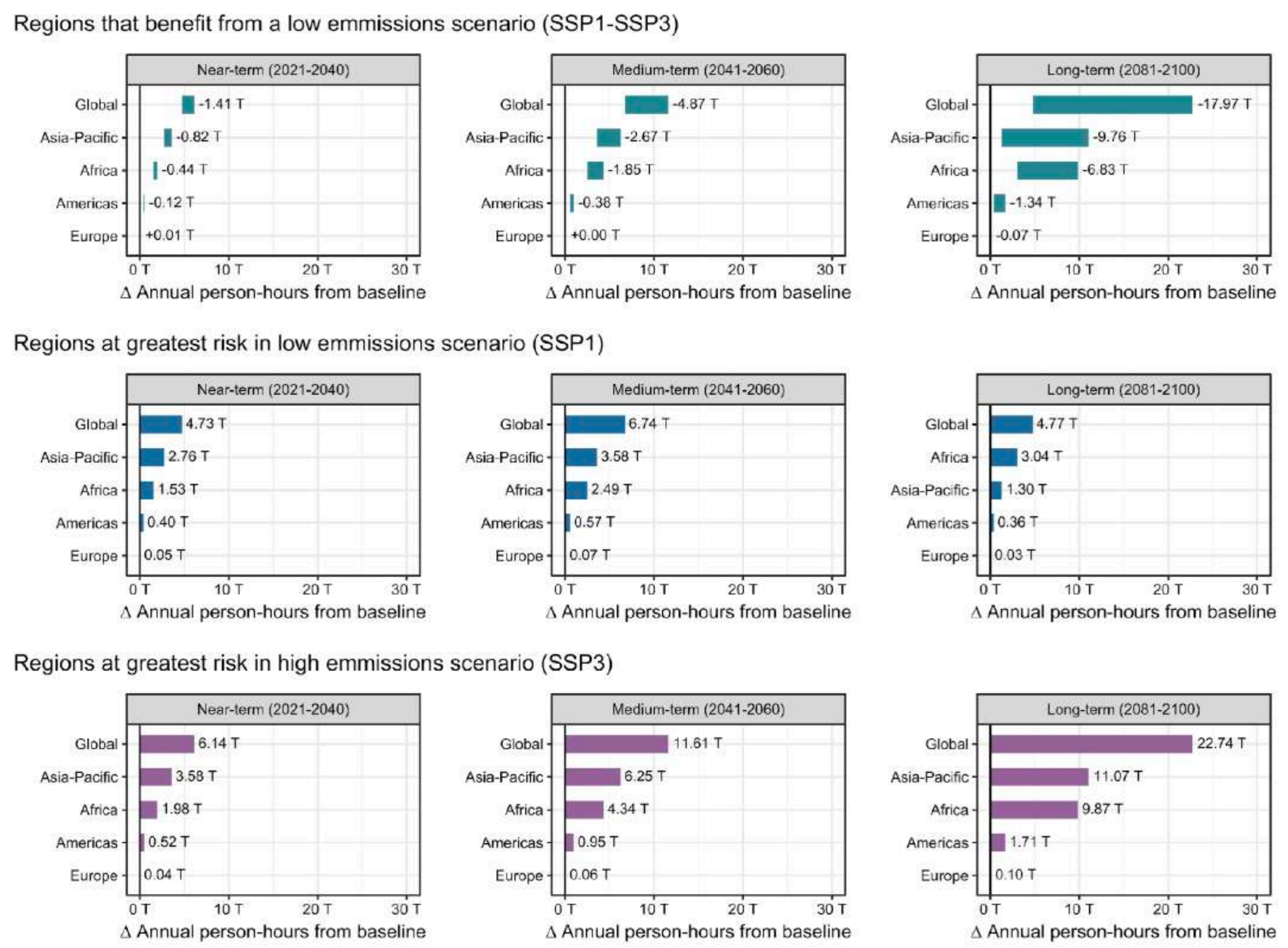


Figure 31: Change in annual person-hours of exposure to at least moderate heat stress risk during moderate intensity physical activity for low-emissions (SSP1-2.6) and high emissions (SSP3-7.0) pathways by region and period. The top panels illustrate the magnitude of benefit a given region may experience from SSP1-2.6 vs. SSP3-7.0. The leftmost edge of each bar denotes the projected value for SSP1-2.6 and the rightmost edge represents the value projected for SSP3-7.0. The bar length and adjacent text show the magnitude of benefit experienced by the corresponding region. The middle and bottom panels illustrate the changes in person-hours of at least moderate risk exposure from the baseline period for SSP1-2.6 and SSP3-7.0, respectively. T = trillion.

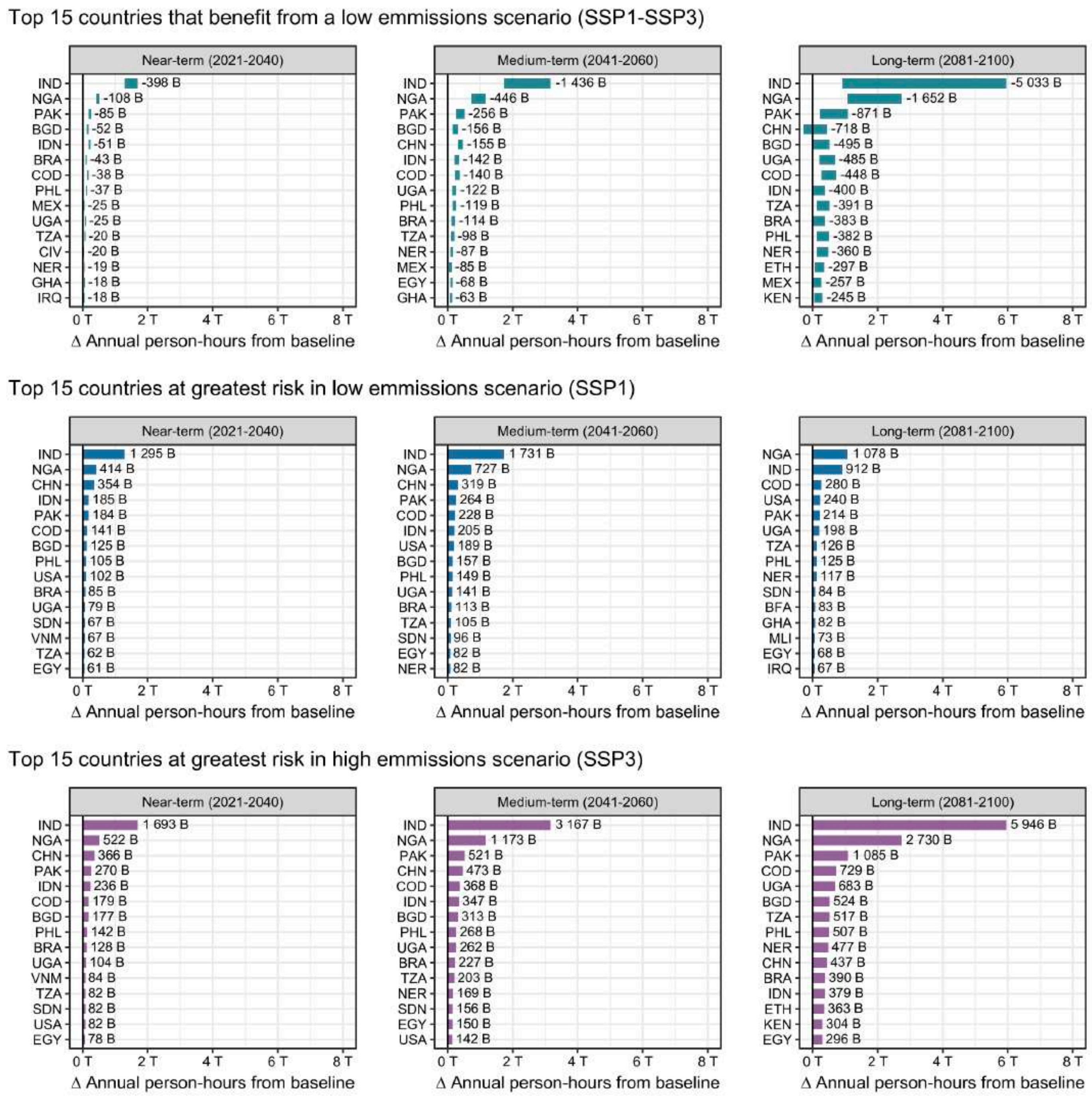


Figure 32: Change in annual person-hours of exposure to at least moderate heat stress risk during moderate intensity physical activity for low-emissions (SSP1-2.6) and high-emissions (SSP3-7.0) pathways by period for the top 15 countries that benefit from the low-emissions scenario. The top panels illustrate the magnitude of benefit a given country may experience from SSP1-2.6 vs. SSP3-7.0. The leftmost edge of each bar denotes the projected value for SSP1-2.6 and the rightmost edge of each bar represents the value projected for SSP3-7.0. The bar length and adjacent text thus show the magnitude of benefit experienced by the corresponding country. The middle and bottom panels illustrate the changes in person-hours of at least moderate risk exposure from the baseline period for SSP1-2.6 and SSP3-7.0, respectively.

and SSP3-7.0, respectively. For work at 400 W in the sun, the corresponding figures are 12% and 20%, with the latter scenario compatible with 3.6°C of heating.

As Figure 4 shows for 21 global sub-regions, the PWHL will increase significantly more in the high-emissions scenario (SSP3-7.0, representing no climate action) than in the low-emissions scenario (SSP1-2.6, representing a trajectory that keeps global mean temperature rise under 2°C). The percentage of labor hours lost increases slightly until 2041–2060 in the low-emissions scenario and stabilizes thereafter. On the contrary, the loss of work hours continues to increase until the end of the century in the high-emissions scenario across most regions. The northern sub-regions (Russia/North Asia, Eastern Europe, Western Europe, and Northern Europe) are the least severely affected under the high-emissions scenario (with less than 1% of all heavy labor hours being lost) and remain practically unaffected under the low-emissions scenario. However, these estimates are based on modeled variations in mean and variance of heat levels and do not reflect the productivity loss occurring during severe heatwaves in these regions.

The greatest increase in the loss of labor hours is projected in the warmest latitudes, including Central Africa (an extra 10.4% of PWHL in the high-emissions scenario, vs an extra 2.3% PWHL in the low-emissions scenario), West Africa (extra 13.3% PWHL in under high emissions vs 3.61% under low emissions), South Asia (extra 10.3% PWHL in under high emissions vs 3.8% under low emissions) and Southeast Asia (extra 12.2% PWHL in under high emissions vs 3.9% under low emissions). In these highly affected regions, there will be on average an extra 7.8 percentage points of heavy labor hours lost under the high-emissions scenario than under the low-emissions scenario (Figure 33).

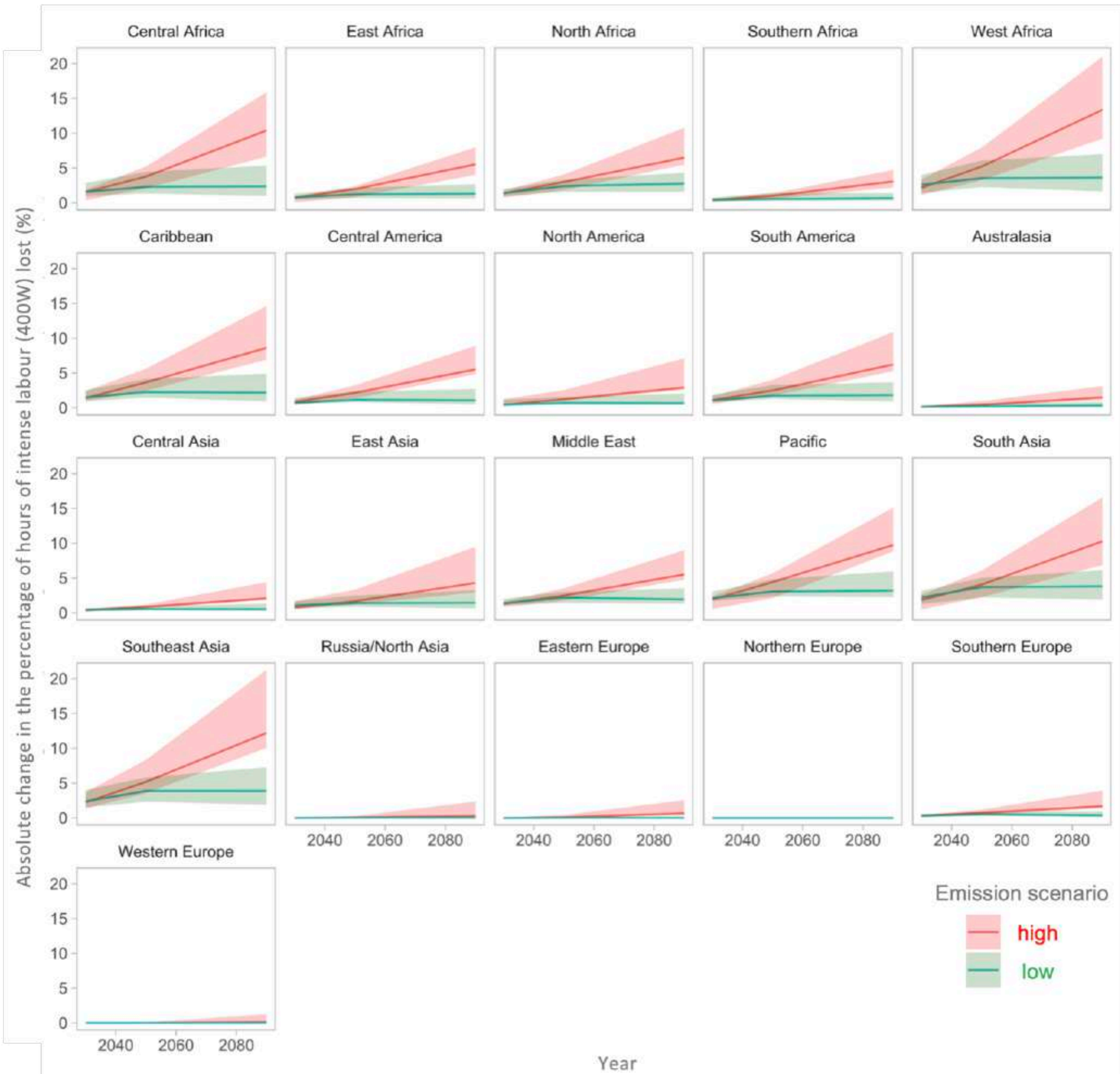


Figure 33 Change in the percentage of high-intensity work hours lost (at 400 W) in the shade under high-emissions (SSP3-7.0) and low-emission (SSP1-2.6) scenarios, by world sub-region

Under the high-emissions scenario, almost half of the African nations are projected to see an increase of PWHL of more than 10% by 2081–2100 (Figure 34). The total PWHL due to heat will have exceeded 25% of the total work hours in hot countries such as Cambodia, South Sudan, Ghana, and Guyana, and most of the severely affected countries are in the tropics (Figure 34). Reducing emissions to SSP1-2.6 limits all but one country's 2081–2100 increase to less than 5% (not shown in Figure 34).

Heat-Related Mortality

At 1.1°C of global mean heating, one third of all heat-related deaths today can already be attributed to climate change (Vicedo-Cabrera et al, 2021). The number of heat-related deaths is set to rise unless more ambitious mitigation and adaptation strategies are implemented. Central and South America, Africa, India, Southeast Asia, and Northern Australia are projected to experience a greater number of days per year where the temperature poses an acute threat to life (Mitchell et al., 2016). Socially deprived populations, such as the elderly, pregnant women, newborns, those with underlying health conditions, and those working outdoors or in uncooled indoor areas are particularly at risk (S. Campbell et al., 2018; Chersich et al., 2020).

This indicator uses an epidemiological model that incorporates estimates of daily non-injury mortality, demographic changes, and temperature, to estimate the potential increase in heat-related mortality of people over 65 years of age under future climate change scenarios, providing an indication of the how the risk will increase if there is no extra adaptation or acclimation (Honda et al., 2014).

Globally, without further adaptation, heat-related mortality in people over 65 is projected to rise in both the high-emissions scenario, representative of one of no climate action (SSP3-7.0), and the low-emissions scenario, compatible with under 2°C of heating by the end of the century. However, the increase in mortality is expected to be markedly more in the high-emissions scenario, particularly in the medium and long term.

In this high-emissions scenario, deaths are projected to rise from 205,000 annual deaths in 1995–2014, to around 484,000 by 2021–2040 (137% increase), 1,090,000 by 2041–2060 (433% increase), and 3,351,000 by 2080–2100 (1537% increase). Under the low-emissions scenario, on the contrary, 481,000 extra heat-related deaths are projected by 2021–2040 (135% increase), 962,000 by 2041–2060 (370% increase), and 1,398,000 by 2080–2100 (683% increase).

These projections expose the number lives that could potentially be saved by meeting Paris Agreement goals, with about 56% of the extra heat-related deaths projected under the high-emissions scenario avoided in the low-emissions scenario compatible with under 2°C of heating by the end of the century, and 91% avoided if temperatures are kept below 1.5°C. More specifically, 3,000 additional lives could be saved by limiting warming to 1.5°C in the near term, a figure that rises to 1,953,000 lives potentially saved by 2080–2100. Despite this, heat-related mortality is projected to rise even if temperatures are kept below 1.5°C of warming, highlighting the urgent need for countries to implement measures to protect vulnerable populations from this growing hazard.

The South Asia sub-region is expected to incur the highest number of heat-related deaths by

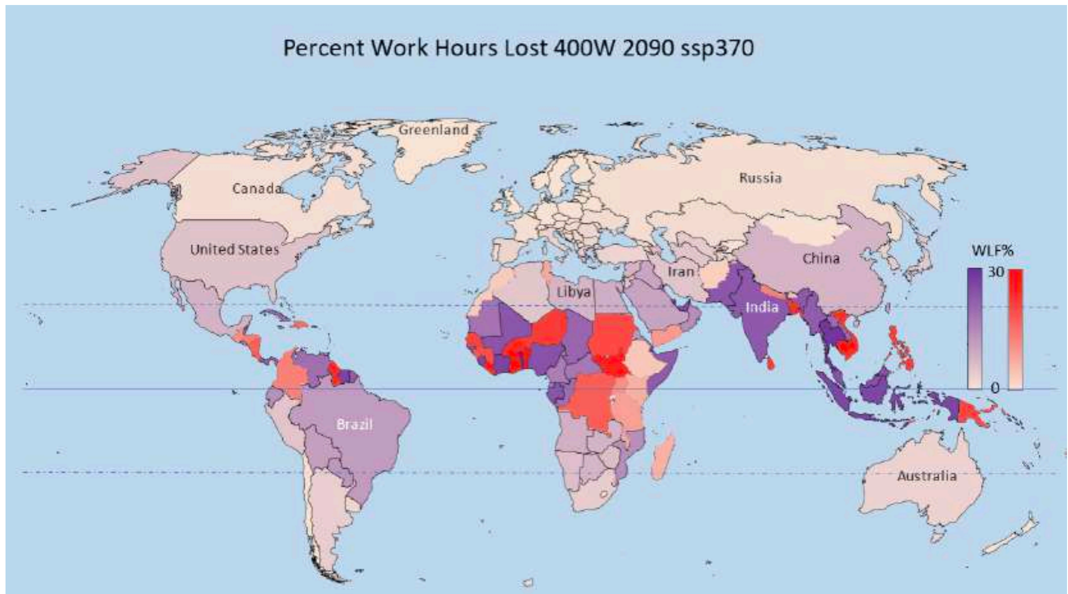


Figure 34: Map of the percentage of work hours lost (at 400 W in shade) in 2081–2100 for SSP3-7.0. Shades of red are Climate Vulnerable Forum (CVF) countries. The intensity of the red and purple gives the percent PWHL, ranging from 0% (for example, Russia and Mongolia) to 30% (for example, Qatar and Benin)

the end of the century under all scenarios, although heat-related deaths will be three times more in the high-emissions scenario than in the low-emissions scenario (Figure 35). East Africa, West Africa, and East Asia are also expected to incur high levels of heat-related deaths under the high-emissions scenario, with 383,000, 265,000, and 226,000 deaths per year by the end of the century, respectively.

As observed with heatwave exposure, heat-related mortality in populations over 65 in Europe is expected to be higher in the low-emissions scenario than in the high-emissions scenario – a finding explained by a lower life expectancy anticipated in Europe under the high-emissions scenario, leading to a smaller over-65 population in this scenario than in the low-emissions scenario.

At country level, India is expected to have the highest number of deaths under the high-emissions scenario by the end of the century, with 980,000 deaths each year (Figure 36). This would be reduced by 71% to 282,000 deaths per year under the low-emissions scenario. The country with the second-highest number of heat-related deaths would be China, with 215,000 deaths a year by the end of the century – a value that could be reduced by 14% to 186,000 deaths in the low-emissions scenario.

Wildfires

The land area burned by wildfires has increased in many world regions, including Amazon, the Arctic, Australia, North America, and parts of Africa and Asia, and fire seasons have lengthened on 25% of vegetated area since 1979 (IPCC, *Sixth Assessment Report, Chapter II*). Data from the Lancet Countdown suggests that, from 2001–2004 to 2018–2021, people were exposed on average to nine extra days of very or extremely high meteorological wildfire danger, with increases observed in 61% countries (Romanello et al., 2022).

Today, up to 90% of wildfires are started by humans – either accidentally, or deliberately as part of industrial forest management and exploitation, agricultural practices, or intentional acts of arson. The drier and hotter conditions associated with climate change increasingly favor the occurrence, intensity, and spread of wildfires, undermining management and control efforts (Balch et al., 2017; Sofiev and Borunda, 2013).

Wildfires can lead to life-threatening thermal injuries, and exposure to wildfire smoke can exacerbate adverse respiratory outcomes, cause acute eye damage, and increase the risk of chronic

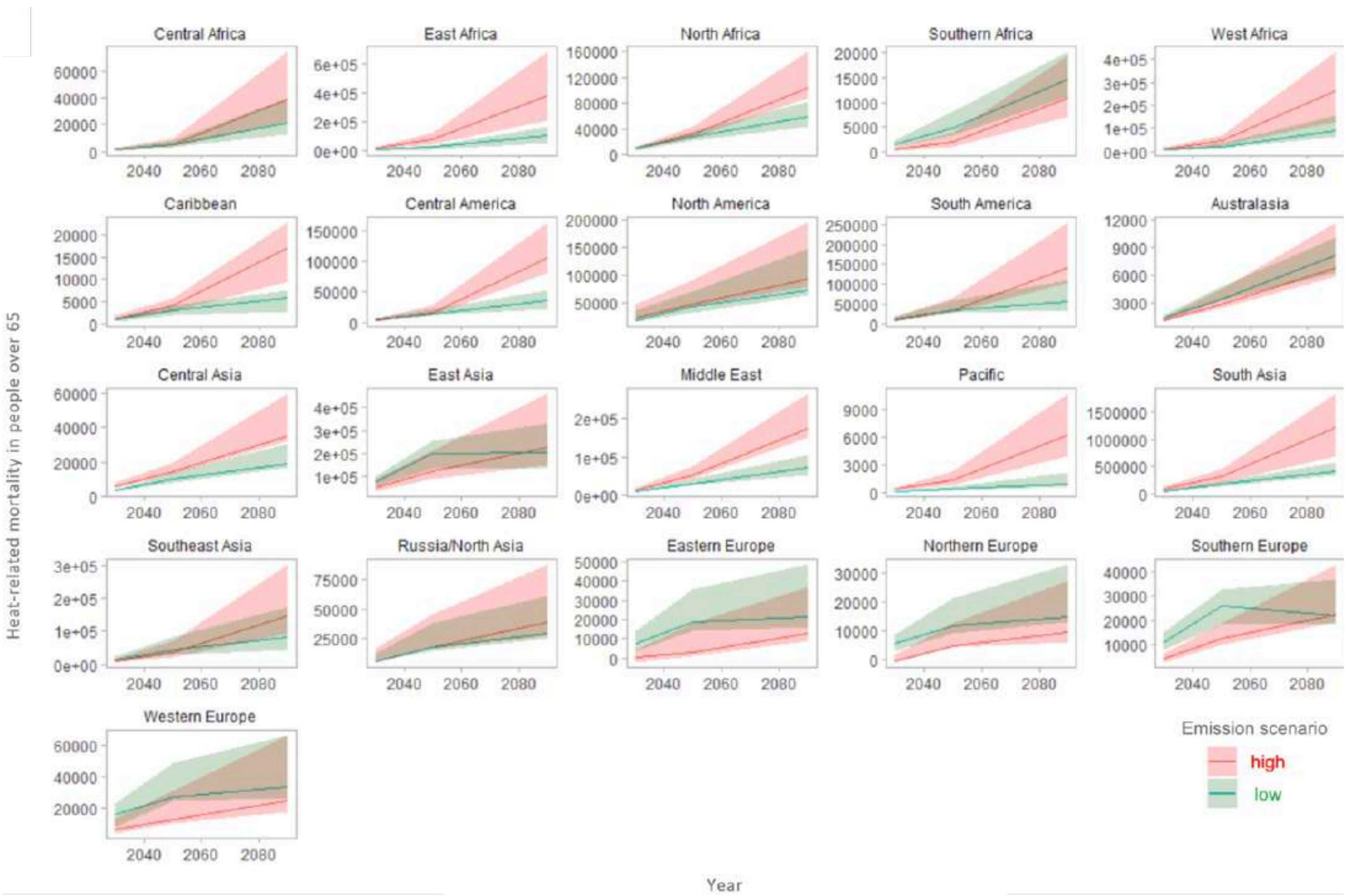


Figure 35: Heat-related mortality under low-emissions (SSP1-2.6) and high-emission (SSP3-7.0) scenarios, by world sub-region. The shaded areas represent the range between the maximum and minimum values obtained using the five GCMs.

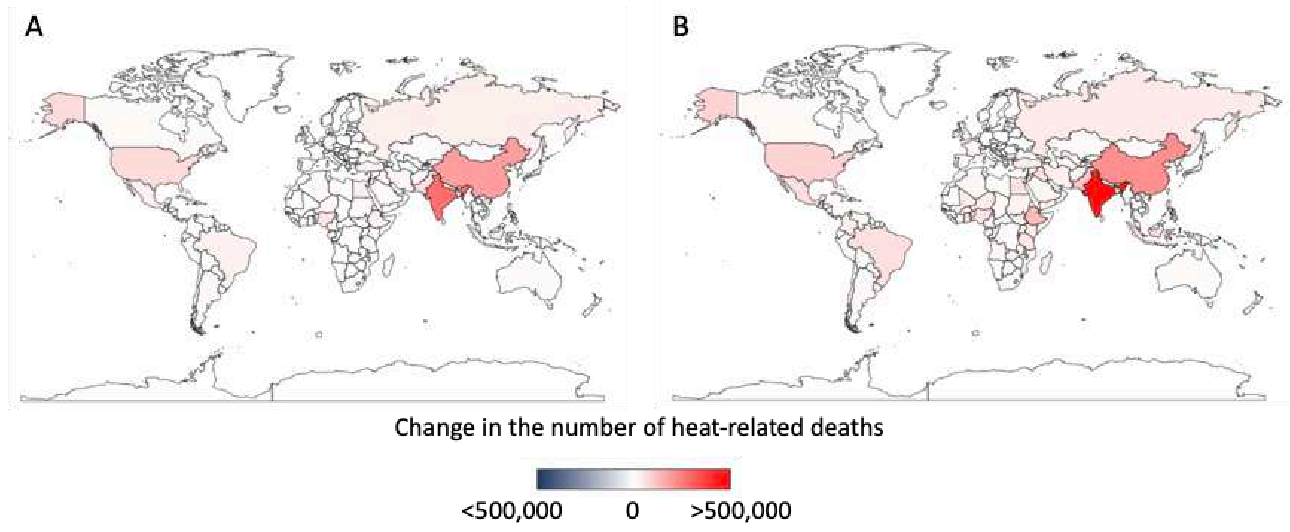


Figure 36: Change in the number of heat-related deaths in low-emissions (SSP1-2.6) and high-emissions (SSP3-7.0) scenarios, compared to 1995–2014

respiratory, cardiovascular, and neurological disease (Reid and Maestas, 2019). When loss of physical infrastructure and disruption of essential services occurs, this can also lead to adverse physical and mental health outcomes. The associated economic losses, particularly in lower income settings where the losses are mostly uninsured, in turn undermine the socioeconomic conditions that health and wellbeing depend on (Kollanus et al., 2017; Masson-Delmotte et al., 2022; Romanello et al. 2022; Xu et al., 2021).

With temperatures, drought, and aridity rising as a result of climate change, the frequency of wildfires is set to increase in most parts of the world, especially under the higher-emission scenarios (Sun et al., 2019). Coupled with growing population numbers, health impacts are likewise set to rise (Reid and Maestas, 2019).

Monitoring the human exposure to days in which the wildfire danger is high can help identify populations at risk and implement adaptive measures to manage wildfire incidence, spread, and the associated impact on human health and wellbeing (Khabarov et al., 2016; Xu et al., 2021). This indicator estimates the number of days people will be exposed to days of very high or extremely high meteorological danger of wildfires, under different future climate change scenarios. It combines population data with estimates of fire danger projections, accounting for changes in daily maximum temperature, minimum relative humidity, precipitation, and maximum wind speed. The indicator is developed based on the Fire Danger Index calculated from future climate projections – numeric rating values 1–6, representing very low, low, medium, high, very high, and extremely high fire danger risk, respectively, determined by daily Fire Weather Index.

Globally, exposure to very high or extremely high wildfire danger is projected to increase in both the low-emissions scenario (compatible with global heating below 2°C), and the high-emissions scenario (representative of a future with no climate action). Under the low-emissions scenario in the near term (2021–2040) (comparable to a global mean temperature rise of 1.5°C), the number of days each person is exposed to very high or extremely high wildfire risk is projected to increase on average by 6.7 days, or 8.5% from a 1995–2014 baseline – a similar increase to the one projected under the high-emissions scenario. This highlights the need for rapid implementation of fire control and prevention measures, including strengthening environmental legislation and institutions, and health system warning and response systems.

However, in the long term (2081–2100), the increase in exposure to wildfire danger is projected to be substantially more in the high-emissions scenario than in the low-emissions scenario, underlining the benefits of ambitious climate action: in the low-emissions scenario, the exposure to very high or extremely high wildfire danger is projected to increase by 9.6 days per person, or a 12.3% increase from baseline. In contrast, exposure is projected to increase three times more in the high-emissions scenario, by 27 days (a 34% increase from the 1995–2014 baseline).

At the sub-regional level, the largest increase in the number of days people are exposed to extremely high or very high wildfire risk by the end of the century is projected to occur in the Middle East (74 more person-days than in baseline, or a 254% increase), followed by the Southern Africa (65 more days, or 516% above baseline), and North Africa (45 more days, or 148% above baseline) (Figure 37). In these regions, the increase in exposure would be substantially less under the low-emissions scenario, with an 18% increase (17 days) from the baseline in the Asia-Pacific region, and a 7% increase (12 days) in Africa. At a country level, the biggest increases in exposure to very high or extremely high wildfire danger by the end of the century are expected to occur in Middle East countries including Yemen, Israel, Jordan and Syria, where exposure is projected to increase by 127 (169% increase), 95 (442%), 88 (61%), and 83 (79%) days per person, respectively. Other countries set to see large increases in exposure under unabated climate change include Botswana, Lebanon, Algeria, Zambia, Benin, and Kenya (Figure 38).

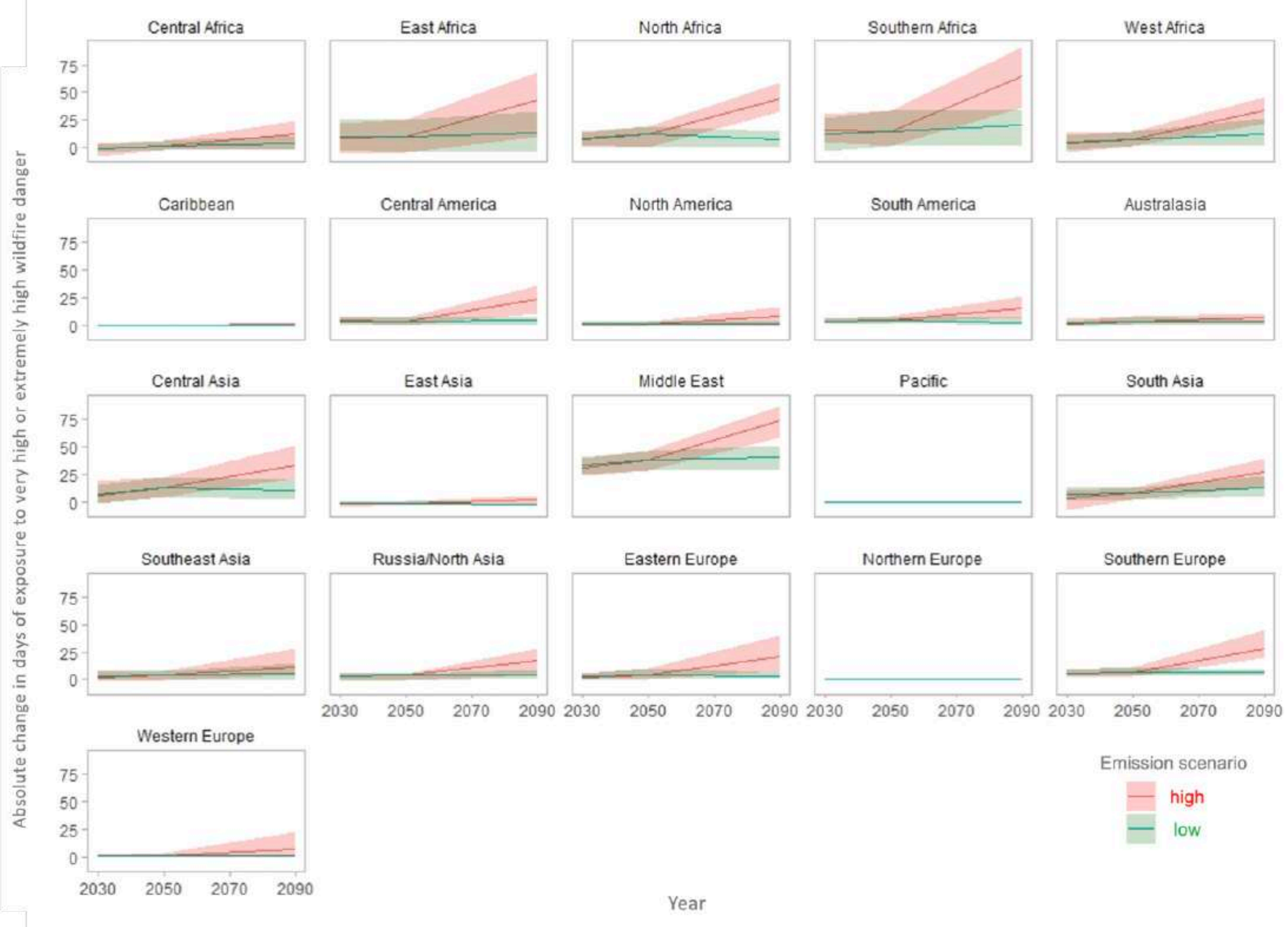


Figure 37: Absolute change in the days of exposure to very high or extremely high wildfire danger per person, in the high-emissions and the low-emissions scenarios, per world sub-region. The shaded areas represent the range between the maximum and minimum values obtained using the five GCMs.

Infectious Diseases

Climate change–driven changes in environmental conditions increase the likelihood of transmission of infectious diseases that are sensitive to the environment, including airborne, waterborne, food-borne, and arthropod-borne diseases (Caminade et al., 2019; Semenza et al., 2018). Changes in air and water temperature, humidity, precipitation patterns, and water accumulation in many cases increase the environmental suitability for the transmission of diseases of public health concern, including dengue, Zika, chikungunya, malaria, vibriosis, West Nile Virus, and many others (Semenza, 2020). This adds extra pressure on disease control and prevention efforts, and increases the risk of disease transmission in areas that might have been previously unsuitable, exposing populations to new and re-emerging diseases. The incidence of disease will be influenced by disease management and control measures, as well as the availability and quality of sanitation services, access to clean water and safe food, healthcare quality, and population movement. The COVID-19 pandemic has exposed the hazards of infectious disease spread on a global scale, and the fragility of our current health systems. As the risk of infectious disease transmission rises, there is an increasing need to strengthen health systems, and implement climate-sensitive surveillance, early warning and early response systems.

Indicators in this section model the future change in the environmentally determined risk for the transmission of infectious diseases of high public health concern, including dengue, malaria, and vibriosis. It is worth noting that modeled cases do not equate to actual expected cases, but are indicators of the potential for outbreaks or risk of infection under different emissions scenarios.

Dengue

Dengue fever is a viral tropical and subtropical disease transmitted to humans by mosquitoes (mostly *Ae. aegypti* and *Ae. albopictus*) and is responsible for a high burden of disease globally. Dengue is a leading cause of serious illness and disease in many low- and middle-income countries, primarily affecting populations in the Caribbean, Central America, South America, Africa, and South Asia (World Health Organization, 2022). Cases of dengue have doubled every decade since 1990, with an estimated almost 60 million cases in 2013, accounting for more than 10,000

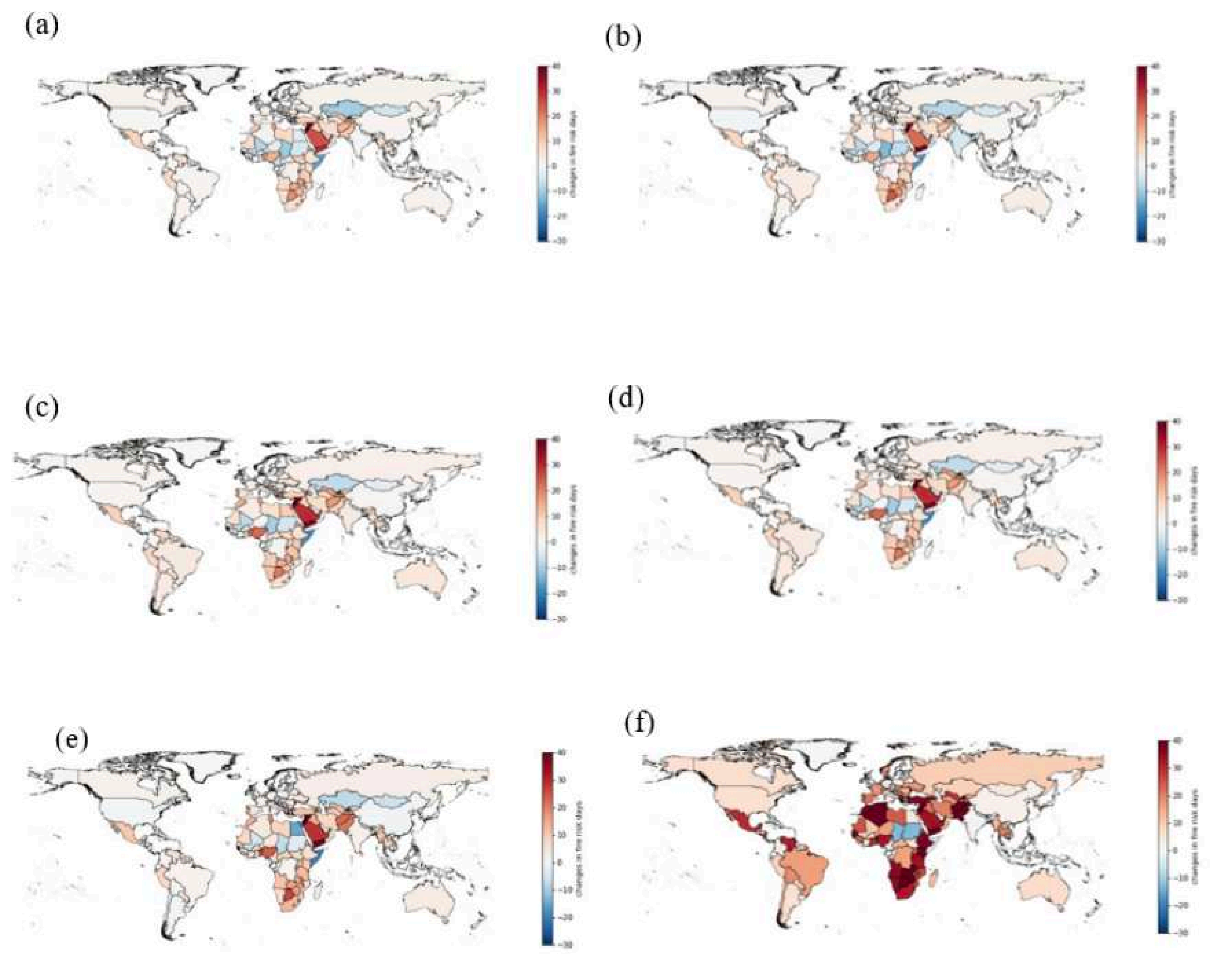


Figure 38: Population-weighted mean changes in extremely high and very high fire danger days for the 2021–2040 period in (A) SSP1-2.6 and (B) SSP3-7.0; 2041–2060 in (C) SSP1-2.6 and (D) SSP3-7.0; and 2080–2100 in (E) SSP1-2.6 and (F) SSP3-7.0, compared with 1995–2014. Large urban areas with population density ≥400 persons/km2 are excluded

deaths and 1.14 million disability-adjusted life-years (Zeng et al., 2018; Stanaway et al., 2016). Approximately half of the global population today resides in areas that are environmentally suitable for its transmission (World Health Organization, 2022). Together with population growth, unplanned and uncontrolled urbanization, increased travel, and inadequate water storage practices, climate change is a main driver behind this increase (Gubler, 2012; L. P. Campbell et al., 2018). The Lancet Countdown estimates that the climatic suitability for the transmission of dengue increased by 11.5% for *Aedes aegypti* and 12.0% for *A. albopictus* from 1951–1960 to 2012–2021, at a global level, driven by changes in temperature and precipitation (Romanello et al., 2022).

This indicator uses a process-based mathematical model to estimate the R_0 (that is, the basic reproduction number, which represents the expected number of secondary infections resulting from one single primary infected person case in a totally susceptible population), for dengue transmission, taking into account the influence of temperature change (Rocklöv et al.). It is worth noting, however, that the models used do not take into account the potential adaptation of the *Aedes* vector in terms of environmental or climatic thresholds, which would likely alter the transmission dynamics of dengue fever, and perpetuate its transmission even under conditions today considered unsuitable.

Under the low-emissions scenario (SSP1-2.6, compatible with global temperature rise below 2°C), the R_0 for dengue transmission is expected to increase slightly by 0.13 (10% above the baseline) for *Ae. aegypti* and 0.08 (12% above the baseline) for *Ae. Albopictus* in 2021–2040, with respect to a 1995–2014 baseline, on average globally. Further into the future, R_0 is projected to increase to 0.19 (15%) for *Ae. aegypti* and 0.12 (16%) for *Ae. Albopictus* above the baseline in 2041–2060; and declined slightly to 0.18 (14%) for *Ae. aegypti* and 0.11 (16%) for *Ae. albopictus* above the baseline by the end of the century (2080–2100). On the contrary, under the high-emissions scenario, projections indicate a considerably higher increase in R_0 for dengue transmission of 0.25 (20%) for *Ae. aegypti* and 0.16 (22%) for *Ae. Albopictus* in 2041–2060 and

0.35 (28%) for *Ae. aegypti* and 0.24 (34%) for *Ae. Albopictus* in 2081–2100 compared to the baseline. In the high-emissions scenario the increase in R_0 would therefore be approximately twice the increase in the low-emissions scenario by the end of the century, noting the heightened risk for dengue transmission under a hotter climate (Figure 39).

Under the high-emissions scenario, increases in R_0 are observed in colder latitudes that are not endemic to the virus in the present day, including southern, western, and central Europe, northern America, southern Australia, southern China (Figure 39). On the contrary, the R_0 over hotter areas, including most of the Sahel, Brazil, Venezuela, Egypt, Libya, Somalia, northern India, and northern Australia, is projected to decrease by the end of the century as temperatures rise and conditions become too extreme for the transmission of dengue by *Aedes* mosquitoes.

The number of countries that have an R_0 above 1, indicating suitability for an outbreak, is projected to increase from 117 to 123 countries (4% increase) from baseline years in the short term under SSP1-2.6 (compatible with 1.5°C of heating), to 123 countries (5% increase) by the end of the century in the low-emissions scenario (compatible with under 2°C of heating), and to 143 countries (22% increase) in the high-emissions scenario (compatible with no climate action). These findings highlight the urgent need for adaptation measures as R_0 is projected to increase, even in a scenario compatible with 1.5°C of heating. R_0 is projected to increase to levels that support epidemic growth (R_0 greater than one) in some areas in which the R_0 is well below one in present day, including southern Europe (Italy, Greece, and Spain) and the Balkans, particularly under the high-emissions scenario, indicating that the Mediterranean region and the Balkans are especially at risk from the re-emergence of dengue. The countries with highest increase in R_0 with respect to the 1995–2014 baseline by the end of the century in the high-emission scenario are projected to be Equatorial Guinea, Congo, the Democratic Republic of Congo, Timor-Leste, and Angola (Figure 40).

Vibrio

Vibrio bacteria are globally distributed aquatic bacteria, ubiquitous in warm estuarine and coastal waters with low to moderate salinity. They include human pathogenic species such as *Vibrio parahaemolyticus, Vibrio vulnificus,* and *Vibrio cholerae* (Trinanes and Martinez-Urtaza, 2021), which can cause severe gastroenteritis, wound infections, ear infections, and life-threatening septicemia (Osunla and Okoh, 2017). Climate change–induced variations in seawater temperature and salinity influence *Vibrio* ecology, abundance, distribution, and patterns of infection, with the incidence of disease outbreaks increasing and the geographic range of infection expanding in recent decades (Martinez-Urtaza et al., 2018; Muhling et al., 2017; Parveen et al., 2008; Deeb et al., 2018). Data from the Lancet Countdown suggests that, between 2014–2021 and 1982–1989, changes in sea salt concentrations and temperature drove the area of coastline suitable for *Vibrio* pathogens to increase from 47.5% to 86.3% in the Baltic, 30.0% to 57.1% in the US Northeast, and from 1.2% to 5.7% in the Pacific Northwest, three regions where vibriosis is regularly reported (Romanello et al., 2022).

Coastal populations are most at risk from the transmission of *Vibrio* in estuarine waters. Currently, 40% of the world's urban population lives in coastal areas and an important number of goods and services are obtained from coastal marine ecosystems. Within this context, shifts in population and demography in coastal areas are likely to play a major role in shaping exposure to *Vibrio* pathogens, and the associated burden of disease.

This indicator estimates the future environmental suitability for pathogenic Vibrio *spp.* in coastal zones globally (<30 km from the coast) and calculates the percentage of the coastal area that is suitable, at least for one month each year, for *Vibrio* transmission. The indicator uses thresholds of temperature above 18°C for sea surface temperature and practical salinity units (PSU) below 28 for sea surface salinity to identify the months in which sea conditions were suitable for the transmission of these pathogens. To account for the risk that coastal populations in particular face, the indicator also estimates the population potentially affected by exposure to *Vibrio,* defined as those located within 100 km of coastal areas exhibiting *Vibrio* suitability.

In baseline years (1995–2014), there were a total of 74,300 km of coastline with suitable conditions for *Vibrio* transmission globally, which represents 5% of the total of the coastline in the planet. Under the low-emissions scenario compatible with global heating under 2°C (SSP1-2.6), this length is expected to increase by 8,933 km (12% increase) in the near term (2021–2040, representative of 1.5°C of heating), by 26,800 km (36% increase) in the medium term (2041–2060), and by 36,500 km (49% increase) in the long term (2081–2100). These findings highlight the urgent need for adaptation measures as health hazards are projected to increase, even in a scenario compatible with 1.5°C of heating. Under the high-emissions scenario compatible with no climate action (SSP3-7.0), the increase in the coastline suitable is markedly higher, particularly towards the end of the century. The coastal area suitable for *Vibrio* could increase by 12,100 km (16% increase) in the near term, by 24,400 km (33% increase) in the medium term, and by 76,669 km (103% increase) in the long term – reaching a total of 151,000 km of suitable coastline (10% of the global total) towards the end of the century.

The countries most affected by changes in sea salt concentrations and temperature have been identified in the Baltic region, Gulf

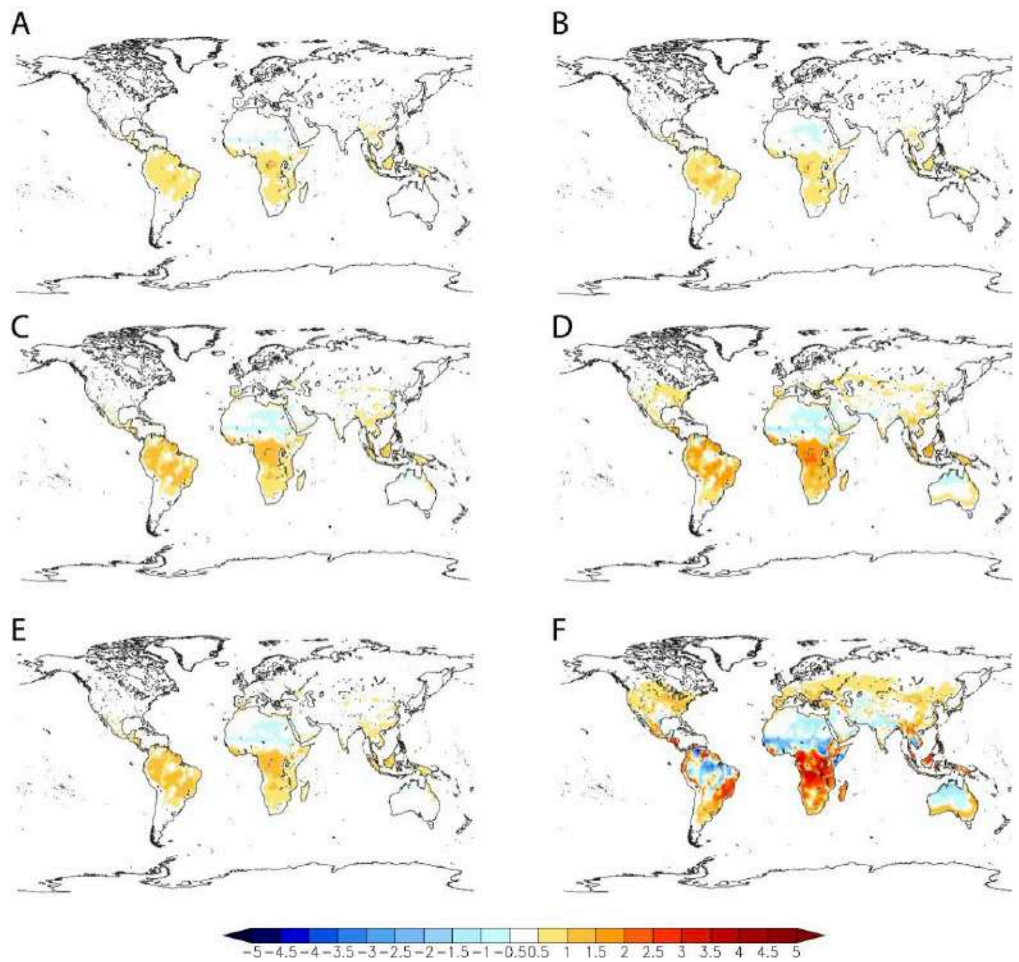


Figure 39: Mean model ensemble future changes in R_0 for 2021–2040 (A and B), 2041–2060 (C and D) and 2081–2100 (E and F) under the low (first column, A, C, and E) and high (second column, B, D, and F) emissions scenario relative to the reference period (1995–2014) for Ae. aegypti.

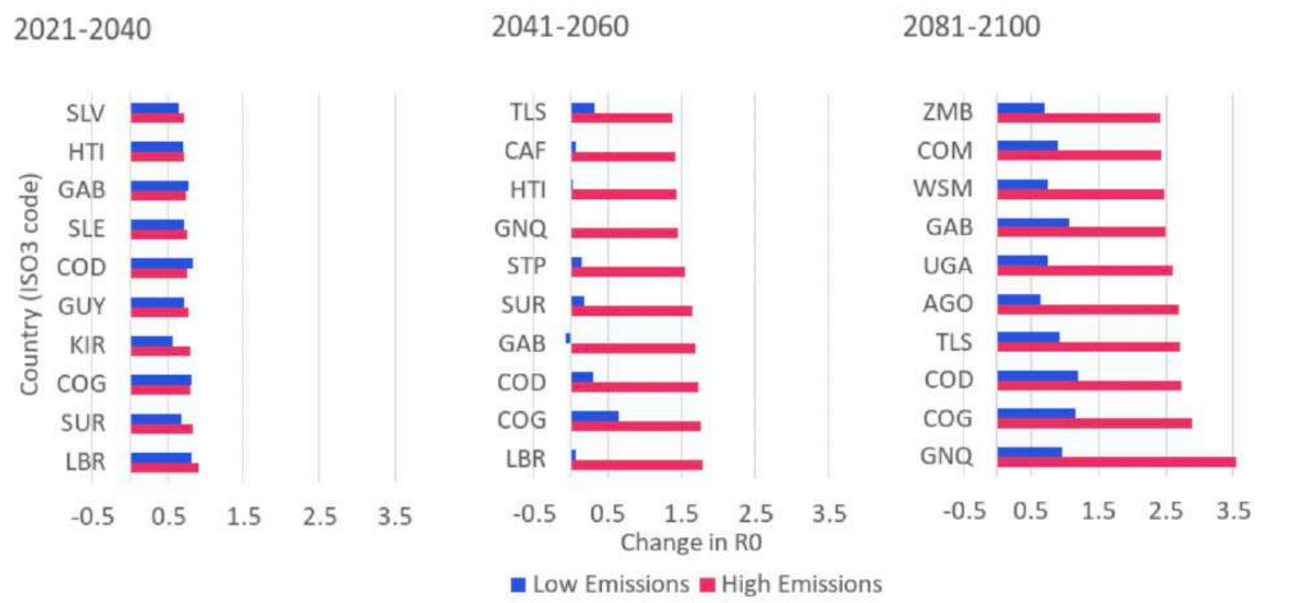


Figure 40: Top 10 countries (indicated by ISO3 code) with the highest absolute increase in R_0 under the high-emissions scenario in the short (2021–2040), medium (2041–2060) and long term (2081–2100), with respect to the 1995–2014 baseline

of Guinea, North America, and Peru, Uruguay, and Venezuela in South America. Particularly relevant is the situation in the Baltic areas, with countries showing values ranging from 80–100% of coastline suitable for *Vibrio* by 2100 under the high-emissions scenario (Figure 41).

In the baseline period (1995–2014), data suggests that a total of 467 million people (8% of the global population) lived near coastal areas suitable for *Vibrio* over the historical period and, consequently, were potentially exposed to the pathogen and at risk of infections. According to projections of population growth in those areas showing favorable conditions for *Vibrio*, it is expected an extra 621 million people (remaining around a value of 8% of the global total population with the future fluctuations) would be at risk from *Vibrio* transmission by 2080–2100 under the low-emissions scenario and could reach a value of 1,121 million (9.5% of the global total population) under the high-emissions scenario.

Malaria

Malaria is a leading cause of global morbidity and mortality, with Sub-Saharan Africa bearing the highest burden of cases concentrated among the under-five population (Dao et al., 2021). Despite much recent progress in its control, it remains one of the most serious challenges to global health. According to the latest World Malaria Report, there were 241 million cases in 85 endemic countries in 2020, with an annual mortality rate of 15 deaths per 100,000 population at risk (World Health Organization, 2022). The seasonality and spatial distribution of malaria cases are affected by weather parameters such as temperature, precipitation, and relative humidity, which influence the population dynamics and biting rates of the *Anopheles* mosquitoes that transmit the disease (Wang et al., 2022).

This indicator uses empirically determined thresholds of temperature, relative humidity, and precipitation to identify the number of months per year in which the environmental conditions were suitable for the transmission of *Plasmodium falciparum*, the most widely spread pathogen causing malaria (Grover-Kopec et al., 2006). Suitability for a particular month was defined as the coincidence of precipitation accumulation greater than 80 mm, average temperature between 18°C and 33°C, and relative humidity greater than 60% (Grover-Kopec et al., 2006). These combined values reflect the limits for the potential transmission of *Plasmodium falciparum* parasites according to current biological thresholds. Longer transmission seasons will result in a higher burden of malaria disease, unless strong adaptation measures are implemented.

As the climate changes, areas of the world which in 1995–2014 were not suitable for malaria transmission will begin having climatic conditions that would favour the transmission of this disease. In the short term, under the low-emissions scenario (compatible with 1.5°C of heating), 12% of the areas with no historic malaria suitability will become newly suitable for malaria transmission. In the high-emissions scenario, 38% of currently non-suitable areas will become suitable for malaria transmission, particularly towards northern latitudes (Figure 42).

There are however marked regional differences in the projected change of the length of the transmission season for malaria under future global heating. In the low-emissions scenario compatible with 2°C of heating (SSP1-2.6), a steady increase in the number of months suitable for malaria transmission is observed in East Asia, South and North America, Russia/North Asia, and Northern Europe. In Africa and Australasia, a slight increase is expected in the medium term, with the transmission season shortening towards the end of the century under this scenario. In the high-emissions scenario compatible with no climate action (SSP3-7.0), on the contrary, a marked increase in the number of months suitable for malaria transmission is projected by the end of the century in higher latitudes (such as North America, Northern Asia, and Europe, as well as in the Middle East, and Central and Eastern Asia), increasing the risk of emergence of this disease in locations in which it is not established today. Under this high-emissions scenario, however, the model predicts a shortening of the transmission season in warmer latitudes like those of South and Central Americas, the Caribbean, Africa, and Australasia (Figure 43), with temperatures in hotter regions of the globe expected to compromise the survival and transmission of *Plasmodium* parasites. However, these predictions do not take into account the potential adaptation of both the vector and the parasite to the climatic changes, which could potentially perpetuate its transmission even under conditions

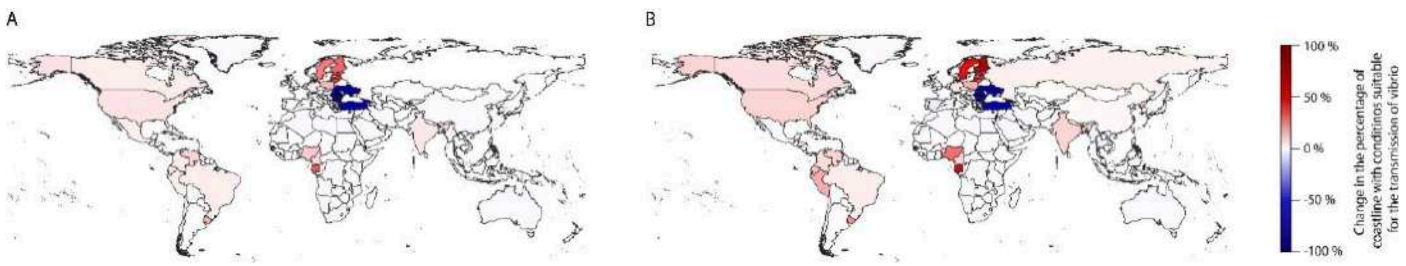


Figure 41: Absolute change in the long term (2081–2100) in the percentage of the coastline with conditions suitable for the transmission of Vibrio pathogens, under the (A) low-emissions and (B) high-emissions scenarios.

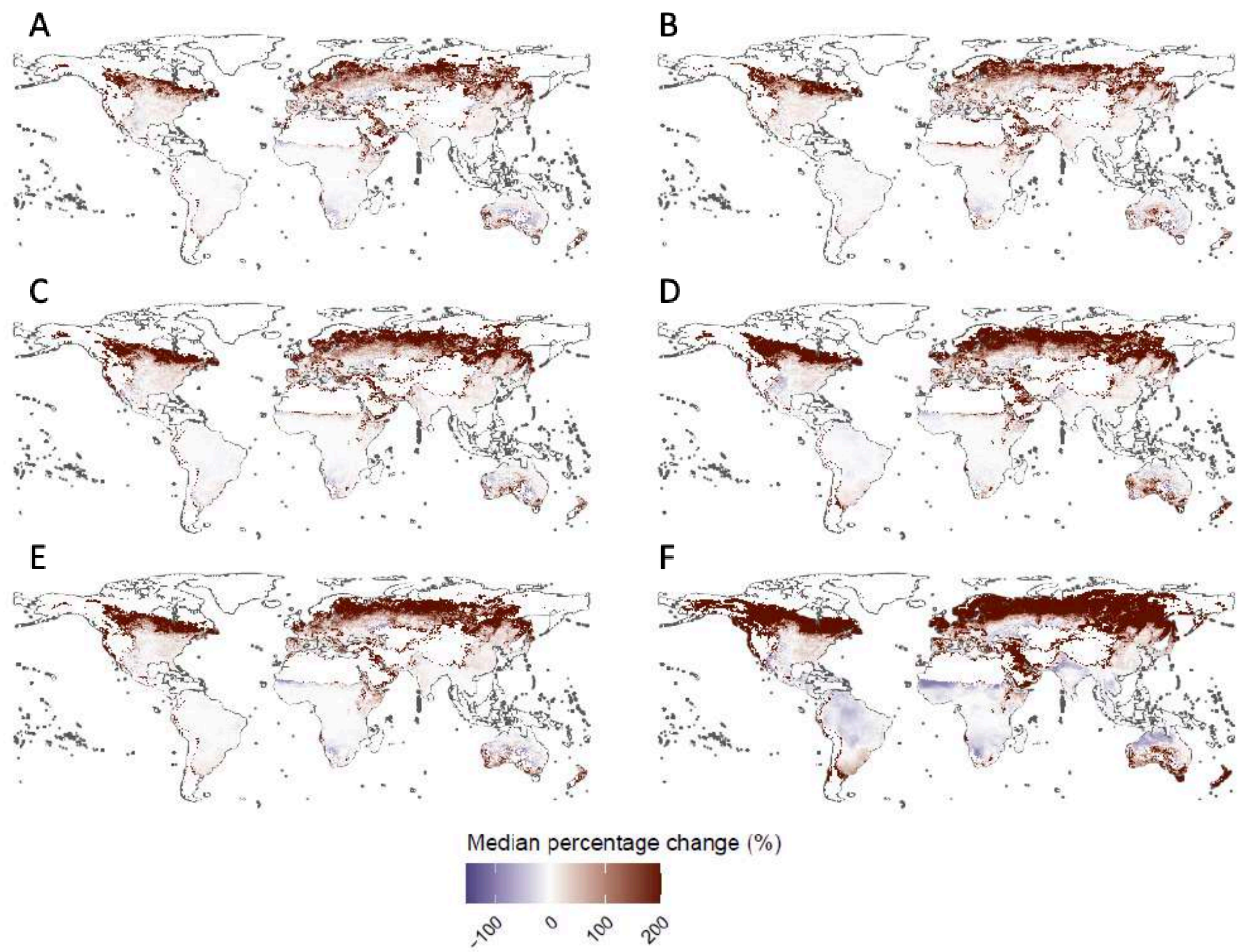


Figure 42: Median percentage change in the projected length of the transmission season for malaria for 2021–2040 (A and B), 2041–2060 (C and D) and 2081–2100 (E and F) under the low-emissions scenarios (first column, A, C, and E) and high-emissions scenarios (second column, B, D, and F), relative to the reference period (1995–2014) for Ae. aegypti

in which it would not survive today.

Public health efforts around the globe have successfully eliminated malaria in many countries and are reducing the burden of disease in those where it remains active. Based on these results, higher latitudes are at risk of malaria (re-) introduction and local transmission unless measures are put in place to control the expansion of mosquitoes and the parasite.

Crop Productivity and Food Insecurity

Food security, as per the United Nations' Committee on World Food Security, requires people to have, at all times, physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life (World Food Summit, UN Food and Agriculture Organization (FAO), 1996). This depends on the stability, safety, availability, and affordability of food. Food insecurity is one of a number of factors linked to malnutrition, which can have multiple adverse effects on people's health, including permanent effects on children if it impairs physical and mental development.

Food production is increasingly being compromised by climate change, due in part to the impact on crop yields of extreme weather conditions, including heat and extremes of precipitation; changes in soil and water salinity; and changing spatial-temporal incidences of crop pests and diseases (Dasgupta and Robinson, 2022; Chen et al., 2021). Food affordability depends on the price of food and household incomes, both of which are affected by climate change, whether through the disruption of food systems or through reducing incomes due to reduced labor supply and/or labor productivity. Nutritional security that enables adequate physical and mental development, and active and healthy lives, is a fourth pillar of food security. The nutritional content of some crops appears to be negatively affected by increasing carbon dioxide levels in the atmosphere; and increasing frequency and intensity of drought reduces access to clean water and sanitation, thereby reducing effective food utilization (Capone et al., 2014). A lack of essential nutrients and absence of a diverse intake of foods is associated with a range of chronic conditions including type 2 diabetes and cardiovascular disease, malnutrition (including stunting and obesity), and poor cognition and mental health (Thomas et al., 2021).

Despite global efforts and commitments towards hunger eradication, the prevalence of undernourishment has increased since 2017, and the number of undernourished people increased by 161 million to 720–811 million between 2019 and 2020 (FAO).

Indicators in this section explore how climate change is impacting the critical determinants of food security.

Crop Yield Potential

Driven by agricultural technologies, plant breeding, and improved management, crop yields have tripled since the 1960s. However, climate change–driven increases in extremes of heat, alteration in rainfall patterns, extreme weather events, and marine heatwaves are affecting food productivity, threatening to reverse this trend. Events such as droughts, floods, and extreme weather are increasingly affecting crop productivity. Higher temperatures can shorten the lifecycle of crops, leading to lower yields (Liu et al., 2018), and data from the Lancet Countdown estimates that, globally, the higher temperatures in 2021 shortened growth seasons of maize by 9.3 days, and of winter and spring wheat by six days, compared to the average in 1981–2010 (Romanello et al., 2022). As the planet heats, these impacts are projected to increase and, without much improved adaptation, over 30% of the land area used today for crop and livestock rearing could become unsuitable for that purpose by 2100 under the high-emissions scenario (SSP5-8.5) (H.-O. Pörtner DCR et al., 2022).

This indicator calculates the temperature-driven 20-year mean change in the time it takes for maize, a major staple crop used here as a representative crop, to reach maturity ("crop growth duration"). Crop growth duration is defined as the time taken to reach a location-specific target of accumulated growing degree-days (with lower and upper daily thresholds of 5°C and 30°C, respectively), defined as the mean over the typical duration to harvest from the typical planting date for maize at the location.

The change in crop growth duration is used as a proxy for change in potential crop yield (the shorter the growing season, the less time the crop has to accumulate biomass). As such, it allows for the potential influence of increasing heat on the production frontier to be assessed independently of other more uncertain changes, such as the incidence of extreme weather events and changes in precipitation patterns. The effective temperature-driven change in crop growth duration will also vary between different regions, and crop yields will also be influenced by farmer practices and high temperature extremes.

This indicator projects that crop growth duration will decline in every single country of the world under both low and high emissions scenarios, relative to the baseline period of 1995–2014. There is little difference between the two scenarios until 2040–2060, with a 12% (17-day) decrease in the low-emissions scenario compatible with 2°C of heating and 13% (19-day) decrease in the high-emissions scenario, compatible with no climate action. After this period, under the low-emissions scenario, there is a slight improvement, with the crop growth duration lengthening on average by about 1.4 days at a global level. However, the crop growth duration in all countries still remains shorter than that observed over the 1995–2014 reference period. In the high-emissions scenario, the reduction in duration continues to the end of the century at least. Looking at 2080–2100, the average global crop growth duration would be 14 days shorter in the high-emissions scenario than in the low-emissions scenario and would be 30 days shorter than in 1995–2014 – a 20% reduction. The data exposes the increased risk to crop productivity under less ambitious decarbonization.

There is nonetheless strong geographical variability in the reduction in crop growth duration, with the largest differences observed in cooler environments, including European sub-regions, Russia/North Asia, North America, and Southern Africa (Figure 44). More specifically, by the end of the century under the high-emissions scenario, northern and western Europe will experience a 35% (53-day) and 26% (43-day) reduction in crop growth duration, respectively. Russia/North Asia will see a reduction of 29% (37 days), North America 30% (48 days) and Southern Africa 31% (61 days). South Asia is the sub-region projected to

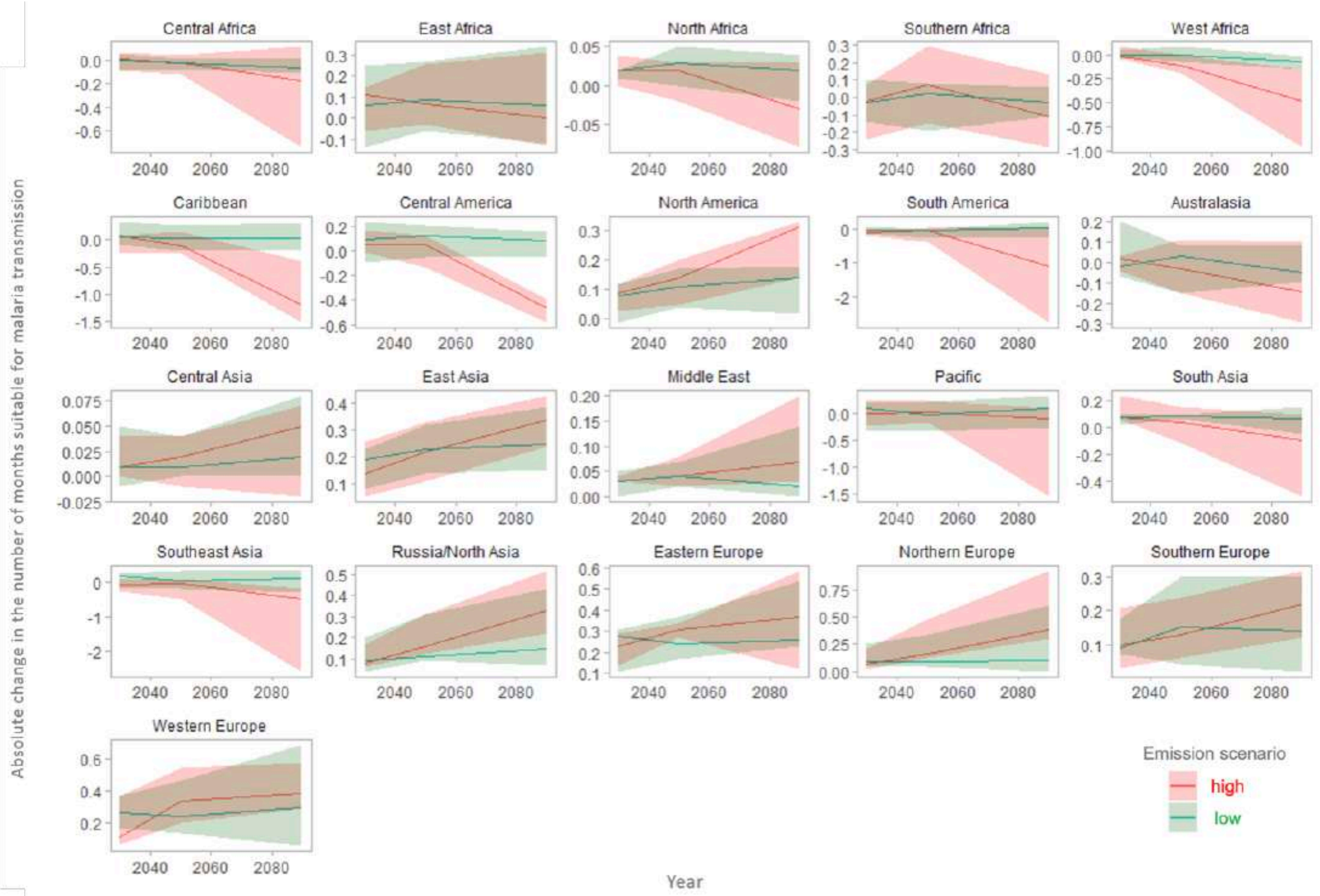


Figure 43: Sub-regional absolute change in the length of the transmission season for malaria with respect to the 1995–2014 baseline, for the high- and low-emissions scenarios. The shaded areas represent the range between the maximum and minimum values obtained using the five GCMs.

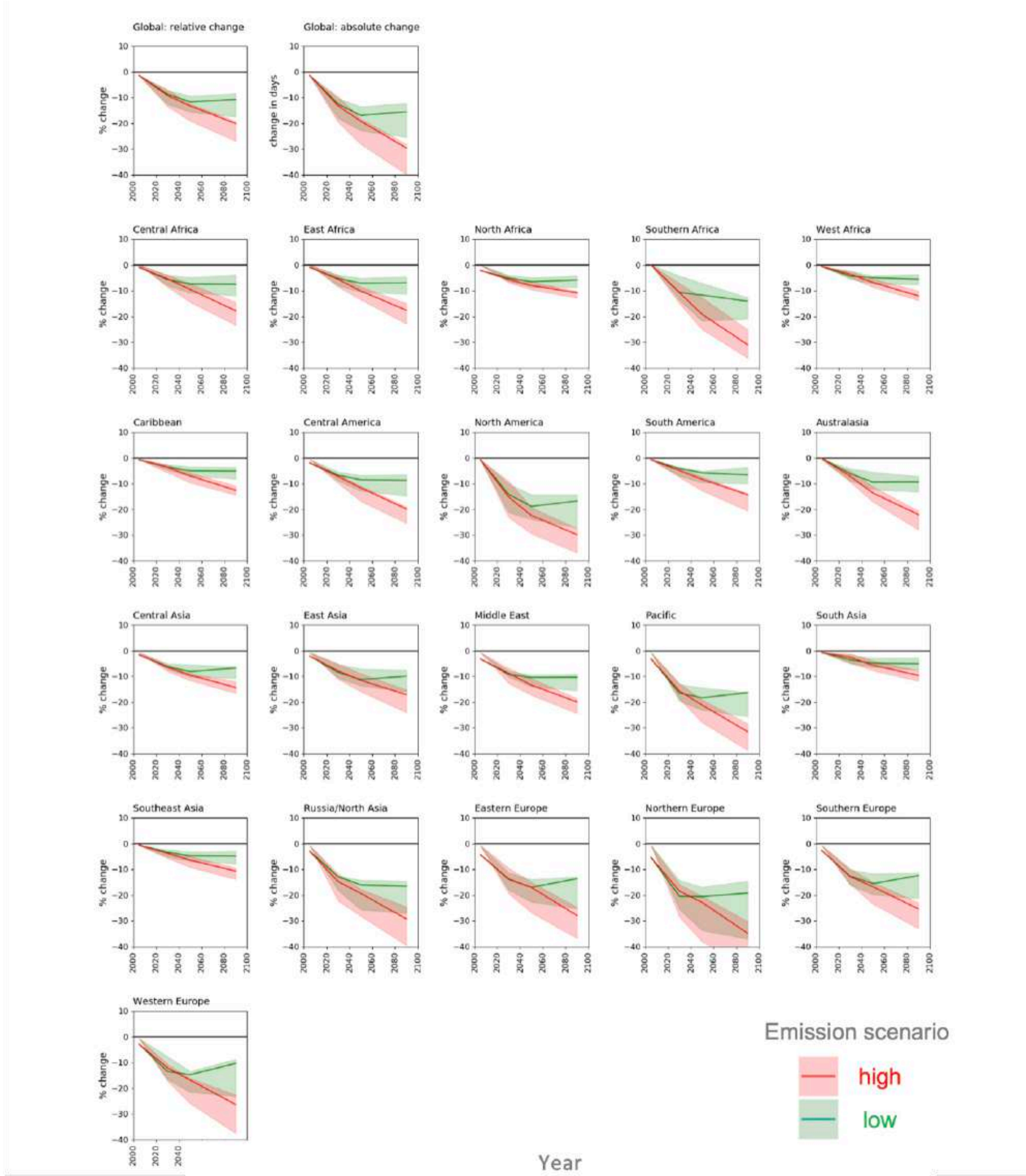


Figure 44: (A) Global absolute and relative change, and (B) sub-regional change in crop growth duration with respect to a 1995–2014 baseline, for the high- and low-emissions scenarios. The shaded areas represent the range between the maximum and minimum values obtained using the five GCMs.

be the least affected by rising temperatures, with a 10% (11-day) reduction in duration.

This is partly because the increases in temperature are greatest there, and partly because the shortening in crop growth duration has an upper-limit cap, which means that once this limit is exceeded, the crop growth season is not expected to reduce further.

There is relatively little uncertainty in the magnitude of change across the five climate models. These results expose the heightened risks to crop productivity under a higher-emissions scenario.

Heat and Food Insecurity

Increases in the number of heatwave days and drought events can affect food insecurity and undernutrition through multiple pathways, including through the impacts of heat stress on crop yields, on agricultural and non-agricultural labor (therefore on crop production and income), on health, on food prices, and on food supply chains (H.-O. Pörtner DCR et al., 2022). Data from the *Lancet* Countdown estimates that, globally, heatwave days in 2020 were associated with about 98 million more people reporting moderate to severe food insecurity relative to 1981–2010.

This indicator computes plausible impacts of future climate change on food insecurity by combining the econometric estimates from Dasgupta and Robinson (2022) with future warming scenarios. The indicator uses panel data regression controlling for both location and time-fixed effects. To operationalize the concept of climate change, it focuses on the number of heatwave days during the four major crop growing seasons in each region. A heatwave is defined as a period of at least two days where both the daily minimum and maximum temperatures are above the 95th percentile of the respective climate in each region.

The prevalence of moderate or severe food insecurity (as measured by the FAO's Food Insecurity Experience Scale) is projected to increase due to future heating under all scenarios (Figure 45). During the 2021–2040 period, under the lower-emissions scenario of SSP1-RCP2.6, moderate or severe food insecurity is projected to be 3.7 percentage points higher than the reference period of 1995–2014, but only 1.9 percentage points higher during the 2081–2100 period, reflecting the benefits of achieving a net zero target by 2041–2060 (Table 4). Under the high-emissions SSP3-RCP7.0 scenario, moderate to severe food insecurity is projected to be 4.1 percentage points higher during the 2021–2040 period than the reference period, and 12.8 percentage points higher during the 2081–2100 period, demonstrating the detrimental effects of not reaching the net zero target. The highest increases in food insecurity from future climate change are projected to be in Sierra Leone, Liberia, Central African Republic, and Somalia, countries that already face high levels of food insecurity. With food insecurity projected to increase under all scenarios, and given how detrimental climate change is likely to be for food security for all but the most optimistic scenarios, policy makers need to focus on both affordability and availability of food through policies that target the most vulnerable. This could involve expanding safety nets, and investing in climate-smart agriculture and resilient food systems.

Scenario	SSP1-RCP2.6			SSP3-RCP7.0		
	2021-2040	2041-2060	2081-2100	2021-2040	2041-2060	2081-2100
Moderate-severe food insecurity	3.7	2.3	1.9	4.1	6.6	12.8

Table 4: Change (percentage points) in moderate to severe food insecurity due to climate change–induced change in the number of heatwave days with respect to the 1995–2014 baseline

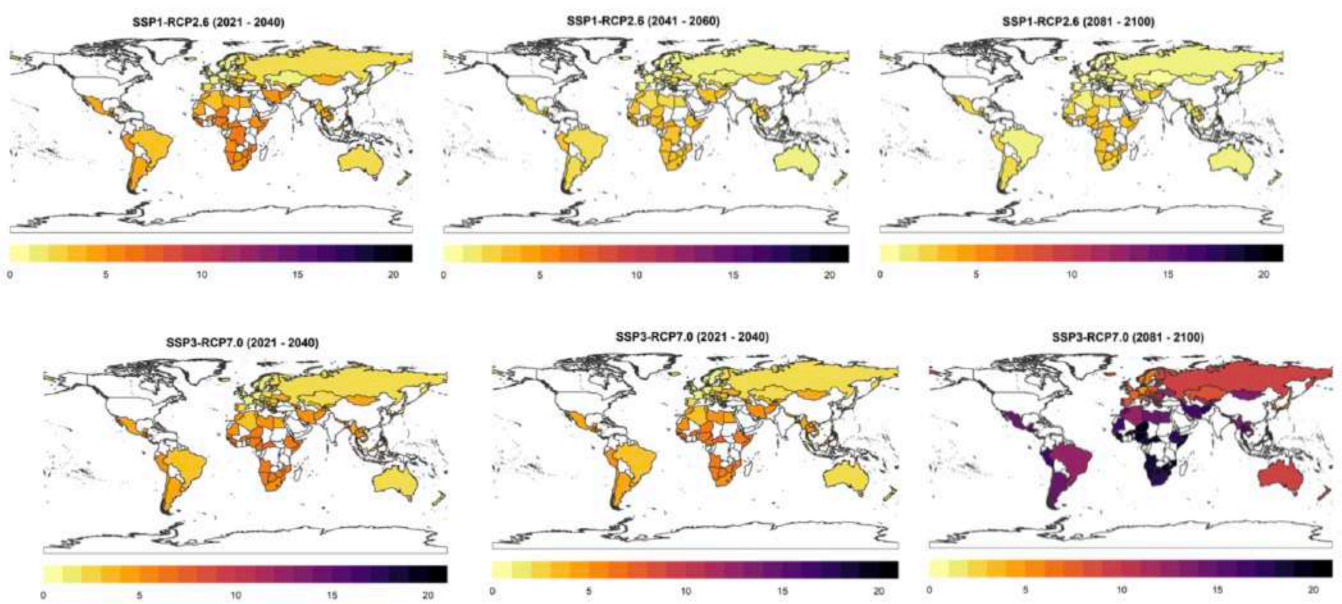


Figure 45: Change (as percentage points) in moderate to severe food insecurity due to climate change–induced change in the number of heatwave days with respect to the 1995–2014 baseline

Conclusion

The data shown in this section exposes the potentially catastrophic health consequences of climate inaction, and the major health gains that would arise from adopting urgent policies today to keep global mean temperature rise to well below 2°C.

The health risks of climate change are expected to rise as the planet heats, thereby increasing the pressure on health systems globally, many of which have limited capacity to adapt to climate-related health challenges effectively. The higher temperatures will increasingly lead to direct health harm, by exposing vulnerable age groups to life-threatening heatwaves, reducing the number of hours available for undertaking physical activity safely, and increasing heat-related morbidity and mortality. In addition, the rising heat will increasingly undermine people's capacity to work, putting workers at risk of heat stress, compromising their wellbeing, and affecting the socioeconomic conditions on which health depends.

The impacts of heat on health are expected to increase even under 1.5°C of heating, but could be catastrophic under 3.6°C of heating in a no climate action scenario. Yet, these impacts will not be felt uniformly throughout the world, and the regions expected to be most strongly affected are Africa (particularly Central and West Africa), the Caribbean, and South and Southeast Asia – low-middle income regions that are highly vulnerable to health shocks and have a more limited capacity to cope with and adapt to climate hazards than high-income settings.

Rising temperatures, together with aridity and drought, will also put people at risk of exposure to wildfires, with associated risk of adverse physical and mental health outcomes through direct injury, exposure to wildfire smoke, disruption of essential services, and loss of assets. This is particularly evident towards the end of the century, with the most affected countries projected to be highly vulnerable low- and middle-income countries in Africa and the Middle East under a scenario in which no climate action is taken. However, high-income countries in Southern and Eastern Europe, which have seen devastating wildfire seasons in recent years, are also projected to be affected under this scenario. The rise in exposure to very high or extremely high wildfire danger is, however, projected to be substantially less in the low-emissions scenario compatible with 2°C of heating, which could avoid 64% of the increase in exposure expected under a no climate action scenario.

Findings exposed in this section also show that climate change will affect the distribution and risk of transmission of infectious diseases, including those such as dengue and malaria, which today contribute to a substantial burden of disease. Weather conditions are projected to become increasingly suitable for the transmission of mosquito-borne diseases in colder latitudes, particularly if no climate action is taken. In the case of dengue, for example, the number of countries with conditions suitable for outbreaks is projected to increase by 22% in a no climate action scenario towards the end of the century, including in countries in Southern Europe and the Balkans – regions that in the present day are not endemic. Keeping to around a 1.5°C global mean temperature rise may avoid 77% of the increase in the number of countries with suitable conditions. Similarly, the length of the transmission season for malaria is expected to increase substantially in northern latitudes under all future scenarios, with particularly sharp increases towards the end of the century in a no climate action scenario.

While the suitability for the transmission of these vector-borne diseases is expected to decrease in hotter, currently endemic areas like Sub-Saharan Africa, this is a consequence of the climate becoming unsuitable for the survival of multiple arthropods, with potentially profound impacts on local ecosystems. In the case of *Vibrio* pathogens, a rising proportion of the world's coastline would become suitable for the transmission of these bacteria, with a doubling from baseline expected if no climate action was taken. Therefore, as temperatures continue to rise, an increasing number of people will be exposed to heightened environmental risk for infectious diseases transmission, particularly under unabated climate change. If adaptive responses are not unrolled at pace, this will likely result in an increased burden of infectious diseases globally.

Food security will also be increasingly undermined by the changing climate. The rising temperatures are projected to shorten the duration of crop growth seasons, posing risks to crop yield potential. This reduction is expected to be higher towards the end of the century and with countries in colder areas, with Europe, Russia/North Asia, North America, and South Africa expected to be the most affected. Yet, 58% of the global shortening in crop growth duration projected in this scenario could be avoided globally if temperature rise was kept at 1.5°C. The increased incidence of heatwaves is also projected to result in an increase in moderate or severe food insecurity. The worst impacts are projected to occur under the high-emissions scenario towards the end of the century, with an increase in moderate or severe food insecurity of 12.8 percentage points – 10.9 percentage points higher than in the low-emissions scenario compatible with under 2°C of heating. The highest increases in food insecurity due to future climate change are projected to be in Sierra Leone, Liberia, Central African Republic, and Somalia, countries that already face high levels of food insecurity.

These results expose the exacerbated health risks that can be expected if climate commitments are not met, and underscore the urgency of taking meaningful climate change mitigation action to protect world populations from potentially catastrophic health impacts (Watkiss et al., 2007).

As the data shows, both high- and low-income countries are expected to see substantial health benefits from limiting global mean temperature rise to 1.5°C. Nonetheless, the health risks of climate change are expected to increase even under the most ambitious decarbonization scenario. With climate change already affecting the health of populations all around the world today, the consequences of such increase could be catastrophic to many. It is therefore imperative that countries enact urgent climate adaptation plans for health, identify and protect vulnerable populations, and prepare health systems to cope with the increased healthcare demands that the health impacts of climate change will bring about.

Economic

FINRES

V. Economic: Macroeconomic Consequences of Climate Change

A. Introduction

Droughts, floods, heatwaves, and tropical cyclones can have detrimental consequences for economic development. Countries have experienced steep increases in inflation as a response to droughts and tropical cyclones – especially in small island nations – as they have the potential to damage or destroy infrastructure and disrupt economic activities. With climate change further modifying temperature and precipitation patterns, macroeconomic indicators are projected to be increasingly affected with GDP per capita projected to reach lower levels than expected, while inflation and interest rates are projected to rise.

In this section, the research focuses on estimating the past and future relationships between climate change, especially temperature and precipitation, and macroeconomic indicators – namely GDP per capita growth, inflation, and interest rates. While there is a growing body of scientific literature on GDP per capita and inflation, very few publications have addressed the question of interest rates, even less so for all countries globally.

The method for this analysis allows for a first-of-its-kind appraisal at the national level for all countries thanks to the use of advanced statistical techniques published earlier in *World Development* (Baarsch et al., 2020).

B. Indicators

To investigate the macroeconomic consequences of climate change at different levels of warming, three indicators are analysed: GDP per capita growth, inflation, and interest rates. The effects of climate variability and change on GDP per capita growth and inflation are estimated using temperature and precipitation, following an econometric approach developed by Baarsch et al. (2020). The potential effects of climate change on interest rates are simulated using the deviations in GDP per capita growth and inflation induced by climate change as inputs to the Taylor rule (John B Taylor 1993), a rule applied by central banks in low- to high-income countries to determine interest rates.

1. GDP Per Capita Growth and Inflation

a. Theoretical Background, Methodology, and Caveats

Macroeconomic analysis in response to climate warming starts by taking stock of the extent to which countries already experience economic losses in response to climate change. This analysis of vulnerability of macroeconomic indicators is performed using a piecewise panel regression, an econometric approach published in World Development (Baarsch et al. 2020). The coefficients resulting from the panel regression are then calibrated at the country level using Bayesian hierarchical calibration. After estimating countries' macroeconomic vulnerability to temperature and precipitation extremes, the third step of the analysis consists of applying the inferred vulnerability to the projected changes in climate in two scenarios: SSP126 (called the "below 2°C scenario") and SSP370 (called the "no climate action scenario"). For both scenarios, three time slices are considered: near term (2021–2040), mid term (2041–2060), and end of the century (2081–2100). Also the analysis proposed to appraise the macroeconomic impacts at different global warming levels: 1.5°C (approximated with SSP126 for the 2021–2040 period), 2.0°C (SSP370 for the 2041–2060 period), and about 3.6°C (SSP370 for the 2080–2099 period).

The methodology implemented for inflation and GDP per capita growth in this study is a combination of an approach published in 2015 (Burke, Hsiang, and Miguel 2015) in which a country's mean annual temperature drives a multi-country panel regression combined with a more recent approach (Baarsch et al., 2020) in which precipitation is normalized to facilitate comparison of heterogeneous precipitation levels across countries. For both regressions, on GDP per capita and inflation, the potential biases induced by heteroskedasticity and autocorrelation are minimized using the Newey-West estimator. In addition, still building on this last publication, the results of the regression analysis are calibrated thanks to a Bayesian hierarchical calibration at the country level to ensure that the vulnerabilities estimated econometrically are an accurate representation of a country's climatic vulnerability.

Previously most econometric analyses used a quadratic representation of the effect of temperature on economic outputs. Following this approach, which is recognized as a mathematical simplification (see for example Burke et al. 2015 for supplementary information), an "optimal" temperature level above and below which economies perform non-optimally is approximated. For countries with temperatures below the optimum temperature level, warming temperatures induced by climate change are projected to improve economic performance. For this study and following an extensive literature review (see methodological annex), a different approach was implemented: estimating a "kink" from which economic performance decreases because of increasing temperature.

Before the kink or "break point," economic performance is not affected by changing temperature (neither positively nor negatively). Since such an approach is particularly complex to infer in an econometric estimation, it is integrated at the calibration phase. Thanks to the calibration, the temperature break points are estimated at the country level, reinforcing the robustness and accuracy of the simulated results and therefore projections.

In addition to temperature, the effects of hydrometeorological extremes are also considered in the regression analysis. Monthly local precipitation patterns are normalized using the Standardized Precipitation Index (SPI) and aggregated so that extreme dry and wet events are defined according to the local climatic conditions of a country – for a country with significantly different precipitation patterns, different thresholds of extreme dryness or wetness are used. The same applies at the global level. In this way, the model can isolate the specific effects of these extremes on GDP per capita and inflation.

Even though the model can provide a precise country-level perspective on the economic consequences of climate variability and change, three main limitations induced by an econometric-based approach and the data used in this analysis are as follows:

1. Econometrics on climate change on economic variables works by analogy (Hallegatte, Hourcade, and Ambrosi, 2007) by inferring the effects of past weather extremes and patterns on economic outputs. Because of this approach, the effects of sea-level rise on macroeconomic indicators that are not yet detectable in economic time series cannot be integrated in the modelling. Also, major and unprecedented hazards that could form in the future cannot be integrated due to the complete reliance on past, observable experience.
2. The model does not account for the direct and indirect consequences of [high] wind speed on macroeconomic indicators and therefore limits the integration of the potential consequences of tropical cyclones. However, as the model already includes the consequences of extreme wet events that can be induced by tropical cyclones, these are not absent from the modeling results. They suffer from a partial assessment of the whole consequences induced by high wind speed destructiveness and disruption.
3. The relatively large size of the grid cell from climate models (0.5°, or about 50 km at the equator) limits the ability of the model to replicate satisfactorily the climate of small islands and/or countries with diverse topography. This is because most of the cells covering these countries are not representative of territorial characteristics; for example, oceans that warm at a slower rate (for islands), and cannot adequately distinguish the areas exposed to extreme precipitation events, especially higher-altitude ones. In follow-up analyses on small island states, climate data with a higher resolution could be used to improve the inference and assessment of past and future impacts on these countries.

Indicators	GDP & Inflation
Input variables	• Population-weighted precipitation normalized using the Standardized Precipitation Index (SPI), Population weighted temperature (ISIMIP database for historical and projected climates) • Socioeconomic variables influencing GDP per capita growth and inflation, as control variables (World Bank – World Development Indicators) • GDP per capita (World Bank – World Development Indicators) • Monthly general consumer price index (International Labor Organization)
Methods	• Econometrics (piecewise regression in panel) • Income-level panel estimation augmented using a Bayesian hierarchical calibration at the country-level

Table 5: Summary of input variables and methods for modelling GDP per capita and inflation

b. Key Findings: GDP Per Capita Growth

With a changing climate, countries' economies may face growing negative impacts from climate-related disasters such as droughts or heatwaves. The droughts and heatwaves observed across Europe and China in the northern summer of 2022 or the floods in Pakistan in September 2022 illustrate the disruptive consequences of climate-related disasters that translate into GDP loss through reduction in consumption, production, or modifications in the trade balance.

In the below 2°C scenario, economic losses measured in deviation of GDP per capita growth remain at a low level, between -10% and 0% deviation compared to the baseline – even by the end of the century. On the other hand, in the no climate action scenario, losses could be at least twice as high with Northern and Central Asian countries among the most affected economies (Figure 46).

In the near term (2021–2040), GDP per capita growth is project to change relative to baseline by -1.1% in Africa, by -0.9% in Americas, by -1.7% in Asia, by -1.9% in Europe, and by -0.6% in Oceania for a below 2.0°C scenario, and by -1.2%, -1.0%, -1.6%, -2.2%, and -0.6%, respectively, for the no climate action scenario.

In the mid term (2041–2060), GDP per capita growth is project to change relative to baseline by -1.7% (+50%) in Africa, by -1.4% (+48%) in Americas, by -2.5% (+44%) in Asia, by -2.8% (+43%) in Europe, and by -0.9% (+38%) in Oceania for a below 2.0°C scenario, and by -2.8% (+122%), -2.3% (+131%), -3.6% (+122%), -4.4% (+102%), and -1.7% (+186%), respectively, for the no climate action scenario. (The figure in brackets indicates the change compared to near term in the same scenario.)

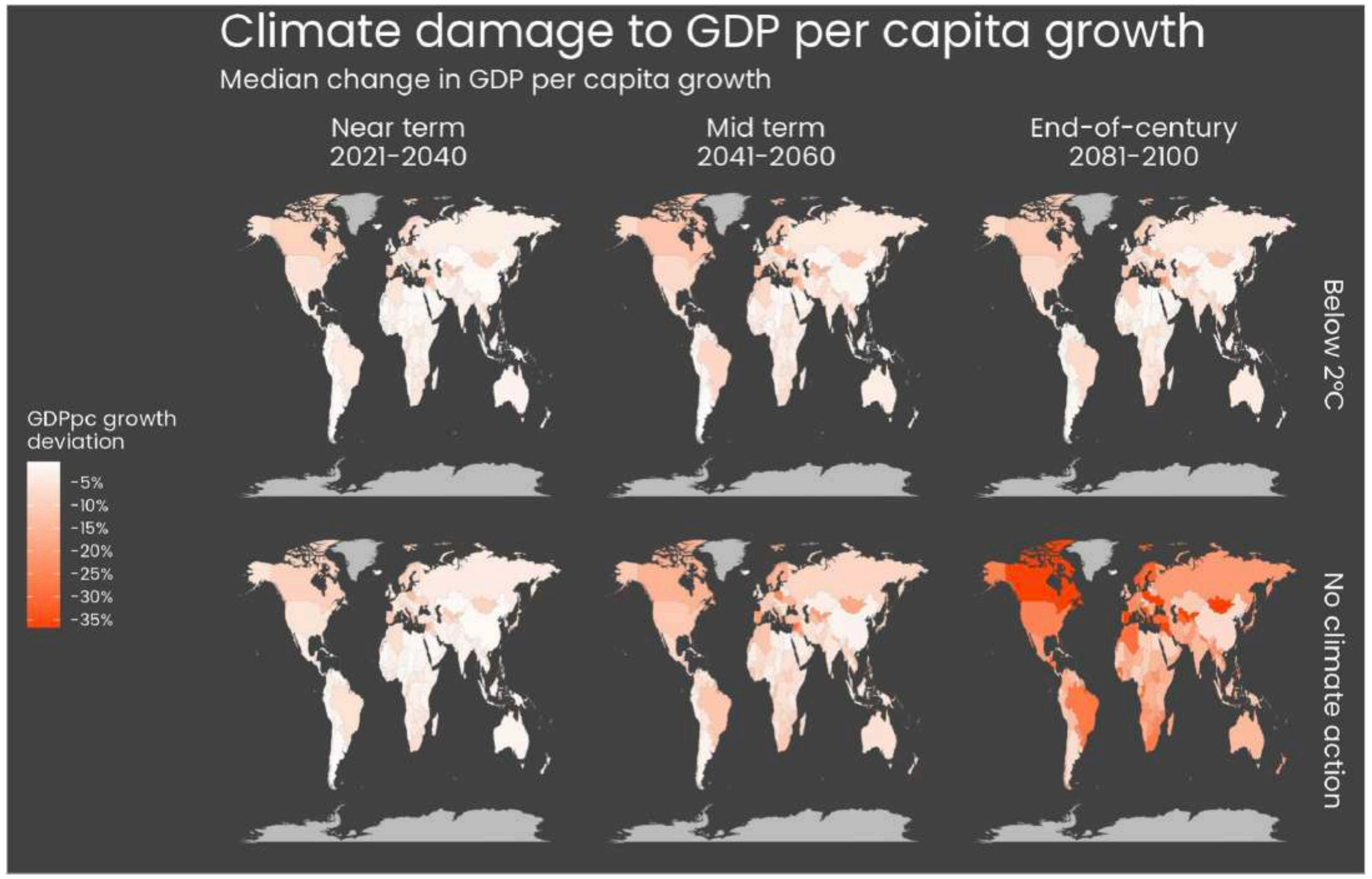


Figure 46: Effects of climate change on GDP per capita growth in the below 2°C and no climate action scenarios for three time slices: near team (2021–2040), mid term (2041–2060), and end of the century (2081–2100). The results are expressed in percentage of GDP per capita growth. Source: Authors' calculations based on World Bank – World Development Indicators (WDI) for socioeconomic data and ISIMIP for the past and projected climate data.

By the end of the century (2081–2100), GDP per capita growth is projected to change relative to baseline by -1.7% (+56%) in Africa, by -1.4% (+50%) in Americas, by -2.6% (+50%) in Asia, by -2.8% (+44%) in Europe, and by -0.9% (+43%) in Oceania for a below 2.0°C scenario, and by -7.9% (+531%), -7.5% (+639%), -10.0% (+517%), -11.8% (+439%), and -5.1% (+763%), respectively, for the no climate action scenario.

At all levels of future warming, the global region that is projected to be the most affected by the consequences of climate change is Central Asia, with a mean change in GDP growth of -3% at 1.5°C, -6.1% at 2.0°C, and down to -16.3% if no stringent climate action is implemented. The second most affected is projected to be North America, due to the large impacts observed in Canada at all levels of warming (see Box 2.). Southern African countries could face the largest consequences with -9.9% in the absence of adequate mitigation policies, followed by Central and Eastern Africa, and finally Western Africa at -8.6%, -7.7%, and -6.6%, respectively.

As explained in the methodology (section above), the projections for the Pacific and Caribbean island states largely underestimate the macroeconomic consequences of climate change as they suffer from three fundamental limitations: the consequences of sea-level rise on macroeconomic indicators are not considered, the model does not take into account the consequences of high wind speed, and the resolution of the climate models is too low to adequately capture the actual climate of these islands. These limitations lead to comparatively low projected macroeconomic consequences of climate change for

Continent	GWL 1.5°C	GWL 2.0°C	No climate action
Africa	-1.1%	-2.8% (+150%)	-7.9% (+611%)
Americas	-0.9%	-2.3% (+153%)	-7.5% (+711%)
Asia	-1.7%	-3.6% (+110%)	-10.0% (+484%)
Europe	-1.9%	-4.4% (+131%)	-11.8% (+515%)
Oceania	-0.6%	-1.7% (+160%)	-5.1% (+683%)

Table 6: Mean continental deviation in GDP per capita growth. The percentages in parentheses indicate the change compared to 1.5°C

Box 2: Canada and Northern Economies' Results

The results of the modeling on GDP per capita growth available in this study depict a different pattern from past and recent publications of the projected impacts of climate change on economic growth. In most studies, authors traditionally find that Northern economies would benefit from the consequences of climate change. This benefit is driven by an econometric hypothesis that assumes that economies grow until the country reaches an optimal temperature.

Past this level, any further increase in temperature leads to negative macroeconomic consequences. For example, Burke et al. (2015) found that the global optimal temperature was about 13°C for all countries – therefore any economy with a mean annual temperature below this level would largely benefit from increasing temperature until it reaches the optimum level. Consequently, numerous studies have projected major increases in GDP for Russia, Scandinavian countries, and Canada.

However, in this study a very different pattern is observed. Canada, for example, will suffer major losses to its GDP growth as temperature increases, with no benefit in a short to mid term resulting from global heating. Specifically for Canada, a recently published study (Sawyer et al. 2022), based on bottom-up microeconomic evidence, found similar results to this analysis. The authors find that GDP growth could be reduced by 5% in the near term (around 2025), 6% by mid century, and between 11% and 27% by the end of the 21st century. With similar timeframes and scenario characteristics, the present analysis projects the following decrease in GDP growth: 4% in the 2021–2040 period, 7% by mid century, and finally a median 19% by the end of the century. The results provided by both studies – despite the use of different modeling approaches – converge in the direction of a decrease in GDP vrowth for Canada.

In the bottom-up analysis of the macroeconomic consequences of climate change in Canada, the authors point out that the possible benefits for the agricultural sector and hydropower are insufficient to compensate for the negative consequences in the rest of the economy, like heat labor productivity, weather-related disasters, flooding, or change in electricity demand.

If confirmed in more studies for high-income and Northern economies, the implications of such results could be wide ranging.

these regions: -0.6%, -1.5% and from -4.6 to -5.4% for the Pacific and Caribbean countries, respectively, at the same levels of warming as described above.

The most staggering implication of these results is the effect of 0.5°C of warming, from 1.5°C of global mean temperature increase to 2.0°C (Table 6). For all continents and regions, the negative macroeconomic consequences are projected to more than double, with increases ranging from 110% in Asia to 160% in Oceania between these two levels of warming.

With further warming resulting from limited climate action at the global level, the macroeconomic effects could be multiplied up to seven times compared to losses at 1.5°C of warming, with increases ranging from 480% in Asian countries to 711% in the Americas.

These findings on the macroeconomic consequences of climate change are another reminder of the importance of stringent mitigation action in line with the objective of the Paris Agreement to ensure that global mean temperature increase is maintained below 1.5°C above pre-industrial levels. Higher levels of warming could lead to drastic economic consequences, limiting countries' ability to invest in their own adaptation, further aggravating the projected consequences.

c. Key Findings: Inflation

The scientific literature on the relationship between climate-related disaster and consumer price index (or inflation) remains limited and has had less extensive research than the relationship with GDP. Recent publications have provided anecdotal evidence across countries highlighting a relation between climate-related disasters and inflationary circumstances. Taking the example of a drought affecting the Horn of Africa, Laframboise and Loko report that in Kenya as a consequence of the ongoing drought "the domestic price of maize, a staple food crop, increased by more than 150 percent" (2012, p. 26), and led "to significant food inflation with adverse impacts on rural households and the urban poor" (2012, p. 13).

Looking at the consequences globally, Parker (2018) found a significant heterogeneity in the relation between disasters (including those that aren't climate related) and inflationary pressure between high-income countries on one side and low- to middle-income countries on the other. In low- and middle-income economies, the inflationary effect can be long lasting over several years, with a duration that varies depending on the type of disaster.

Similarly for GDP per capita growth, inflation in the below 2°C scenario could face limited influence from climate change (Figure 47). However, in this scenario, several countries in Eastern Europe and Central Asia could face greater inflationary pressure, in line with the results from Parker (2018), according to which low- and middle-income

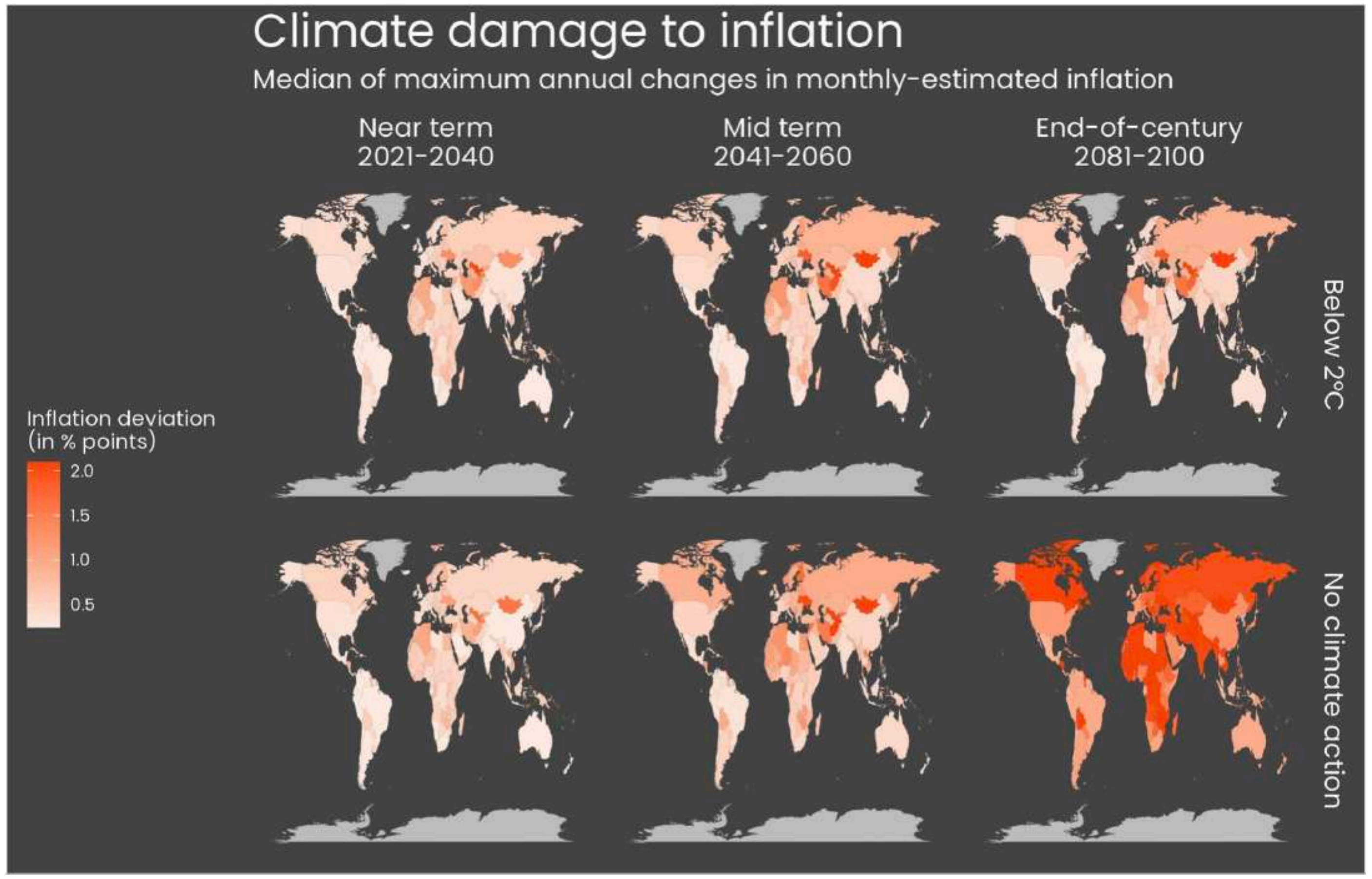


Figure 47: Effects of climate change on inflation below 2°C and no climate action scenarios for three time slices: near term (2021–2040), mid term (2041–2060) and end of the century (2081–2100). The results are expressed in percentage points of inflation. Source: Authors calculations based on World Bank – World Development Indicators (WDI) for socioeconomic data and ISIMIP for the past and projected climate data.

countries could face higher inflationary risks induced by climate-related disasters. In the no climate action scenario, the effects of climate change on inflation are projected to be two to three times those observed for the below 2°C scenario (Figure 47). Non–oil based African economies could also face large inflationary pressures.

In the near term (2021–2040), inflation deviation is projected to change relative to baseline by 0.62 points in Africa, by 0.41 points in Americas, by 0.63 points in Asia, by 0.5 points in Europe, and by 0.6 points in Oceania for a below 2.0°C scenario, and by 0.62 points, 0.4 points, 0.59 points, 0.53 points, and 0.58 points, respectively, for the no climate action scenario

In the mid term (2041–2060), inflation deviation is projected to change relative to baseline by 0.68 points (+10%) in Africa, by 0.45 points (+10%) in Americas, by 0.75 points (+19%) in Asia, by 0.64 points (+28%) in Europe, and by 0.61 points (+2%) in Oceania for a below 2.0°C scenario, and by 0.82 points (+32%), 0.54 points (+35%), 0.9 points (+53%), 0.84 points (+58%), and 0.67 points (+16%), respectively, for the no climate action scenario. (The figures in brackets indicate the change compared to near term in the same scenario.)

By the end of the century (2081–2100), inflation deviation is projected to change relative to the baseline by 0.7 points (+13%) in Africa, by 0.44 points (+7%) in Americas, by 0.78 points (+24%) in Asia, by 0.66 points (+32%) in Europe, and by 0.62 points (+3%) in Oceania for a below 2.0°C scenario, and by 2.27 points (+266%), 1.25 points (+212%), 2.22 points (+276%), 1.81 points (+242%), and 1.1 points (+90%), respectively, for the no climate action scenario.

At all levels of warming, similarly as

Continent	GWL 1.5°C	GWL 2.0°C	No climate action
Africa	0.73	0.93 (+27%)	2.38 (+226%)
Americas	0.57	0.7 (+23%)	1.41 (+147%)
Asia	0.81	1.07 (+32%)	2.39 (+195%)
Europe	0.77	1.12 (+45%)	2.08 (+170%)
Oceania	0.75	0.82 (+9%)	1.24 (+65%)

Table 7: Mean continental level deviation in inflation. The percentages in parentheses indicate the change compared to 1.5°C

Indicators	Interest rates
Input variables	Results for preceding section: • Climate change-induced deviation in GDP per capita growth (deviation to 10-year average) • Climate change-induced deviation in inflation (deviation to 10-year average)
Methods	• Taylor rule (Taylor, 1993) to estimate interest rates based on actual and expected inflation and GDP growth
Data sources	Inflation & GDP growth: own estimates described above

Table 8: Summary of input variables and methods for modelling interest rates

for GDP per capita growth, the global region projected to be most affected by the consequences of climate change is Central Asia, with a mean change in inflation of 1.5 percentage points at 1.5°C, 1.9 points at 2.0°C and up to 4.1 points without further climate action. The second most affected region is projected to be Eastern Europe. Northern Africa and other African regions follow Eastern Europe, with climate-induced inflation from 0.9 points at 1.5°C of warming up to 3.0 points without further mitigation.

West African countries could face the most severe consequences with a 2.7 point increase in the absence of adequate mitigation policies, followed by East Africa, Central Africa, and Southern Africa at 2.1 points, 2.2 points, and 2.1 points, respectively.

On the African continent, two regions are particularly affected by the negative consequences of climate change on interest rates: the countries ranging from Algeria in the North to Guinea in the West and Chad in the East; in the Southern part of Africa: Zambia, Zimbabwe, and Malawi. In South America, Bolivia stands out – possibly induced by currently lower temperatures that are projected to increase faster than the other countries in the region, and rapid changes in precipitation patterns, especially in winter months.

At the difference of GDP per capita, for which the largest share of the negative consequences on GDP results from the effect of temperature, the damage to inflation is driven by hydrometeorological extremes. This change in driver of consequences explains the difference in regions facing the largest impact (with the exception of Central Asia) and the lower effect of warming from 1.5 to 2.0°C as observed for GDP per capita. Even though the effect of 0.5°C of warming is significant, with values ranging from 10% (Caribbean) to 66% (Northern Europe), they are less than half of those measured for GDP per capita.

An additional implication of this analysis at different levels of warming sheds light on the benefit of limiting global mean temperature increase at 1.5°C instead of 2.0°C (Table 7). For all continents and regions, keeping global mean temperature rise below 1.5°C would reduce climate-induced inflationary risks from 10% (Oceania) to 45% (Europe), at an average level of about 30%. With further warming resulting from limited climate action, the inflation effects could almost triple compared to inflation at 1.5°C of warming with increases ranging from 65% in Oceanian countries to 195% in Asia.

2. Interest Rates

a. Theoretical Background

To estimate the future impacts of climate change on interest rates, this study builds on a so-called policy rule. A policy rule is an equation by which central banks can set targeted interest rates as a function of macroeconomic variables. For this study, the estimation relies on the Taylor rule (John B Taylor 1993). The Taylor rule allows for an estimation of interest rates based on four main parameters derived from inflation and GDP growth: the gap between actual inflation and desired inflation and actual economic output growth against the desired output growth. According to Taylor, the two parameters of inflation and GDP should have an equal weight. To account for different decision-makers' preferences, two additional sets of parameters with unequal weight were used to convey the possibility that decision-makers favor GDP growth against inflation or the opposite (additional results available upon request).

The Taylor rule has been explicitly and implicitly (Goncalves,[32] 2015) used in macroeconomic policy across low- and middle-income countries. In an IMF working paper, Goncalves reports that in Kenya, Uganda and Tanzania, central banks respect the Taylor Principle. In Caporale et al.[33] (2018), the authors found that in Indonesia, Israel, South Korea, Thailand, and Turkey, the most accurate representation of the relationship between inflation, economic output, and interest rates was a Taylor rule with a non-linear component to better account for high- and low-inflation regimes.

In a recent World Bank study, Ruch[34] (2021) found that 30 low- and middle-income economies have adopted "inflation targeting regimes." In these economies, the "monetary policy framework" that guides the definition of the interest rates can be measured by a Taylor rule.

The previous economic sub-sections of this Monitor report introduced the results of the effects of climate change and climate-related disasters on inflation and economic outputs. To estimate their impacts on countries' interest rates, these results are integrated in the Taylor rule (as described above) to appraise the evolution of interest rates as a response to the same changes in climate.

The influence of climate-related disasters on interest rates through the Taylor rule can be two-fold. In the case of drought leading to an increase in inflation, the rule would prescribe an increase in interest rates as central banks are expected to tighten monetary policy to keep inflation at reasonable levels. On the other hand, the same drought could also lead to lower-than-expected economic output – causing the central bank to move towards easing monetary policies by lowering interest rates. The objective of this analysis is to indicate a potential trend in interest rates because of climate-related disasters.

In addition to the limitations affecting the projections of GDP per capita and inflation, the main caveats of this analysis are the following:

1. Even though the Taylor rule is well recognized, the decision to adjust interest rates responds to more indicators than those integrated in the Taylor rule. Therefore, the climate change–induced effect on interest rates through this rule represents only a partial perspective.
2. Interest rates derived using this specific methodology are third-order impacts in the sense that they are

computed based on second-order estimates of GDP per capita growth and inflation deviations. Consequently, the level of uncertainty associated with these estimates rises due to the multiplication of uncertainties from climate projections into GDP per capita growth and inflation projections to their effect on interest rates.

The results for interest rates are measured in basis points, with 100 basis points being equal to one percentage point.

b. Key Findings: Interest Rates

The pattern provided by the results on interest rates (Figure 48) mirror those observed for GDP per capita growth and inflation due to the nature of their calculation. Therefore, the most affected areas for either GDP per capita and/or inflation also display similar magnitude when it comes to interest rates.

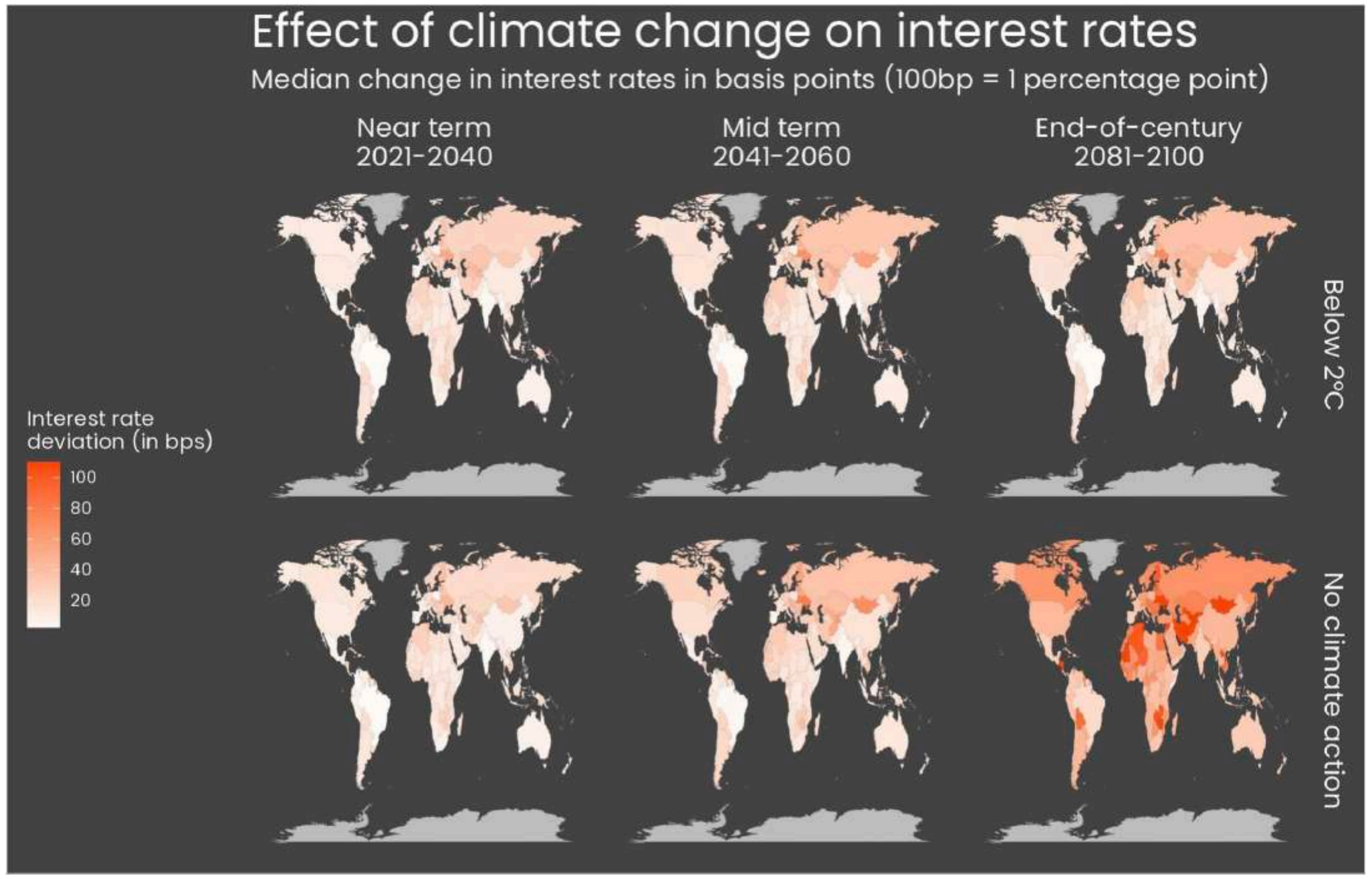


Figure 48: Effects of climate change on interest rates below 2°C and no climate action scenarios for three time slices: near team (2021–2040), mid term (2041–2060), and end of the century (2081–2100). The results are expressed in basis points. Source: Authors calculations based on World Bank – World Development Indicators (WDI) for socioeconomic data and ISIMIP for the past and projected climate data.

Continent	GWL 1.5°C	GWL 2.0°C	No climate action
Africa	20bp	23bp (+16%)	61bp (+214%)
Americas	15bp	19bp (+26%)	41bp (+171%)
Asia	20bp	26bp (+33%)	66bp (+235%)
Europe	23bp	34bp (+49%)	68bp (+194%)
Oceania	21bp	23bp (+5%)	35bp (+63%)

Table 9: Mean continental level deviation in interest rates. The percentages in parentheses indicate the change compared to 1.5°C

The consequences of climate change on interest rates are limited in the below 2°C scenario in comparison to those projected in the no climate action scenario. The projected impacts in the below 2°C scenario range from close to 0 to 30 basis points deviation compared to the baseline scenario. In the high warming scenario resulting from the absence of climate action, the consequences are projected to be three to four times larger. Such increases in interest rates could seriously constrain the ability of governments, firms, and households to invest.

In the near term (2021–2040), interest rates are projected to change relative to baseline by 56 basis points in Africa, by 50 basis points in the Americas, by 68 basis points in Asia, by 165 basis points in Europe, and by 51 basis points in Oceania for a below 2.0°C scenario, and by 56 basis points, 41 basis points, 61 basis points, 163 basis points, and 51 basis points, respectively, for the no climate action scenario.

In the mid term (2041–2060), interest rates are projected to change relative to baseline by 64 basis points (+13%) in Africa, by 55 basis points (+10%) in Americas, by 83 basis points (+21%) in Asia, by 194 basis points (+17%) in Europe, and by 49 basis points (-4%) in Oceania for a below 2.0°C scenario, and by 72 basis points (+28%), 74 basis points (+79%), 123 basis points (+100%), 295 basis points (+81%), and 56 basis points (+10%), respectively, for the no climate action scenario. (The figures in brackets indicate the change compared to the near term in the same scenario.)

By the end of the century (2081–2100), interest rates are projected to change relative to baseline by 65 basis points (+15%) in Africa, by 52 basis points (+4%) in the Americas, by 97 basis points (+42%) in Asia, by 179 basis points (+8%) in Europe, and by 53 basis points (+4%) in Oceania for a below 2.0°C scenario, and by 303 basis points (+438%), 229 basis points (+456%), 405 basis points (+561%), 710 basis points (+336%), and 127 basis points (+149%), respectively, for the no climate action scenario.

At all levels of warming, the global region that is projected to be the most affected by the consequences of climate change is Central Asia, with a mean change in interest rates of 37 basis points at 1.5°C, 47 basis points at 2.0°C, and up to 119 basis points without further climate action. The second most affected is projected to be Eastern Europe (91 basis points without climate action). Eastern Europe is followed by Russia/North Asia region, with climate-induced deviation in interest rates from 26 basis points at 1.5°C of warming up to 67 basis points without further mitigation.

On the African continent, North African countries could face the largest consequences, with an 82 basis point increase in the absence of adequate mitigation policies, followed by West Africa, Southern Africa, East Africa, and Central Africa at 70 basis points, 60 basis points, 53 basis points, and 49 basis points, respectively. In between Southern and Eastern Africa, a pocket of major impact is observed in countries such as Zimbabwe, Zambia, and Malawi – in line with the strong drying and warming signal projected for this region of Africa, which could lead, as modeled here, to drastic macroeconomic consequences.

Middle Eastern countries could face an up to 60 basis points increase in the scenario without further climate action. East Asian countries are exposed to an average increase of 72 basis points.

In June 2015, heavy rains in Ghana led to catastrophic consequences in Accra, the capital city. A gas station where affected people found shelter exploded, causing more than 150 casualties. In addition to the social and human consequences of the floods, the event also undermined Ghana's macroeconomic indicators. First, right in the aftermath of the floods, the cedi, the national currency, fell by 1.4% against the dollar, the lowest level observed for the currency since 1994.

This decline further aggravated the already weak position of a currency that had dropped by 22% against the dollar since the beginning of 2015. Second, Ghana's debt yield increased by eight basis points to 8.89% compared to 8.25% less than a year earlier. At a time when the government needed several hundreds of millions of dollars for

Box 3: Macroeconomic and Financial Consequences of Ghana's 2015 Floods

In June 2015, heavy rains in Ghana led to catastrophic consequences in Accra, the capital city. A gas station where affected people found shelter exploded, causing more than 150 casualties. In addition to the social and human consequences of the floods, the event also undermined Ghana's macroeconomic indicators. First, right in the aftermath of the floods, the cedi, the national currency, fell by 1.4% against the dollar, the lowest level observed for the currency since 1994.

This decline further aggravated the already weak position of a currency that had dropped by 22% against the dollar since the beginning of 2015. Second, Ghana's debt yield increased by eight basis points to 8.89% compared to 8.25% less than a year earlier. At a time when the government needed several hundreds of millions of dollars for reconstruction in the aftermath of the floods, its ability to borrow funds from the international market was severely constrained by both the lowered local currency value and an increased debt yield (Moses Mozart Dzawu and Paul Wallace 2015; Neo Khanyile and Paul Wallace 2015).

reconstruction in the aftermath of the floods, its ability to borrow funds from the international market was severely constrained by both the lowered local currency value and an increased debt yield (Moses Mozart Dzawu and Paul Wallace 2015; Neo Khanyile and Paul Wallace 2015).

With interest rates being computed as a function of both deviations in GDP per capita and inflation, the effects across warming levels by continent reflect those observed for these two indicators.

The continent that would gain most from maintaining the global mean temperature increase at 1.5°C in line with the objective of the Paris Agreement is Europe, with a 49% increase in interest rates induced by a 0.5°C increase in temperature. Europe would be followed by Asia and America, with 33% and 26% increases in interest rates because of temperatures increasing from 1.5°C to 2.0°C above pre-industrial levels. The response of economies to a rise in temperature from 1.5°C to 2.0°C depends on numerous factors, such as the vulnerability of inflation and GDP per capita to temperature changes and precipitation.

The evolution of the local climate is also very heterogeneous across countries and climate models. At a higher level of warming induced by insufficient climate action, the continent that would be exposed to the most drastic increase in interest rates is projected to be Asia followed by Africa, with each of these continents facing a potential multiplication by three in interest rates from global mean temperature rise of 1.5°C and warming resulting from the absence of meaningful climate action.

Top down view of the shallow river. You can see tracts of sand that revealed a water shortage. This predicts drought and crop failure in agriculture
by Ungrim
Link : https://stock.adobe.com/fr/images/top-down-view-of-the-shallow-river-you-can-see-tracts-of-sand-that-revealed-a-water-shortage-this-predicts-drought-and-crop-failure-in-agriculture/376254766

Methodology

Biophysical Impacts

Novel artificial intelligence approaches, as well as unique socioeconomic datasets, are used to characterize present-day climate conditions, including climate impacts and existing socioeconomic vulnerability. Potential scenarios of future climate conditions, including associated impacts and socioeconomic projections, using climate and impact models, aim to describe future climate risks for vulnerable countries.

These approaches include:

- Application of machine learning to large literature collections on climate change for the identification and classification of research studies on climate impacts
- A unique high-resolution dataset of socioeconomic vulnerability, available at the sub-national level for several countries, particularly low- and middle-income nations
- Projections of climate hazards, climate impacts, and socioeconomic conditions using climate and impact models for various emissions/warming pathways for several countries across the world.

These new datasets are used to provide an assessment of present climate conditions and vulnerability, along with observed climate change and impacts attributable to climate change. Scenarios of future climate and development pathways are applied to produce future projections of climate impacts and socioeconomic vulnerability.

Observed Climate Impacts

The state of climate impact research is assessed through an analysis of a database of studies likely to document the impacts of climate and climate change on human and natural systems. Because of the great extent of this literature, studies are identified and classified according to the system in which the impact occurs, the climate variable driving the impact, and the location(s) studied, using a machine-learning algorithm trained to replicate the way humans labeled a smaller set of documents (Callaghan et al. 2021). Review of documented losses and damage, highlighting regional disparities in impact documentation, is done through analyses of the database.

Detectable and attributable trends in temperature and precipitation are calculated following the methodology developed in Knutson et al. (2013) and Knutson and Zeng (2018). In each case, we compare observed trends in each grid cell (2.5°C grid cells for precipitation, 5°C grid cells for temperature) with trends in scenarios that simulate the climate system with human influence (anthropogenic forcing) and without human influence (natural forcing) on the climate. Where trends are not consistent with natural forcing, but are consistent with anthropogenic forcing, we class these as attributable to human influence on the climate.

This data is complemented with an updated database of climate impact literature, developed in Callaghan et al. (2021). Using training data and algorithms developed in the original paper, a literature search on climate impacts was performed and a prediction was offered on whether each study does indeed provide evidence of climate impacts, as well as the human or natural system in which the impact occurs. The table of impact categories is given in the supplementary data of the original paper.[35] Fine-grained labels were designated by humans. These labels were then aggregated to the broad categories, and the machine-learning algorithm was trained on these categories, and produced predictions in these categories.

The climate driver of those impacts is also predicted, and the location studied is extracted. These results are then presented through the density of studies where, if a study mentions two grid cells, one of which has an area of 10 square kilometers and the other has an area of 20 square kilometers, one third of the study is allocated to the first grid cell and two thirds are added to the second.

Observed Socioeconomic Conditions

The objective is to provide a broad set of vulnerability indicators for inclusion in the Climate Vulnerability Monitor. Following the IPCC (2018), the following socioeconomic dimensions of risk management are distinguished: economy, education, gender, health, infrastructure, governance, and demography. These dimensions are measured by 11 indicators chosen based on literature and data availability from three internationally recognized sources. Table 10 provides an overview of the dimensions of vulnerability that are distinguished, the indicators used to measure these dimensions, and their sources. A description of the distribution of these indicators is provided below.

The socioeconomic dimensions of risk management used in this report include the economy, education, gender, health, infrastructure, governance, and demography. To measure the separate dimensions, 11 indicators were used derived from three internationally recognized sources.

The economic dimension is measured by GDP per capita, purchasing power parity (in constant 2017 international $) and the poverty headcount ratio at US$3.20 (2011 PPP) a day, both derived from the World Development Indicators of the World Bank.[36] Less developed countries have fewer resources to cope with climate change events and the damage caused by such events. At the level of individuals and households, the poor are more exposed to natural hazards and are more vulnerable to its impacts (Hallegatte et al. 2020; Hallegatte et al. 2018; Thomas et al. 2019; Cutter et al. 2003; Hallegatte, Vogt-Schilb et al. 2017; Hallegatte, Fay, et al. 2019; Thomas et al.; Cutter et al.). Less developed countries face greater impacts from climate change and have larger vulnerable populations that are least able to adapt to the consequences of climate change (Sarkodie & Strezov, 2020; IPCC, 2018; Beg et al. 2002) (Sarkodie and Strezov; IPCC *Summary for Policymakers — Global Warming of 1.5 °C*; Beg et al.).
Education is measured by the mean years of schooling of the adult (25+) population, derived from the United Nations Development Program (UNDP 2022). Lack of access to information and knowledge is one of the major factors influencing social vulnerability. Lower education constrains the ability to receive and understand warning and recovery information (Cutter et al. 2003) More highly educated people and societies are better prepared for disasters and to better respond to them, consequently experiencing fewer negative impacts and recovering faster (Muttarak and Lutz 2014).

Gender inequality is measured by the Gender Development Index of the United Nations Development Programme.[37] Gender is an important aspect of vulnerability. Women and girls are at greater risk of dying in disasters (Sultana, 2014; Andrijevic et al., 2020) (Andrijevic, Crespo Cuaresma, Lissner, et al.; Sultana), are often not included in decision making and sometimes acted against in recovery and reconstruction projects (Houghton, 2009; Sultana, 2010, 2014) (SULTANA; Sultana). Climate change not only reflects pre-existing gender inequalities, but also reinforces them (Eastin, 2018). At the same time, women often have better capacity to cope with climate change, better understanding of risks. and better social relations (Rufat et al., 2015) (Rufat et al.).

Dimension	Indicators	Source national indicator (link) [a]
Economic Development	GDP per capita PPP (constant 2017, international $)	World Bank[b]
Inequality	Gini coefficient	World Bank
Human Development	Human Development Index (HDI)	UNDP[c]
Education	Mean years of schooling 25+	UNDP
Gender	Gender Development Index (GDI)	UNDP
Health	Life expectancy at birth	UNDP
Infrastructure	Access to clean water and electricity	World Bank
Communication	Access to mobile phone and internet	World Bank
Governance	World Governance Indicator	World Bank
Demography	Dependency ratio	World Bank
Urbanization	Urbanization	United Nations Population Division

Table 10: Dimensions of vulnerability, their indicators, and their sources

The health dimension is measured by life expectancy at birth derived from the UNDP.[37] Specific groups, such as very young and old people, and people with underlying health conditions, might be more vulnerable to climate change events, as they are more susceptible to dehydration and more vulnerable to infectious diseases (Balbus & Malina, 2009). Also people with underlying health conditions such as diabetes and obesity are more vulnerable (Watts et al., 2021; Cardona et al., 2012; Bouchama et al., 2007) (Watts et al.; Cardona et al.; Bouchama et al.).

Access to infrastructure is indicated by the percentage of people using safely managed drinking water services, the percentage of people with access to electricity, and the number of mobile cellular subscriptions per 100 people, all derived from the World Development Indicators of the World Bank.[38] Access to clean water, electricity, and information are among the most important drivers of resilience (Keim, 2008) (Keim). People without access to clean drinking water and sewage systems are more vulnerable to diseases in the aftermath of a hazard (Miola et al., 2015) (Institute for Environment and Sustainability (Joint Research Centre) et al.). People with limited access to information, such as television, (mobile) phones, or internet might not be aware of the full scale of a hazard, unaware of how to respond, or are not alerted in the first place (Hansson et al. 2020). Reliable communications are vital for the organization of post-event responses after a disaster (Dujardin et al. 2020).

Governance is measured by the World Governance Indicator of the World Bank. Governance has been found to have a clear link to climate change resilience and countries' coping capacity (Andrijevic et al., 2020; Eisenack et al., 2014) (Andrijevic, Crespo Cuaresma, Muttarak, et al.; Eisenack et al.). Good governance makes it easier to develop strategies and implement policies to deal with the impacts of climate change and how to act in times of crisis.

The demographic dimension is measured by the age distribution of the population, indicated by the Dependency Ratio (dependent population divided by working age population) and by urbanization, indicated by the percentage of the population living in urban areas. Both indicators are derived from the World Development Indicators of the World Bank.[40] Households with a large number of dependents have to juggle care for household members and work responsibilities in the case of an adverse climate event (Flanagan et al., 2011; Cutter et al., 2003) (Flanagan et al.; Cutter et al.). Rapid urbanization may be associated with slums and informal settlements, which are often located on peripheral lands more vulnerable to climate change events. Rural communities are potentially also vulnerable since they are often a lower priority for governments and have less access to basic infrastructure (IPCC *Summary for Policymakers — Global Warming of 1.5 °C*).

Economic Growth and Poverty

The lowest current levels of GDP per capita are found in Sub-Saharan African countries and some island states such as Vanuatu, the Comoros and Haiti. Somewhat higher GDP levels are found in South and South East Asian countries. Latin American countries tend to be somewhat wealthier, and the countries with the highest GDP levels can be found in Europe, North America, Australia and some countries in the Middle East. **Poverty levels** follow a similar but reversed pattern. The countries with the highest poverty levels, measured as the percentage of the population living below USD$ 3.20 per day, can be found in Sub-Saharan African countries and South East Asian countries. Central and South American countries have lower levels of poverty, followed by Southern European countries, Canada, the United States, Australia and Japan. The lowest levels of poverty can be found in former Soviet Union and Eastern European countries and countries.

Demography, Education, and Health

The dependency ratio measures the size of the dependent population (young and old) compared with the working-age population. A higher dependency ratio indicates the economically active population face a greater burden to support those who are economically dependent (typically, children and the elderly). The dependency ratio is lowest in small nations, such as Andorra, Liechtenstein, and island nations, such as Maldives and Saint Lucia. Asian countries with large elderly populations such as Japan and Latin American countries have somewhat higher rates. African countries, such as Niger, DRC, and Uganda, have the highest dependency ratios.

On average, the lowest levels of education can be found in Sub-Saharan African countries and several South Asian countries, and the highest levels in industrialised countries. However, there is substantial variation within world regions and the pattern is less clear cut compared to the economic indicators. CVF countries Samoa, Fiji, and Sri Lanka, for instance, have education levels on par with several Southern European countries. Life expectancy at birth is lowest in Sub-Saharan African countries, followed by some Asian countries such as Pakistan and Myanmar, and island states such as Fiji, Papua New Guinea, and Haiti. In most Latin American and Middle Eastern countries, life expectancy is somewhat higher. The longest life expectancy is found in European countries, Japan, Australia, and Canada.

Gender Inequality

The Gender Development Index, which indicates the difference in human development between men and women, is lowest in Middle Eastern, Asian countries such as Yemen and Afghanistan, and several Sub-Sahara African countries (Fig. xxe). The highest levels of gender development can be found in the former East Bloc, Eastern European countries, the former Soviet Union, Mongolia, several Latin American, and some Southern African countries.

Infrastructure

The level of urbanization is lowest in Sub-Saharan Africa and island states such as Samoa, Saint Lucia, Sri Lanka, Papua New Guinea, and some South Asian countries. In the Middle East and Northern Africa, urbanization is higher, and in European and other Western countries urbanization is highest. Not surprisingly, the city states of Monaco, Singapore, Hong Kong, and Kuwait have the highest urbanization rates. Regarding infrastructural factors, the percentage of persons with access to clean water is lowest in Sub-Saharan African countries such as South Sudan and DRC, and the East Asian country of Papua New Guinea. Figures in Latin America, the Middle East, and Asian countries are higher. In the Western countries, figures are highest with 100% of the population having access to clean water. For access to electricity, we observe a similar pattern with the lowest levels in Sub-Saharan Africa, where in many countries less than half the population has access to electricity. In Asia and Latin America, the figures are higher and in Western countries, percentages are 100%. Access to the internet through mobile phones, measured by the number of mobile cellular subscriptions per 100 persons, is very unequally divided, with numbers ranging from as low as 12 for South Sudan to almost 300 for Hong Kong. The lowest numbers are found in Sub-Saharan African countries, Samoa, Yemen, Papua New Guinea, and Afghanistan. Figures of over 100 subscriptions are found in countries such as Morocco, Philippines, Sri Lanka, and Vietnam.

Governance

The level of governance, as measured by the World Governance Index (WGI), is lowest for countries with ongoing conflict such as Somalia, South Sudan, Syria, and Yemen. Countries with the highest index are the stable democracies of Western Europe, Canada, Australia, and Japan. Most CVF countries are somewhere in the middle.

GDL Vulnerability Index

In the report, these separate indicators are used, as well as the GDL Vulnerability Index (GVI), an overall index that combines the information included in the 11 dimension indicators to provide an overall picture of vulnerability of countries across the globe (Huisman and Smits, 2022). The advantage of such an overall index is that it consists of only one number, which makes it easy to compare different situations and monitor changes over time. A disadvantage is that it does not contain information on which aspects of vulnerability policy makers should focus on to improve. Besides an overall index, separate dimension indices remain important.

The GVI was constructed by applying principal component analysis of a database that contained values of the 11 indicators for 184 countries in 2015–2020. On the basis of the indicator weights from this analysis, an additive formula is derived with which any country or region for which the values on the indicators are known can be ranked on the GVI.

The GVI can potentially range from 0 to 100, with a value of 0 indicating very high vulnerability and a value of 100 very low vulnerability. The actual range in the year 2020 runs from around 20 for countries such as Singapore, Luxembourg and Hong Kong to around 85 for countries like Chad, South Sudan and Somalia. Further details on the construction of the GVI can be found in Huisman and Smits (2022).

Global Status of Adaptation

This report considered several questions surrounding ongoing global adaptation efforts, drawing on the most comprehensive global database of scientific studies on adaptation, drawn together by the Global Adaptation Mapping Initiative (GAMI) (Berrang- Ford et al. 2021). GAMI is a comprehensive database of documented evidence of adaptation on a global scale (https://globaladaptation.github.io/). The database uses machine-learning techniques to gather and synthesize peer-reviewed literature on climate change adaptation. The database provides insight into several questions on adaptation, including which sectors are adapting, which climate hazards are being addressed by adaptation, and what kinds of constraints, barriers, and limits to adaptation are faced. Adaptation responses are defined as follows (Berrang-Ford et al.):

- Behavioral/cultural: this involves enabling, implementing, or undertaking lifestyle and/or behavioral changes as an adaptation response. Behavioral/ cultural adaptation responses include actions such as people making changes to their homes and land to protect them from floods, fires, and heat; relocating or migrating from hazards; or adopting crops and livestock that are adapted to drought, pests, and encroaching salinity. Individuals shift to other economic and livelihood activities, abandon fishing for farming, or change food consumption practices to cope with environmental risks.
- Ecosystem-based: this entails enhancing, protecting, or promoting ecosystem services as an adaptation response. Ecosystem- or nature-based adaptation responses, such as the natural regeneration of plant species, intercropping, and mulching are used across all regions, most notably in Africa, and Central and South America.
- Institutional: this entails enhancing multi-level governance or institutional capabilities as an adaptation response. Institutional adaptation responses include actions such as creating policies, programmes, regulations, and procedures, and establishing formal and informal organizations; for example, social support groups, climate insurance services, and capacity building and financial assistance programmes.
- Technological/ infrastructure: this involves enabling, implementing, or undertaking technological innovation or infrastructural development as an

Thematic Categories	Indicators	Output dimensions
Temperature	Daily maximum near-surface air temperature	in °C
	Daily minimum near-surface air temperature	in °C
	Daily mean near-surface air temperature	in °C
Water	Precipitation (Rainfall+snowfall)	in mm
	Snow fall	in mm
	Surface runoff	in mm
	Discharge	in m^3/sec
	Maximum of daily discharge	in m^3/sec
	Minimum of daily discharge	in m^3/sec
	Drought Index (SPEI)	severity
	Extreme precipitation (RX5day)	in mm
Storms	wind speed	in m/sec
Agriculture	Total soil moisture content	kg/m^2
	Yields (maize)	t ha^{-1} per growing season
	Yields (rice: first growing period)	t ha^{-1} per growing season
	Yields (rice: second growing period)	t ha^{-1} per growing season
	Yields (soy)	t ha^{-1} per growing season
	Yields (winter wheat)	t ha^{-1} per growing season
	Yields (summer wheat)	t ha^{-1} per growing season

Table 11: Thematic categories, indicators and their output dimensions used to estimate the biophysical impacts of climate change.

adaptation response. Technical and infrastructural adaptation responses are also common, most notably in Europe and in cities, particularly in the water sector.

Climate Projections

This information is derived from an ensemble of climate and climate impact models used in the latest Intersectoral Impact Model Intercomparison Project 3 (ISIMIP3).[41] All the impact models (IMs) employed in ISIMIP3 are forced with the latest generations of five global climate models (GCMs) from the Coupled Model Intercomparison 6 (CMIP6) initiative.

A set of illustrative emissions scenarios, called the Shared Socioeconomic Pathways (SSPs), cover a range of possible future development of anthropogenic drivers of climate change. They include scenarios with high and very high GHG and CO2 emissions, scenarios with intermediate GHG emissions and CO2 emissions remaining around current levels until the middle of the century, and scenarios with very low and low GHG emissions and CO2 emissions declining to net zero around or after 2050, followed by varying levels of net negative CO2 emissions. Emissions vary between scenarios depending on socioeconomic assumptions, levels of climate change mitigation and, for aerosols and non-methane ozone precursors, air pollution controls.

Two scenarios have been selected for analysis in the CVM3:

- **SSP126:** A scenario with low GHG emissions and CO2 emissions declining to net zero after 2050, followed by net negative CO2 emissions. This scenario leads to below 2°C by the end of the 21st century. It is referred to in the CVM3 as the "below 2°C scenario."
- **SSP370**: A scenario with high and very high GHG emissions, and CO2 emissions that roughly double from current levels by 2100. This scenario is approximately 3.6°C by the end of the 21st century. It is referred to in the CVM3 as the "no climate action scenario."

For both above mentioned scenarios, the time series is divided into following time slices:

- Baseline (1995–2014)
- Near term (2021–2040)
- Mid term (2041–2060)
- Long term (2081–2100).

Projections of biophysical and socioeconomic indicators are provided for the above-mentioned scenarios for the near term (centered around 2030), mid-century (centered around 2050), and long-term (centered around 2090).

Biophysical Indicators

All biophysical indicators presented in this report are meant to provide information on projected changes for end-of-the-century no-climate-action (SSP3-7.0 or SSP370) and below 2°C (SSP1-2.6, or SSP126) scenarios. ISIMIP3 does not have a 1.5°C compatible scenario; therefore, a 1.5°C compatible scenario is estimated by assuming that the temperatures stay at approximately 1.5°C throughout the century. The near-term time slice out of SSP126, which reaches 1.5°C by 2030, is also used to represent the medium- and long-term projections for the 1.5°C assessment. The IPCC has assessed many more pathways in its Working Group III report on mitigation which shows that accelerated action to reduce emissions and energy demand in the next 10 years can hold temperature rise to 1.5°C with low or no overshoot in this century (*IPCC_AR6_WGIII_SPM.Pdf*).

The results are presented as differences for each projection period against the baseline period. Two approaches are adopted to display the results; a spatial map for each indicator showing the median value for each country; and bar graphs for each Climate Vulnerable Forum (CVF) member country for both scenarios as well as three future time periods. In addition to median values, uncertainty ranges are also plotted for bar plots. The uncertainty in impact projections is estimated from the spread in the projections from all gas chromatography–mass spectrometry general circulation models GCMs for climate indicators or GCM-IM combinations for sectoral impact indicators. The length of each bar in the bar-plot represents an uncertainty range of 13th to 87th percentile.

GCMs used for the calculation of indicators as well as to force the impact models have been bias-adjusted, meaning that biases between the values simulated by each GCM and those from an observation-based reference dataset over a common period have been corrected, and that this correction has been applied to the whole period simulated by the GCMs (assuming that the identified biases stay constant over time). The correction was done independently for each variable, grid cell and month. The bias adjustment was performed on the regular 0.5° grid onto which the CMIP6 GCM data were interpolated.

List of indicators derived from ISIMIP3 GCMs and Impact Models are presented in green blue colours respectively in Table 11.

For each GCM, the parameters required to calculate Standardised Precipitation-Evapotranspiration Index (SPEI) are derived using the 1995–2014 baseline simulation data at each grid point using gamma fitting. The fitted parameters are then utilized to calculate the projected drought indices in the future time period. Though SPEI can be calculated at various lengths of interest, only results for a length of 12 months are presented for brevity. Furthermore, the droughts are classified according to the levels of severity. SPEI value of -1.5 is considered as severe drought, hence this value is used to define the threshold. Therefore, occurrence of drought as the total number of drought events in the entire study period (i.e., baseline and future periods) are calculated. Results are presented as the difference of drought occurrence from future and the baseline periods.

RX5day is calculated as a maximum of five day precipitation in a year. This climate index is a measure of heavy precipitation, with high values corresponding to a high chance of flooding. An increase of this index with time means that the chance of flood conditions will increase.

Socioeconomic Indicators

Projections of socioeconomic indicators were provided for the 2 SSPs considered in the CVM3 These indicators were chosen in conjunction with indicators of observed socioeconomic conditions.

Country Spotlights

Country spotlights were developed for five countries (Ghana, Kenya, Saint Lucia, Bangladesh, and the Philippines) selected as representatives of the most climate-impacted vulnerable countries. The development of these country spotlights (regional case studies) was carried out by sourcing input from the CVM3 project team, as well as leveraging Climate Analytics' regional staff to provide insights specific to the regions and countries chosen.
The inputs were obtained through interviews, questionnaires and other stakeholder engagement endeavours in accordance with standard scientific practices. These case studies also provide a unique entry-point for a story-telling based approach to accessing the full data space that the CVM3 provides.
Tangible stories and observed impacts were identified and presented in an interactive way (scrolly-telling on the Data Explorer and country spotlights in the report), using engaging formats that will allow non-experts to engage and make use of the content. This section focused on thematic areas such as: climate hazards, observed impacts of climate change, and projections of biophysical indicators emblematic of climate hazards and sectors of particular interest to the country.

Dimension	Indicator	Source
Demography	Dependency ratio	Wittgenstein Centre for Demography and Global Human Capital (2018) (Lutz et al.)
Economy	GDP/capita PPP	SSP Public Database (Version 2.0) (Riahi et al.)
Education	Mean years schooling Educational Attainment	Wittgenstein Centre for Demography and Global Human Capital (2018) (Lutz et al.)
Gender	Gender Inequality Index	Andrijevic et al., 2020 (Andrijevic, Crespo Cuaresma, Lissner, et al.)
Governance	Governance Index	Andrijevic et al., 2020 (Andrijevic, Crespo Cuaresma, Muttarak, et al.)
Health	Life expectance at birth	Wittgenstein Centre for Demography and Global Human Capital (2018) (Lutz et al.)
Inequality	Poverty headcount	SSP Public Database (Version 2.0) (Riahi et al.)
Urbanization	Urban share	SSP Public Database (Version 2.0) (Riahi et al.)

Health

Indicators on health and climate change presented in this report were developed following the indicators and models from the *Lancet* Countdown (Romanello et al., 2022) and developed by researchers following the methodologies described below. While their approaches and methods vary, these indicators all capture one or various components of the health risks posed by climate change. However, these indicators do not capture the potential influence of any adaptation or behavioural changes that might occur in response to these risks, nor do they capture the influence of any parameters other than those described below.

Unless otherwise stated, the indicators incorporate environmental variables taken from the Inter-Sectoral Impact Model Intercomparison Project's 3b protocol (ISIMIP3b). Indicators were processed for five bias-corrected Global Climate Models (GCMs) (GFDL-ESM4, IPSL-CM6A, MRI-ESM1, MPI-ESM2, and UKESM1) for two future scenarios: a low-emission scenario (SSP1-2.6) and a high-emission scenario (SSP3-7.0). Indicator means were processed for a reference baseline period of 1995-2014, and for three future time slices representing the near- (2021-2040), medium- (2041-2060), and long-term (2081-2100) future. Indicators were processed at the grid-cell level, and aggregated at the country, sub-regional, regional or global level using shapefiles for world countries provided by the World Bank(The World Bank). Gridded population data used is from NASA's SEDAC Population Base Year and Projection Grids Based on the SSPs, v1.01 (2000–2100)(Jones, B.), for each SSP corresponding to the future scenarios analysed (SSP1 and SSP3). The age distribution of the population data was extracted from the work by Briggs et al(Briggs).

Data are presented as relative or absolute change with respect to baseline (1995-2014), for each of the future time slices. The data for the five GCMs is aggregated for each time slice and each future scenario, and presented as median, maximum and minimum.

Heat and Health

Exposure of Vulnerable Populations to Heatwaves

Methods

The indicator defines a heatwave as a period of 2 or more days where both the minimum and maximum temperatures are above the 95th percentile of the local climatology (defined on the 1995–2014 baseline). This reflects the definition from published scientific literature on the topic(De Perez et al.). It also aims to capture the health effects of both direct heat extremes (i.e. caused by high maximum temperatures) and the problems associated with lack of recovery (i.e. caused by high minimum temperatures) over persisting hot periods(Di Napoli et al.). Many populations are particularly vulnerable to the health impacts of heat extremes including the elderly, newborns, those with chronic medical conditions (such as diabetes and heart, lung and kidney disease) and pregnant women. This indicator on a particularly vulnerable group: people above the age of 65 (Xu et al.; M. Romanello, Di Napoli, et al., 2022).

The exposure indicator is defined as number of person-days of heatwave, which is calculated by multiplying the number of days of heatwave in a year at a given location by the number of vulnerable people at that location. In this way, the indicator captures both the changes in duration and in frequency of heatwaves, as well as the changing demographics that might mean an increased in the size of the vulnerable exposed(Chambers).

Days of heatwave per year were calculated at a 0.5x0.5° grid resolution, and the number of days of heatwave per year per grid cell was averaged for each time period.

The number of persons over 65 was derived by combining the population from NASA SEDAC population projections for SSP1 and SSP3 with the demographic projections by Briggs et al. The fraction of population in each age bracket (child, adult, over 65) per grid cell from the work of Briggs et al. was multiplied with the total population in each grid cell from the SEDAC data.

The heatwave exposure projections were obtained by multiplying the heatwave days per grid cell averaged over each time period by the over 65 population per grid cell in the middle of the time period.

Data

1. Climate data from the ISIMIP project version 3b
2. Population from NASA SEDAC Population Base Year and Projection Grids Based on the SSPs, v1.01 (2000–2100)(Jones, B.)
3. Demographic data from Briggs et al.(Briggs)

Caveats

In order to estimate the time evolution of demographics, data from diverse sources were combined in order to obtain estimates of both the spatial and temporal characteristics. This has been subject to limited validation. Some regions have limited demographic data. Others show changes in political boundaries which can cause discontinuities in the spatial assignment of demographic values. Due to its nature, this indicator cannot capture the implementation of cooling or other adaptation interventions that might help reduce the exposure of people to the heat. It also does not capture a change in other vulnerable populations, such as those with underlying health conditions, or children under 1 year of age.

Heat and Physical Activity

Methods

Heat stress risk was estimated in accordance with the 2021 Sports Medicine Australia Extreme Heat Policy(Sports Medicine Australia), which estimates heat stress risk of 34 sports stratified into 5 separate classifications based on metabolic rate and clothing/equipment worn. For each classification group, heat stress risk is defined as low, moderate, high, or extreme using the prevailing temperature and humidity combination based on a fundamental human heat balance analysis, which accounts for the level of thermal compensability and sweating requirements. These models are also adjusted for the effects of thermal radiation from the sun (assuming clear skies), and 1 m/s of air flow from wind. Daily mean, minimum and maximum temperatures, and daily mean relative humidity, were retrieved from the ISIMIP3b data repository for the 5 GCMs used in this analysis. For the purposes of this analysis, the lowest sport risk classification, leisurely walking, was used, as this indicator is meant to be applied to general populations rather than elite athletic populations.

The number of hours in each grid cell during daylight hours (local time) with a recorded temperature and humidity combination that exceeded at least the threshold for "moderate", "high", and "extreme" heat stress risk was tabulated for each year. The equations used to estimate heat stress risk for physical activity utilise inputs of concurrent ambient temperature and humidity, and are taken from the new Sports Medicine Australia (SMA) Extreme Heat Policy(Sports Medicine Australia). Specifically, the temperature-dependent humidity thresholds were defined using the following functions:

Moderate heat stress risk:
$f(x) = 312.87417 - 2.978581x - 0.7192763x^2 + 0.025056x^3 - 0.000253x^4$

High heat stress risk:

$f(x) = 534.921743 - 28.102641x + 0.457071x^2 - 0.000171x^3 - 0.000046x^4$
Extreme heat stress risk:

$f(x) = 525.352514 - 26.726214x + 0.482818x^2 - 0.002708x^3 - 0.000012x^4$

where x is 2-metre temperature in a given hour and $f(x)$ is 2-metre relative humidity (derived from dew point temperature) in a given hour. These threshold functions are defined by Sports Medicine Australia as the boundary above which the risk of exertional heat illness changes and preventive action should be taken:(Chalmers and Jay)

"moderate" heat stress risk: additional rest breaks should be undertaken

"high" heat stress risk: active cooling strategies (e.g., water dousing) should be implemented

"extreme" heat stress risk: activities should be suspended due to heat

The functions in the 2021 Sports Medicine Australia Extreme Heat Policy extend to a minimum ambient temperature of 26˚C. Accordingly, any values recorded below this temperature, irrespective of ambient humidity, were determined as presenting a "low" heat stress risk.

The R package *suncalc* was used to determine sunrise and sunset times for each cell on a given date. *suncalc* relies on a solar calendar and thus is expected to provide accurate projection data across the next 100 years. Using these sunrise and sunset times, the hours of daylight for each day and derived hourly temperature in the sun were determined using equation 2(Luedeling). The average daily temperature and average RH for a given day were then used to back-calculate dew point temperature (assuming it is constant throughout the day), and following from the dew point, hourly relative humidity (RH) values were calculated. Plotting hourly temperature against hourly RH allowed calculation of the number of hours above the risk threshold.

Data
1. Climate data from the ISIMIP project version 3b
2. Population from NASA SEDAC Population Base Year and Projection Grids Based on the SSPs, v1.01 (2000–2100)(Jones, B.)
3. Demographic data from Briggs et al.(Briggs)

Caveats
It is acknowledged that the estimation of heat stress risk for a given exercise category may not be uniform across the entire population, and that risk estimates in particular may be different for young children and pregnant women. A more detailed interpretation model of heat effects on exercise would incorporate individual factors such as age, health status, physiology, and clothing. The Sports Medicine Australia Extreme Heat Policy assumes clear skies and therefore will overestimate heat stress risk when cloud cover is present, and at earlier and later times of the day if ambient temperatures are elevated. The future integration of surface solar radiation intensity that accounts for these factors would improve this indicator. Furthermore, it was assumed that population averages for an entire year were applicable to each hourly grid cell, which may not be accurate, but would still provide a rough estimate of population assuming an even rate of influx and outflux from each cell at the country level.

Heat-Related Mortality

Methods
The indicator models the global total number and spatial pattern of heat-related mortality that could be expected assuming no further adaptation, and taking into account a fixed global exposure-response function which was previously published(Honda et al.).

The heat-related excess mortality in one day E is expressed as:

$$E = y_0 \times Pop \times AF$$

Where y_0 is the non-injury mortality rate on that day, *Pop* is the population size and *AF* is the attributable fraction on that day(Honda et al.). Because every day's mortality rate is hard to obtain, is computed as the yearly non-injury mortality rate from the Global Burden of Disease data, divided by 365.

AF is calculated via the relative risk (*RR*) which represents the increase in the risk of mortality resulting from the temperature increase. *RR* is regressed as $RR = exp^{\beta(t-OT)}$, so *AF* is calculated as

$AF = \frac{RR-1}{RR} = 1 - exp^{-\beta(t-OT)}$ (Institute for Health Metrics and Evaluation (IHME) Global Health Data Exchange (GHDx))

where t is the daily maximum temperature, β is the exposure-response factor and OT is optimum temperature, and both parameters were adopted from Honda et al. (2014).(Honda et al.) The method was applied to gridded daily 2m temperature data from CMIP6 ISIMIP3b dataset, and gridded population data from the CIESIN population dataset and ISIMIP Histsoc records. The number of persons over 65 was derived as in the indicator on heatwave exposure, by combining the population from NASA SEDAC projections for SSP1 and SSP3 with the demographic projections by Briggs et al. The fraction of population in each age bracket from the work of Briggs et al. was multiplied with the total population in each grid cell from the SEDAC data.

The heat-related mortality was first calculated at grid level at 0.5° spatial resolution. Then it was accumulated to global level to produce a time-series analysis.

Data
1. Climate data from the ISIMIP project version 3b
2. Population from NASA SEDAC Population Base Year and Projection Grids Based on the SSPs, v1.01 (2000–2100)
3. Demographic data from Briggs et al.
4. Mortality rate data is from the Global Burden of Disease[2]

Caveats
This indicator applies a unique exposure-response function across all locations and times. While its use has been demonstrated in different geographies, it does not capture local differences in the health impacts from heat exposure, which can be significant. Also, this analysis assumes exposure-response function is constant. It does not capture changes in response to heat exposure that might happen over time, as a result of acclimation and adaptation. Not capturing these changes could result in an over-estimation of heat-related deaths in later calendar years. Annual average mortality rates are used, rather than daily mortality rates ( ). Given baseline mortality can be higher in colder months, this may lead to an overestimation of overall mortalities. Nonetheless, the trends of change in mortality due to heat exposure should still be conserved. Only the heat-related mortality of the 65-and-older population was calculated this time, but more work needs to be done to include working group people.

Reduced Labour Productivity

Methods
The methodology for this indicator has been updated and improved from previous work in this area, now also accounting for the impact of solar radiation on people's capacity to work.

The full analysis method is described in the paper by Kjellstrom and collaborators(Kjellstrom et al.).

The input data is based on the ubiquitous 0.5 x 0.5 degrees grid cells for climate and population. It covers predicted trends for the 21st century and the indicator is based on a method that can calculate labour capacity loss at country level.

Daily data from 1995 to 2100 is processed in the following way:

Analysis originates from daily ambient mean and maximum temperatures and specific humidity, as well as short wave radiation downward. These temperature inputs are used to calculate the dew point temperature and hence the heat stress index Wet Bulb Globe Temperature in the shade and including the effect of solar radiation to calculate WBGT in the sun.

Estimation of WBGT in sunlight from a measure of solar irradiance together with a measure of WBGT indoors

WBGT is defined by two formulas(Ken Parsons) – one applying to outdoor situations where there is exposure to the sun and one applying to indoors or outdoors with no sun exposure (e.g. in the shade)

(1) $wbgt = 0.7\ T_{natural\text{-}wet\text{-}bulb} + 0.3\ T_{air}$ (no short-wave radiation)
(2) $wbgt = 0.7\ T_{natural\text{-}wet\text{-}bulb} + 0.2\ T_{globe} + 0.1\ T_{air}$ (incident solar radiation)

In (2), wbgt is WBGT, T_{globe} is the temperature of a 0.15m diam black globe (albedo 0.95) fully exposed to short wave radiation, $T_{natural\text{-}wet\text{-}bulb}$ is the natural wet-bulb temperature, and T_{air} is the air temperature.

For an indoor environment, (1) was adapted by Bernard (1999)(Bernard and Pourmoghani) to make use of the meteorological psychrometric wet bulb temperature ($T_{psychometric\text{-}wet\text{-}bulb}$) (i.e. a whirling wet bulb thermometer) together with a correction for wind speed (V_{wind})

(3) $wbgt = 0.67\ T_{psychometric\text{-}wet\text{-}bulb} + 0.33\ T_{air} - 0.048\ log_{10}V_{wind}\ (T_{air} - T_{psychometric\text{-}wet\text{-}bulb})$

where V_{wind} is the wind speed in m/s between 0.3 to 3m/s

In our earlier work(Lemke and Kjellstrom), we further adapted (3) for an indoor environment, to:

(4) $wbgt_{shade} = 0.67\ T_{psychometric\text{-}wet\text{-}bulb} + 0.33\ T_{air}$

To estimate the WBGT in accounting for solar radiation ($wbgt_{sun}$), Liljegren's adaptation was used, and adapted through an analysis Automatic Weather Station records from Darwin Airport (2020). WBGT under solar radiation is therefore defined using wind temperature and short wave radiation (I_{swh}) as:

(8) $wbgt_{sun\text{-}est} = wbgt_{shade} + (3.8 - ln(V_{wind})) \times I_{swh} / 1000$

This formula was validated against 19,286 observations at Darwin AWS, when the sun was well above the horizon, and the discrepancy of 0.16°C was considered good. The formulation was then applied to three other months, summer and winter, dry and wet at Darwin AWS with similar results.

Subsequent examination of 18 other weather stations world-wide supported the notion that this formulation was more generally applicable if one assumed a windspeed of 2 m/s and the constant coefficient reduced from 3.8 to 3.5, giving the following equation, which was used for the processing of this indicator:

(9) $wbgt_{sun\text{-}est}$ = $wbgt_{shade}$ + 3.5 I_{swh} / 1000

The other factor that needs to be considered for short-wave radiation data is the conversion from a daily average solar radiation (supplied by ISIMIP) into the peak midday value. Provided there are no clouds during midday the solar radiation variation during the day has been well documented (Bird 1981). Using integral comparison between the mid-day hour and the 24 hours, this conversion factor was on average 2.8. This conversion factor was confirmed using the data from Darwin and also, on a global level, the data from NASA (2021) where the data in the "Solar Insulation at midday" file was divided by the data in the "All sky insulation" file.

(10) So the total uplift factor = rsds * 2.8 * 3.5 /1000

where rsds is the downward short-wave radiation at the surface from ISIMIP. This formula assumes a fixed windspeed of 2m/s.

Work Loss Fraction (WLF)

Twelve hourly heat indices are synthesised from daily temperatures by assuming four hours at WBGTmax, four hours at WBGTmean and four hours at the midpoint between WBGTmean and WBGTmax. These three WBGTs form the input for the daily work capacity loss estimations using the methodology described below. From the total of all work hours lost in the relevant time period work-loss fractions (WLF, the proportion of work time lost relative to the potential working hours in the relevant time period) at three different metabolic rates, in both the shade and the sun, are calculated, and a selection of these are presented in this indicator.

For indoor work, exposure was assumed to be atmospheric heat in the shade without effective air conditioning, by applying the WBGT values as described above for each workday. For outdoor work, the uplift factor based on solar irradiation (as described in the section *Estimation of WBGT in sunlight*... above) is added to WBGTmax.

The impact of heat on labour capacity also depends on clothing (assuming light clothing for all) and metabolic rate based on physical work activity. Our methodology considers three metabolic rates: 200W (light work, sitting or moving around slowly), 300W (medium intensity work) and 400W (heavy labour).

The function relating WLF (the fraction of time lost relative to potential work time) to a given WBGT level is given by the cumulative normal distribution (ERF) function:

(11) $$Loss\ fraction = \frac{1}{2}\left(1 + ERF\left(\frac{WBGThourly - WBGTaver}{WBGT_{SD} * \sqrt{2}}\right)\right)$$

where WBGTaver and $WBGT_{SD}$ are the parameters (Table 12) in the function for a given activity level(Kjellstrom et al.). If the daily loss fraction is less than 1% - i.e. less than 7 minutes per day, then this loss was ignored as it can be incorporated in resting time during normal work.

Table 12. Input values for labour loss fraction calculation.

Metabolic rate	WBGTaver	$WBGT_{SD}$
200 Watts	35.5	3.9
300 Watts	33.5	3.9
400 Watts	32.5	4.2

Considering these three metabolic rates, as well as sun and shade conditions of work, shade WLFs for 200W, 300W and 400W, and 400W in the sun have been calculated for each land-based grid cell.

Populations

For each grid cell within a country, the working age population (age 15-64 years, Briggs 2021) for each time period is used for WLF weighting: E.g. highly populated locations contribute proportionally more to a country's WLF than sparsely populated ones.

Populations in grid cells that overlap country borders have been apportioned to the relevant countries based on higher resolutions population distribution within the cell (variable CountryPop% in the formula below).

For a simple weighted average of each of the six annual country WLFs the following calculation is applied (suffix www = wattage 200, 300 or 400W, Ss = Sun or Shade):

(12) WLFwwwSs (per country and time period) =

(Σ(for each country grid-cell): CellPopulation * CountryPop%

* WLFwwwSs(per cell and time period))

/ Σ(for each country grid-cell): CellPopulation * CountryPop%

Data

1. Climate data from the ISIMIP project version 3b
2. Population from NASA SEDAC Population Base Year and Projection Grids Based on the SSPs, v1.01 (2000–2100)(Jones, B.)
3. Demographic data from Briggs et al.(Briggs)
4. Darwin Airport AWS Station Details ID: 014072 Name: DARWIN NTC AWS Lat: -12.47 Lon: 130.85 Height: 0.0 m. http://www.bom.gov.au/products/IDD60801/IDD60801.95122.shtml
5. Sector employment data was obtained from the International Labour Organization's ILOSTAT database(Internatiional Labour Organization)

Caveats

Relative labour capacity losses have currently been calculated in the absence of demographic predictions, i.e. employment sector statistics are currently only available for up to 2030 (ILO). Future employment sector development, e.g. further reducing agricultural work in favour of the service sector in many countries, have a significant effect on predicted work capacity loss for the end of the century. Absolute labour capacity loss figures can only be estimated when plausible employment sector modelling is available. This indicator does not take into account potential adaptation measures that might reduce labour hours lost, including change in work schedules during the day, or adoption of cooling techniques.

Wildfires

Exposure to Very High or Extremely High Wildfire Risk

Methods

This indicator tracks human exposure to days in which the meteorological danger risk for wildfires is very high or extremely high. It is developed based on the fire danger index (FDIs) calculated from future climate projections, overlaying it with population data to calculate the average number of days people were exposed to days of very high or extremely high wildfire risk in each country. FDIs are numeric rating values 1-6, representing very low, low, medium, high, very high, and extremely high fire danger risk, respectively, determined by daily Fire Weather Index (FWI). Specifically, in the first step, we ran the Global ECMWF Fire Forecasting (GEFF) model to calculate daily FWI values. The input data were daily gridded climate data at 0.5° × 0.5° resolution derived from the ISIMIP3b dataset, for five general circulation models (GCMs) In the second step, the FWI values were categorized into six levels of FDIs by the European Forest Fire Information System (very low: <5.2, low:5.2-11.2, moderate: 11.2-21.3, high: 21.3-38.0, very high: 38.0-50.0, extremely high: ≥50.0). The changes in mean number of days of very or extremely high wildfire risks (defined as FDI≥5) were collected for three projection periods (i.e., near-term, medium-term and long-term), compared with the baseline period.

Gridded population data were derived from SSP1 and SSP3 scenarios (for SSP1-2.6 and SSP3-7.0, respectively) from NASA SEDAC data with a spatial resolution of 0.5° × 0.5°. Population density data was further calculated based on population data and land area data from NASA SEDAC GPW v4.11 dataset at 0.5° × 0.5° grid cell. The population density data was used to calculate population-weighted mean days of fire risk. To capture wildfires, rather than urban fires, pixels with population density higher than 400 persons/km² were excluded.

Data

1. Climate data from the ISIMIP project version 3b
2. Population from NASA SEDAC Population Base Year and Projection Grids Based on the SSPs, v1.01 (2000–2100)(Jones, B.)

Caveats

The FWI represents a potential fire risk calculated on meteorological parameters. It does not represent actual fire events. The actual fire events can be also influenced by anthropogenic factors, such as human-induced land use and land cover changes, industrial-scale fire suppression, and human induced ignition. Also, the FWI does not account for the potential fertilizer effect of CO_2 and the associated changes in vegetation and thus the fuel load of fire. Additionally, the FWI doesn't consider potential changes in lightning ignitions, which can be affected by climate change, nor the potential impact of environmental conservation regulations or wildfire control and management capacities.

The FWI calculation requires daily temperature, relative humidity, wind speed at 12:00 am at local time and precipitation at 12:00 am at local time accumulated over the previous 24 hours. Since the daily temperature, relative humidity, wind speed at 12:00 am at local time are difficult to obtain for projection, we replaced them with the daily maximum temperature, minimum relative humidity, and maximum wind speed. To ensure consistency, we used the same input parameters to calculate FWI values for the baseline period.

Infectious Diseases

Dengue

Methods

The for dengue, i.e. the basic reproduction number, which is the expected number of secondary infections resulting from one single primary infected person case in a totally susceptible population was computed using the formula

$$R_0 = \frac{Vb_h}{r_h}$$

(Rocklöv and Tozan). The vectorial capacity (V), which express the average daily reproductive rate of subsequent cases in a susceptible population resulting from one infected case, was computed using the formula

$V = ma^2 b_m \frac{p^n}{-\ln p}$ where a is the average vector biting rate, b_m is the probability of vector infection and transmission of virus to its saliva, is the extrinsic incubation period while is the daily survival probability. All these parameters are temperature dependent and are further described in the work by Rocklöv et al(Rocklöv and Tozan)(Rocklöv, Quam, et al.)(Rocklöv, Tozan, et al.).

The ratio between number of mosquitoes to the number of humans, is central to V and the R_0 value (*m*). Here, a model is used to estimate mosquito populations of *Aedes aegypti* and *Aedes albopictus* separately. The original mosquito-population models provide results in terms of the number of individuals of *Ae. aegypti* per breeding site (*X*), or the number of *Ae. albopictus* per hectare (*Y*)(Liu-Helmersson, Brännström, et al.)(DiSera et al.). In order to appropriately estimate *m*, i.e. mosquito population density per human population density (*p*), *X* was multiplied by $f(p,a,c)$ = $a * g(p,c)$ where a equals to the number of breeding-sites per human, and *Y* by $f(p,a/b,c)$ = $a * g(p,c)/b$ where *b* equals the average number of breeding sites per hectare. The function $g(p,c) = p^2/(c^2 + p^2)$ is an increasing sigmoidal function that equals the viability of domesticated mosquito-populations in relation to human population density. The parameter c is the inflection point of the function g. It represents the population-size around which the spatial covariance between people and mosquitos is changing significantly – i.e., depending on the actual spatial structure of people and mosquitos. Accordingly, $f(p,a,c)$ is the multiplicative factor *m* in V, which allowed to straightforwardly estimate correct values for *a*, *a/b* and c by fitting R_0 to R_0-data that was available for a subset of the spatiotemporal points(Colón-González et al.).

Numerically V and abundance estimates was computed at 0.5 x0.5 spatial resolution based on the ISIMIP3b data(Lange). The ISIMIP3b atmospheric climate input data are bias adjusted and statistically downscaled based on outputs from Phase 6 of the Climate Model Intercomparison Project (CMIP6). V and vector abundance were run for both *Aedes* aegypti and *Aedes* albopictus vectors. Gridded population from CIESIN, with population breakdown weighted as per David Briggs gridded population data set version 2 (BriggsV2) were used in the computation of R_0. For Dengue (albopictus) and Chikungunya, *Aedes albopictus* vector abundance estimates were used in the computation of *m* while for Dengue (aegypti) and Zika *Aedes aegypti* abundance estimates were used. Further annual length of transmission season (LTS) was computed by summing the number of months in a year when R_0 was greater than 1 following the work by Colón-González et al(Colón-González et al.).

The gridded R_0 and LST for Dengue (Aedes *aegypti),* Dengue (Aedes *albopictus),* Chikungunya (*Aedes albopictus*) and Zika (*Aedes aegypti*) were extracted and averaged by Country, region/sub-region, and at global level.

Data

1. Daily climate data (2m air temperature) from the ISIMIP project version 3b
2. Population from NASA SEDAC Population Base Year and Projection Grids Based on the SSPs, v1.01 (2000–2100)(Jones, B.)

Caveats

Key caveats and limitations of the V model and its parameterisation are fully described in works by Liu-Helmersson et al. and Rocklöv et al.(Liu-Helmersson, Stenlund, et al.)·(Liu-Helmersson, Quam, et al.)·(Rocklöv and Tozan) The predicted R0 should not be confused with actual dengue cases, although it is an indicator of the potential for outbreaks(Rocklöv, Quam, et al.)·(Rocklöv, Tozan, et al.).

Vibrio

Methods

This indicator focuses on mapping environmental suitability for pathogenic *Vibrio* spp. in coastal zones globally (<30km from coast). *Vibrio* ecology, abundances, distributions, and patterns of infection are often strongly mediated by environmental conditions. On the basis of the consensus in the literature on what environments *Vibrio* infections may thrive, the indicator uses thresholds of >18°C for Sea Surface Temperature (SST) and <28 PSU for Sea Surface Salinity (SSS) to identify the months in which sea conditions were suitable for the transmission of these pathogens. The high resolution (0.25° in the ocean) simulations from the CNRM/CERFACS modelling group for CMIP6 were used for this purpose, as lower resolution fields don't properly capture coastal dynamics.

Caveats

The results are derived on the basis of suitable SST and SSS conditions only, and do not include other potentially important drivers (e.g., globalisation), environmental predictors of pathogenic *Vibrio* infections (e.g., cholorphyll-a, turbidity) or disease case data. Nevertheless, these associations have been explored and are reported in the supporting references included above.

Data

1. Sea surface temperature and sea surface salinity data from CNRM/CERFACS modelling group for CMIP6

Caveats

The results are derived on the basis of suitable SST and SSS conditions only, and do not include other potentially important drivers (e.g., globalisation), environmental predictors of pathogenic *Vibrio* infections (e.g., cholorphyll-*a*, turbidity) or disease case data. Nevertheless, these associations have been explored and are reported in the supporting references included above.

In the global analysis, the slope of the trendlines over the time series is mostly flat for the tropical/subtropical region and the southern Hemisphere. However, the SST-only suitability shows a strong upward trend in the southern hemisphere, indicating that on average temperature conditions are also improving growth conditions for *Vibrio* in these areas, while SSS is generally limiting.
However, locally suitable SSS conditions will also occur in these regions based on, for example, variation in local rainfall and river runoff, which can make these regions sporadically suitable for *Vibrio* infections.

Malaria

Methods

The malaria indicator focuses on determining global changes in the length of the transmission season, measured as number of months per year suitable for transmission of the malaria parasites(M. Romanello, McGushin, et al., 2022).

The climate suitability for malaria was based on empirically derived thresholds of precipitation (*pr*), near surface temperature (*tas*), and near surface relative humidity (*hurs*) for Plasmodium falciparum, which were obtained from the ISIMIP3b simulation round(CIESIN).

Suitability for a particular month was defined as the coincidence of precipitation accumulation greater than 80 mm, average temperature between 18°C and 33°C, and relative humidity greater than 60%(Grover-Kopec et al.). These combined values reflected the limits for potential transmission of *Plasmodium falciparum* parasites. The number of months with suitable conditions was calculated at the finest possible resolution and later averaged to country, region and sub-region.

Data

1. Climate data from the ISIMIP project version 3b

Caveats

These results are based on climatic data, not malaria case data. The malaria suitability climate thresholds used are based on a consensus of the literature. In practice, the optimal and limiting conditions for transmission are dependent on the particular species of the parasite and vector(Gething et al.). Control efforts might limit the impact of climate variability and climate change on malaria risk or conversely, climate conditions may either enhance or hamper control efforts(Snow et al.).

Heat and Food Security

Crop Growth Duration

Methods

This indicator estimates the 20-year mean change in the time for maize crop to reach maturity as determined by its temperature accumulation ('crop growth duration'), relative to the typical time to harvest for maize in 1981-2010. It is reported as both absolute change in number of days, and as a percentage difference from 1995-2014. The indicator is calculated at a spatial resolution of 0.25x0.25°, and national, regional and global averages are calculated by weighting each grid cell by the area under maize cultivation. It is worth noting that maize crop is used here as a representative crop, being a major staple in many parts of the world, and is not intended to be an indicator of food security.

Crop growth duration is defined as the time taken to reach a location-specific target accumulated growing degree-days (with lower and upper daily thresholds of 5°C and 30°C respectively). The location-specific target accumulated growing degree-days is defined as the mean over the typical duration to harvest from the typical planting date for maize at the location, calculated over the period 1981-2010, and grid cells with a target of less than 1000°C-days are excluded. The change in crop growth duration in each year is expressed relative to the typical duration to harvest.

The indicator is calculated using daily temperatures, which are estimated from ISIMIP3b monthly data by interpolating the ERA5 monthly mean temperatures to the daily step (preserving the monthly mean). The climate scenarios are applied to the ERA5 monthly mean temperatures using the delta method. For each climate model and emissions scenario, the change in 20-year mean monthly temperature for each grid cell is calculated relative to the model 1995-2014 mean monthly temperature. The delta method as applied here assumes no change in either day-to-day or year-to-year variability in temperature. The first assumption is reasonable because the indicator is based on accumulated temperature and day-to-day variability has little effect. The second assumption is also reasonable because the indicator is expressed as a 20-year mean.

Maize planting dates and time to harvest are taken from the SAGE crop calendar, and assumed not to change in the future(Sacks et al.). The time to harvest varies across the globe from less than 80 days to more than 160 days. The planting dates and time to harvest represent broadly the 1990s and early 2000s. The area of maize crop is taken from the MIRCA2000 crop data base, and again assumed not to change over time(Portmann et al.). The maize crop extent data do not distinguish between maize grown for grain and maize grown for forage or biofuels.

Data

1. Climate data from the ISIMIP project version 3b and from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis(Muñoz Sabater)
2. Planting date and time to harvest taken from the MIRCA2000 dataset of the Center for Sustainability and the Global Environment

Caveats

The relationship between change in duration and change in potential yield varies from place to place, depending on how the change in duration varies through different crop development stages and how close current temperatures are to low and high temperature thresholds affecting the assimilation of biomass. Actual crop yield – in the absence of changes in farmer practices – is also affected by high temperature extremes and/or lack of water during critical periods. It is possible that both of these may have a greater effect on yield in the future than change in crop growth duration. Changes in crop growth duration are also potentially sensitive to the temperature thresholds used to calculate growing degree days.

Malnutrition and Hunger

Methods

The methodology of this indicator is based on Dasgupta and Robinson (2021)(Dasgupta and Robinson). To track the impact of climate change and income on the incidence of food insecurity, it uses panel data regression controlling for both location and time fixed-effects. To operationalise the concept of climate change, it focuses on the number of heatwave days during the four major crop growing seasons in each region(World Health Organization). A heatwave is defined as a period of at least two days where both the daily minimum and maximum temperatures are above the 95[th] percentile of the respective climate in each region.

Historical Analysis

The historical analysis, for the regression, was done using reanalysis data. The gridded 95th percentile of daily minimum and maximum temperatures, taken from the ERA5-Land hourly dataset, are calculated for 1986–2005(Muñoz Sabater). The indicator uses the lagged number of heatwaves during the crop growing seasons for each crop for each year during 2014–2020.

The regression also includes a twelve-month Standardized Precipitation Evapotranspiration Index (SPEI) as a measure of drought. SPEI-12 was computed using precipitation data from ERA5-Land monthly averaged dataset and the SPEI package in R(Beguería et al.; Muñoz-Sabater et al.). Drought also affects food insecurity and undernutrition in complex ways, including through hygiene and sanitation.

Two dependent variables are used from FAO FIES (Food Insecurity Experience Scale) data: the probability of moderate to severe food insecurity; and the probability of severe food insecurity. To account for unobserved heterogeneity such as differences in food and storage policies across countries and changes in the prices of food items from year to year, the econometric specification also includes both location and time (year) fixed-effects. The panel data specification can be written as follows:

$$FS_{it} = f(Heat_{it}) + X\beta_{it} + \alpha_i + \gamma_t + \varepsilon_{it}$$

Where FS_{it} is the probability of moderate to severe food insecurity or probability of severe food insecurity, $f(Heat_{it})$ is the change in the number of heatwave days during the four major crops growing seasons; and $X\beta_{it}$ is a vector of relevant variables affecting food insecurity - income, droughts, a dummy to control for the COVID-19 pandemic in 2020. ε_{it} is a random error term.

Food Insecurity Under Future Climate Change

We estimate food insecurity under a *no climate change* scenario (1995-2014) using the historical data from five GCMs from in ISIMIP3b, and then compare the food insecurity outcomes from this scenario against climate projections from three time epochs, 2021-2040 (near-term), 2041–2060 (medium term), and 2081–2100 (long term) under both SSP1-2.6 and SSP3-7.0, to obtain the change in future food insecurity outcomes compared to synthetic historical food insecurity. The output is percentage-point change in food insecurity indicators due to future climate change compared to a reference period of 1995-2014, aggregated to the country level.

Data

1. Hourly climate data (2m air temperature and total precipitation) from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5-Land reanalysis
2. Food insecurity from the FAO Food Insecurity Experience Scale(Saint Ville et al.)
3. Climate data from the ISIMIP project version 3b

Caveats

The main caveat for temperature anomaly food insecurity indicator is the possible recall bias in the survey data and the bias that may have been introduced to interviews during the pandemic being conducted by phone instead of in-person visits.

Economic

1. Proposed Method

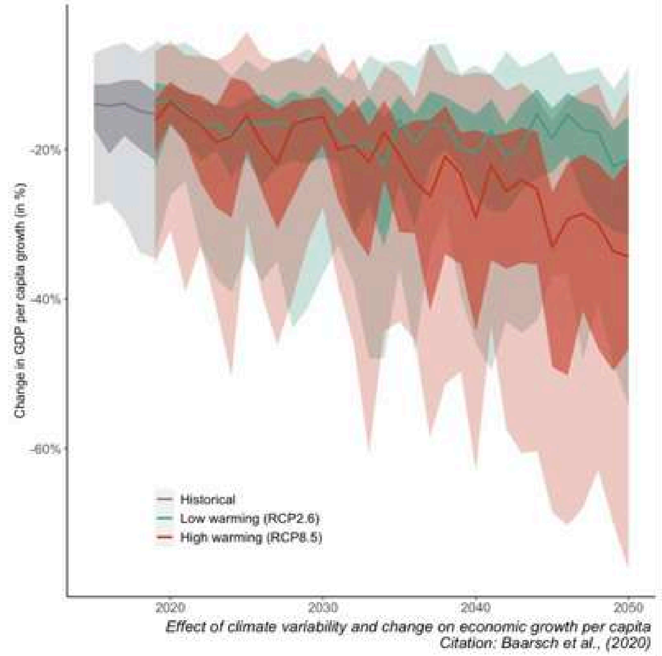
In line with the objectives provided in the inception report, we propose a method that would meet them while also providing additional results relevant to economic decision-making at the country-level.

The proposed methodological approach would rely on a method developed and published in Baarsch et al., (2020) that relates hydro-climatological extremes (droughts and floods) and changes in temperature (Figure 50) with aggregate (Figure 49) economic outputs. The method has already been peerreviewed and implemented in several publications from international organizations (e.g., World Bank, UNECA, UNEP, African Development Bank). Also, it was worth adding that the method and the results it provides are already being used by Governments in Africa (e.g., Cameroon, Mali and Senegal).

To feed the debate on loss and damage at the UNFCCC, the analysis will also provide an estimate vof recent past macroeconomic losses associated with climate variability and change. To this end, the same macro-econometric model (as described above) will be used to hindcast economic risks, measured in percentage points of GDP growth. Climate-induced economic risks could be aggregated over a selected period to estimate the potential impact and deviation from a scenario in which climate change would have remained constrained. For every low- and middle-income country (for which the assessment is possible in terms of data availability), the report will provide at least three main information:

(1) Adaptation gap: A range estimate of the adaptation gap, measured as the average deviation in GDP per capita growth induced by climate variability and change over the selected period.

(2) Aggregate economic risk: A range estimate of aggregate economic risks over the selected period compared to a reference period (both periods to be agreed upon).



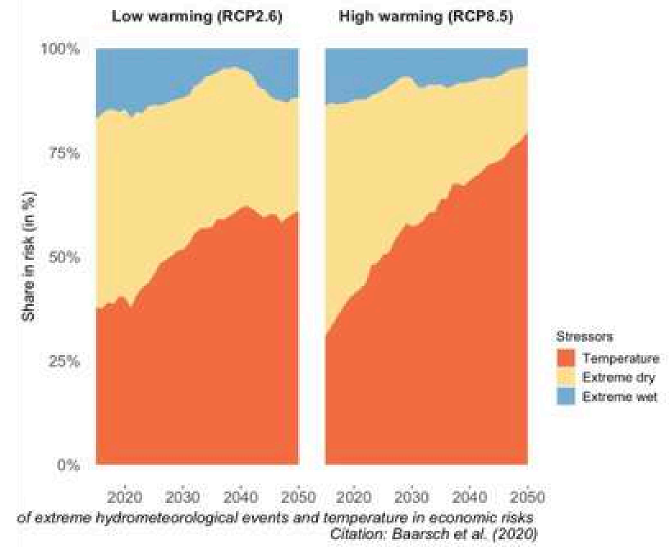


Figure 49 Effect of climate variability and change on economic growth per capita in GDP per capita Ghana - example of model results

Figure 50 Influence of temperature and precipitation extremes in growth risk – example of model results.

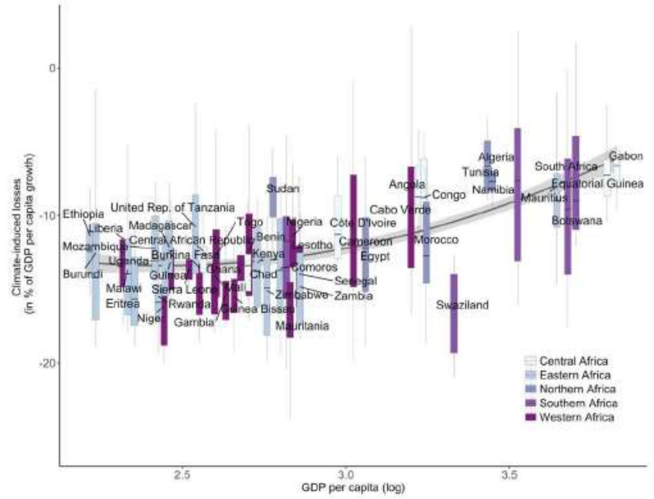


Figure 51 Annual climate-induced (precipitation and temperature combined) losses in the period 1986-2005 measured in percentage of GDP per capita growth.

The results (see example from our recent publication in Figure 51) will be presented as maps and graphs in a report of 15-20 pages, and a separate methodological annex.

To embrace the depth of information available in the upcoming version of the CVM, and building on our work with Ministries of Economics and Finance, we propose several additions to the existing model published in 2020:

- Additional climate-related hazards: exposure to tropical cyclones and wind extremes will be tested and – if possible – integrated in the economic model, particularly for Small Island Developing States (SIDS). Some considerations will be made about sea-level rise, even though existing methods to evaluate the consequences of sea-level rise on economic development remain partial or at a microeconomic scale.
- Finally, complementary to the effects on GDP and value added, we also propose to add two new key economic indicators, often requested by policymakers in countries where finres operates:
    - *Inflation*, estimated econometrically (Parker, 2018).
    - *Interest rates*, estimated with the Taylor rule (Taylor, 1993), which is mainly derived from economic output and inflation.
    - *Debt sustainability*, a qualitative discussion will be provided owing to the potential effects on GDP, inflation and interest rates.

Additionally, the analysis of the economic impacts of climate variability and change will also integrate an in-depth country-level verification of the modelled results using historical data (Figure 52) and uncertainty assessment. This assessment will quantify the respective levels of uncertainty originating from climate-related and non-climate-related parameters (Figure 53).

2. Data

2.1. Climate Data

finres' economic model relies on high-resolution (geographical and temporal) climate data. For consistency between the different sections of the CVM, finres will use same climate data: EWEMBI or its recent update W5E5 (Lange, 2019; Lange et al., 2021) for the historical climate and biascorrected CMIP6 GCMs, for the projections, from the ISIMIP database, for scenarios consistent with CMIP5 RCP2.6, RCP4.5 and 8.5 scenarios.

2.2. Socioeconomic Data

The socioeconomic data are sourced from the World Bank World Development Indicators database. For inflation, we will rely on ILO database of monthly inflation.

3. Methods

3.1. Effects of Climate Variability and Change on GDP

Model Framework

To measure for the future disaster and climate risks to which countries could be exposed, the economic framework is developed following the concept of "*risk triangle*" (Crichton, 1999), consistent with latest IPCC SREX conceptual definition of disaster risk (IPCC, 2012). The concept of "risk triangle" defines risk as the combination of three components: hazard intensity and frequency, exposure and vulnerability. With each component conceptually determining the length on of the sides of the triangle, hence for example large exposure combined with no vulnerability would lead to limited risk.

The economic framework for this analysis therefore integrates these three components:

- Hazard: Intensity and frequency of precipitation and temperature extremes as well as mean, the model considers the intensity of precipitation and temperature extremes by using the gridded monthly precipitation and temperature for both historical and projections data.
- Exposure: Exposure of the countries to these disasters, economic exposure is approximated by weighting the overall country area with population density, considering more densely populated areas produce higher economic output and hence have a higher exposure (Nordhaus, 2006).
- Vulnerability: Country-level historical sensitivity to precipitation and temperature mean and extremes; country specific vulnerability is provided by a non-linear regression model, which measures the sensitivity of GDP per capita to various levels of precipitation intensity and temperature, following the concept of vulnerability curves largely used for other types of natural disasters (here the example of earthquakes: (Rossetto & Elnashai, 2003)).

As of today, economic assessments have not combined all three components in their consideration of the future impacts of climate change. The following table (Table 1) highlights the difference between the approach used in this analysis and past studies.

Study / Component	Hazard frequency and intensity	Exposure	Vulnerability
Integrated Assessment Models (IAMs)	Models' damages are only measured using mean temperature, therefore excluding precipitation extremes and changes in patterns.	Some models use GDP per capita as a measure of exposure at the national level.	Models' damage functions are calibrated using projections from sectoral studies. The method is increasingly criticized (see e.g. (Pindyck, 2013)). The majority of the damage functions are based on a quadratic function of annual mean temperature.
Current econometricbased methods	No model accounts for changes in mean and extremes precipitation and temperature. Models integrate mean temperature with precipitation as a control variable (Burke et al., 2015; Dell et al., 2012). Studies consider precipitation extremes using an index (Brown et al., 2013). Analyses account for temperature and / or precipitation extremes (Du et al., 2017; Schlenker & Roberts, 2009)	Only a few models weight climate variables with population density (Burke et al., 2015)	Methods rely on an historical econometric analysis of past precipitation and temperature to estimate panel of countries' (or counties) vulnerability. Most recent studies employ non-linear (Burke et al., 2015) or piece-wise (Du et al., 2017) estimation of historical vulnerability.
Method used in this analysis	Model accounts for temperature changes over time as well as precipitation extremes and changes in mean precipitation patterns.	0.5 degree- resolution precipitation and temperature data are weighted using gridded population density (CIESIN et al., 2005).	The model combines a non-linear method to measure the effect of temperature and a piece-wise regression for the vulnerability to precipitation extremes and change in patterns. Vulnerability is first estimated for a panel of countries, and parameters are calibrated at the country-level.

Table 13 Comparison between economic assessment methods

Regression Model

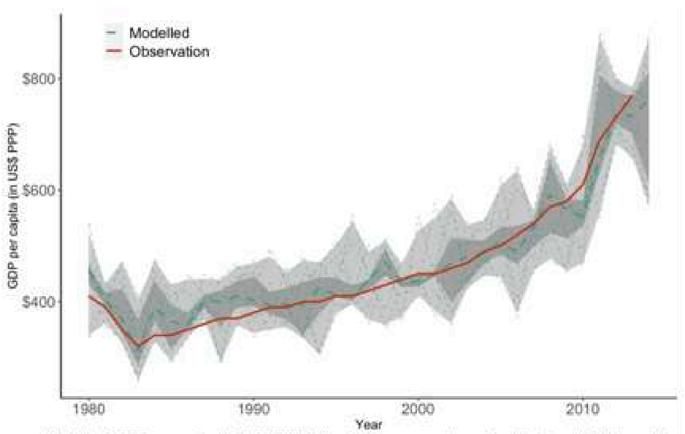
The past and future effects of climate-related disasters and climate change on GDP at the country level are estimated from an macroeconometricbased forecast model. The model uses past and projected grid-level precipitation and temperature data as variables influencing macroeconomic indicators. The guiding principle underlying the estimation is that hazards of same intensity (here precipitation and temperature) will have effects of similar magnitude expressed in change in GDP per capita in the future as they had in the recent past (from 1990-2019, the period on which the regression is performed). This guiding principle is directly based on the concept of climate analogues, widely used in climate and economic literature (Burke et al., 2015; Hallegatte et al., 2007). This econometricallyinferred coefficients for GDP per capita in relation to a given intensity of precipitation and temperature, are called sensitivity and measure the vulnerability of GDP per capita to climate variables.

Sensitivities are inferred using a piecewise multivariate regression model (Equation 1), which uses GDP per capita $(Y_{i,t})$ for country *(i)* and at time *(t)*, as dependent variable, and segments (noted *l*) of precipitation intensity $(X_{r,l,t})$ (similarly to (Schlenker & Roberts, 2009) as well as temperature variation against a historical mean $(T_{i,t} - T'_{i,h})$ - with *h* being the historical period, noted T_{h} as independent variables. The model also includes control variables $(V_{i,t})$ such as oil prices, government spending, external debt, etc., a countrylevel time-invariant fixed effect (ϕ_i) and a non-linear trend $(\theta_i + \theta_i t)$. In Equation 1, *r* denotes a panel of countries – defined by continent and / or income levels.

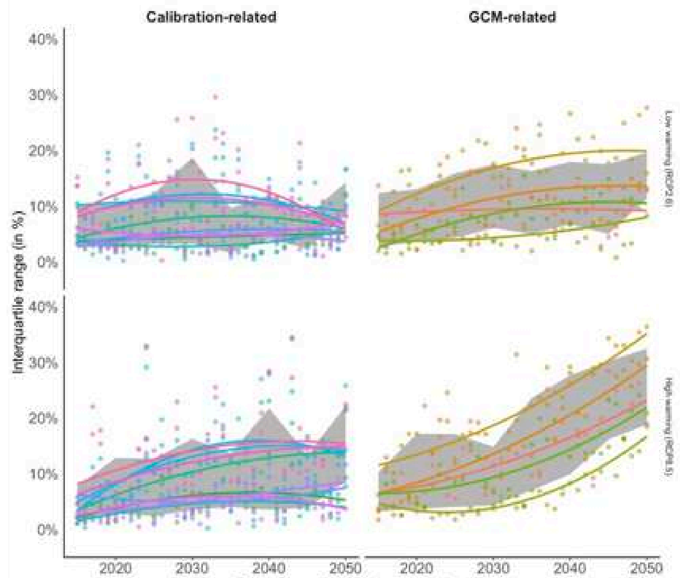
log1Yi' 2 = 4 β)s (X r,s)(+ π)Tk' + εi' + π)(Tk' (+ γ)Vi'; + ϕi + θ)' + θ)'(

Equation 1

Segments of precipitation intensity *(l)* are defined using an index, which normalizes precipitation and allows for comparison from one country to another even though precipitation



Modelled GDP per capita (in US$ PPP) following the regression and calibration (in blue) and the observations taken from the World Bank Development Indicators Database (regression's dependant variable) for Ghana. The thin dashed lines represent the 10 modelled simulations. The results are for the median (line), the 50% confidence interval (dark grey) and the 95% confidence interval (lighter grey).
Citation: Baarsch et al., (2020)



Dispersion of the projections using the Interquartile Range (IQR).
110. In the right panel, the colors represent the 5 Global Circulation Models used for the projections.
Citation: Baarsch et al., (2020)

Figure 52 Model verification using modelled GDP Figure 53 Preliminary representation of sources per capita against GPD per capita observations of economic and climate-related uncertainties from the World Bank Development Indicators Database.

levels are of different magnitude (Brown et al., 2013). The Standardized Precipitation Index (Vicente-Serrano & LópezMoreno, 2005) is here used. Exposure to bins of precipitation intensity is calculated by measuring the percentage of population-weighted area of a country, during a given year, exposed to a segment within the broader range of the index on a monthly basis. For SPI, increments of 0.5 are used, between -1.5 and +1.5, with two additional segments for extreme and severe values below -1.5 and above +1.5 for a total of eight segments (*n* = 8 in Equation 1). The effect of temperature on GDP per capita is measured using a quadratic function (Burke et al., 2015). However, to allow for a variation of the effect of weather and climate across different climates (Mendelsohn, 2016), temperature is integrated in the model employing the deviation from the historical mean $(T_{r} - T'_{\%})$. The piecewise approach has also been used in recent publications, even though this approach was primarily applied to temperature (Du et al., 2017; Schlenker & Roberts, 2009)

.

Country-Level Bayesian Calibration

Sensitivities of GDP per capita to temperature and precipitation are inferred for a panel of countries in the period 1990-2019 (eventually 2000-2019 if enough data is available). However, it is expected that countries within the same panel display large differences across GDP per capita, like any other continents – for example, the GDP per capita of South Africa and Equatorial Guinea are 20 and 50 times higher than Burundi's GDP per capita in 2015 (World Bank, 2022). As a consequence of this large variability of income and presumably of vulnerability to changes in temperature and precipitation (Brooks et al., 2005), the temperature and precipitation vulnerability inferred from the panel could underestimate vulnerability in the most vulnerable (eventually poorest) countries and at the opposite overestimate it in the least vulnerable ones. To address this potential under- / overestimation risk posed by these differences between countries, the model is calibrated for each country independently using Bayesian calibration (DeJong et al., 1996; Gomme & Rupert, 2007).

The regression (Equation 1) is performed for a given pool of countries. The calibration is performed in two steps, a first step consisting in generating a normally distributed ensemble of coefficients following the coefficients and standard errors inferred from the regression and second step consisting in filtering the most fitted coefficients for which the Mean Average Percentage Error (MAPE) is the lowest. The data generating process for the Bayesian calibration is performed using a Monte Carlo Simulation that preserves the distribution of the coefficients of the panel regression, under the following condition, such as:

$$\beta_{i,\$} \quad \text{iid} \sim \quad N(\beta_{=},\$, se_{-1,\#})$$

Equation 2

For this analysis, several thousands of draws are generated, within two standard errors around the mean value of the panel coefficients (noted with the index *r*). GDP per capita for the period 1990-2019 are estimated using the generated coefficients. The filtering is performed for each country

Macroeconomic indicator	Period	Outputs	Delivery
GDP	Historical: 2000-2019	· Macroeconomic adaptation gap, defined as mean economic risks resulting from hydrometeorological, temperature and windspeed.	May 2022
	Future: 2020-2050	· Economic risks (compared to the reference period) · Share of respective climaterelated stressors in economic risks over the period · Cumulated effects on GDP per capita over the period *(to be confirmed)*	Sept. 2022
Inflation	Historical	· Mean inflationary risks (total inflation, food, nonfood) over the historical period	Sept. 2022
	Future: 2020-2050	· Inflationary risks (e.g. change in frequency of high inflationary events) · Share of respective climate-related stressors in inflationary risks over the period	Sept. 2022
Interest rates	Future: 2020-2050	· Trend in interest rates over three rolling periods of 20 years centred around 2030, 2040 and 2050	Sept. 2022

(Table 14 Table of outputs - at the country-level (unless otherwise indicated)).

individually using the Mean Average Percentage Error, leading to the selection of up to 10 different values for each of the regression coefficients. The Bayesian calibration method leads to the inference of β_i and π_i coefficients (with the index *i*) at the national level from panel regression coefficients (initially noted with *r*). The figure below displays the MAPE for each country as well as the number of observations against which the calibration was performed.

Figure 5 Range of mean Absolute Percentage Error (MAPE) for the 10 most fitted sets of coefficients for each African country following panel regression and model calibration. Source: authors' computation.

Projections

The projections up to 2070 are realized using the sensitivity coefficients inferred by the regression model and subsequent calibration ($\beta_{i\$}$ for precipitation intensity and π_{T_i} and π_{T_i} for temperature levels) and exposure to the same range of precipitation intensity and temperature deviation from the historical mean using the grid-level bias-corrected projections of five Global Circulation Models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Lange, 2019). The GDP per capita rollback risk is computed in three scenarios from CMIP6 database which are equivalent in warming levels to the CMIP5 RCP8.5 scenario (called high warming), RCP4.5 (mid-warming) and the IPCC RCP2.6 scenario (called low warming) from 2020 to 2070. For every year, country, model (five GCMs from the CMIP6 database) and scenario (RCP8.5, RCP4.5 and RCP2.6), the economic model produces 10 macroeconomic risk effect estimates for the period 2020-2070 (therefore 50 for every year, country and scenario). The results are available for each country, for which historical and projection of socioeconomic indicators and climate data are available.[42]

Future economic risk (R) is computed on a yearly basis for GDP per capita through the following equation, with i in the reference period (either 20002019 or 1986-2005 depending on the model specifications). A future time period is denoted *f*:

$$R_{L} = 4\, \beta_{i,\$} (X_{i,\$}) (+ \pi_i T_{\&} \;\; ' + \pi (T_{\&}' \; (- CZ1\; 4\; 4\; \beta_{i,\$} (X_{i',\$}) (+ \pi_i T_{\&}' \;\; + \pi (T_{\&}' \; (F$$

Equation 3

Z in the total number of years i. In Equation 3, the parameter R_{i}^{*} =

$$\frac{1}{Z} \sum_{z=1}^{Z} \sum_{l=1}^{n} \beta_{i,l} (X_{it,l})^2 + \pi_i T_{\&}$$

for the period reference period measures

the mean economic risks in the reference period (R) used to adjust future economic risks in both warming scenarios. By subtracting the aggregate risk for the reference period the projections for the period 2020-2070 therefore only accounts for climate variability and climate change effects additional to climatic conditions initially prevailing in the reference period. R is here expressed in percentage GDP per capita growth.

We already conducted an inventory of availability of control variables for the regression analysis across the different continents and income level groups (cf. annex for more details).

Integration of Wind Speed

In addition to temperature deviation and hydrometeorological events, the team will test an upgrade of the modelling framework by integrating windspeed effects on GDP. This integration will be made following the most frequently used approach, which consists in applying a power function to windspeed. The following table provides a summary of the power functions used for estimating the effect of windspeed on GDP and / or damages.

Publications	Power function of wind speed (η)
Emanuel, (2005)	3
Nordhaus, (2010)	9
Bouwer & Wouter Botzen, (2011)	8
Pielke et al., (2008)	6-8
Strobl, (2012)	3.8

Considering the ranges of power functions of windspeed available in the literature, we propose to test the levels of power in the panels, with the objective of keeping the most statistically significant. Considering the macroeconomic perspective of the analysis performed, the integration in the regression will consist in weighting the wind exposure by population (the proxy for wealth creation) and the duration of the event(s) exceeding a given cell-level threshold in line with the method developed by Klawa & Ulbrich, (2003). Even though this method provides reliable estimates for heavy storms, it tends to underestimate impacts from lower intensity events (Prahl et al., 2015).

With the integration of windspeed, the revised formulation of the regression will be as follows.

A first step in the integration of windspeed in the regression function consists in creating $\mathbf{H}_{i}$, the power excess-over-threshold wind accumulation parameter:

$$H_{i} = 4\,K \frac{\sum^{dt} w_p * \left(\frac{v - v_{98}}{v}\right)^5}{\sum^{98} w_p} \quad if \quad v \geq v_{34}; \qquad 0 \quad if \quad v < v_{34}$$

Equation 4

In Equation 4, d indicates the days of the year (to dt, as the end of the year); w_2 is the population density weight assigned to the different windspeed measurements; v and v_{34} are the windspeed, and the 98 index indicates the 98[th] percentile (following Klawa & Ulbrich, 2003). Depending on results, different percentiles might be tested.

With its integration in the initial regression (Equation 1), we obtain:

$$\log 1Y_{i}^{*}\,2 = 4\, \beta_{i\$} (X_{r,\$}) (+ \pi_i T_{\&}' + \pi_i (T_{\&}' \; (+ \zeta_i H_{r} + \gamma_i V_{r} + \phi_i + \theta_r + \theta_i \gamma + \varepsilon_{r}$$

Equation 5

3.2. Climate change and inflation

Existing Literature

As much as the relation between climate related disasters and GDP has been extensively studied in the recent years, the relation with inflation has yet to be further understood. There is therefore limited evidence of this relation in the economic literature and different methods have been employed.

To start with, there is anecdotical evidence across countries highlighting this relation between climate-related disasters and inflationary circumstances. Taking the example of a drought affecting the Horn of Africa, (Laframboise & Loko, 2012) report that in a Kenya as a consequence of the on-going crisis "*the domestic price of maize, a staple food crop, increased by more than 150 percent*" (page 26), and led "*to significant food inflation with adverse impacts on rural households and the urban poor*" (page 13). The drought and its effects aggravated an already weakened macroeconomic state as "*the economy was already dealing with excess demand and credit growth that had led to high inflation, a worsening of external balances, and currency depreciation.*" (pages 15-16).

The consequences observed on inflation in Kenya are consistent with a later publication (Parker, 2018). The authors noted a significant heterogeneity in the relation between disasters (including not climate-related) and inflationary pressure between high income on one side and low to middle income countries on the other. In low- and middle-income economies, the inflationary effect can be long-lasting over several years, with a duration that varies depending on the type of disasters. Focusing only on 15 Caribbean islands, (Heinen et al., 2018) found that hurricanes and floods have limited consequences of welfare losses due to price increase – however rare and most intense events can lead to remarkable losses as a response to inflation. On a study focusing on African countries (Kunawotor et al., 2021), authors found that extreme weather events can cause "significant price hikes" – with production in the agricultural sector being the main channel leading to this inflationary pressure. Owing to this consequence, authors also stressed the need for the consequences of climate-related disasters to be also considered by central banks in their policy decisions. Similar findings were observed in Europe, where climate-related disasters could lead to increase in inflation, especially in relation with food and beverages. Even though the observed are small they are significant across all countries where major differences in effects are also detected.

Proposed Methods

One econometric method and one method based on explainable machine learning (xML) will be tested to explore the relation between inflation, food and non-food inflation and climatic variables.

For the econometric approach, we propose to use a method adapted to the one employed for GDP (section 3.1). The main difference lies in the temporal aggregation of climate data. ILO database provides inflation data on a monthly basis therefore SPI, temperature and windspeed data will also be aggregated on a monthly basis. This approach is however different from the currently used approach that mostly consists in event analysis using reported disasters from the EM-DAT database.[43] In line with the publications reviewed above, we will also investigate the lagged effect of climatic stresses on inflation. The analysis on inflation will be separated in three sub-analyses: one focusing on general inflation, a second one on food inflation and a third one on non-food inflation.

In case the econometric analysis performs poorly, we will explore the possibility of using explainable Machine Learning (xML) methods, such as random forest, knn and XGboost. The ML models will be constrained by observations and findings from existing publications by segmenting results based on the relative importance and SHAP method.

3.3. Climate Change and Interest Rates

To estimate the future impacts of climate change on interest rates, we employ the Taylor rule (Taylor, 1993). The Taylor rule allows for an estimation of interest rates based on four main parameters derived from inflation and GDP: the gap between actual inflation (π_t) and desired inflation (π_t^*) and actual economic output (y_t) vs. desired output (yY_t). In the following equation, r_t^* is the equilibrium interest rate. In Taylor's paper π_t is estimated as inflation over the last four quarters while yY_t is the trend real GDP (over the last 10 years). According to Taylor, the two parameters α_8 and α_9 should be equal to 0.5 and always remain positive.

$$i = \pi_t + r_t^* + \alpha_\pi(\pi_t - \pi_t^*) + \alpha_y(y_t - \bar{y}_t)$$

Equation 6

As a results of the above sections, the influence of climate change and climate-related disasters on inflation and economic outputs will be estimated. The results will then be used to appraise the evolution of interest rates as a response to the same changes in climate. As inflation increases (for example because of a drought), the Taylor rule incentivizes an increase in interest rates as central banks are expected to tighten monetary policy to keep inflation at reasonable levels. On the other side, the same drought could also lead to a decrease in expected economic output – conducting to easy monetary policies (i.e., lower interest rates).

The objective of the analysis performed under this section is to indicate a potential trend in interest rates (upwards, downwards, and stable) as a consequence of climate-related disasters. The significance of the trend will be described using usual statistical tools.

$$\text{trend in} \quad i \approx \alpha_\pi(\pi_t - \pi_t^*) + \alpha_y(y_t - \bar{y}_t)$$

Equation 7

Projections performed on GDP, inflation and interest rates will run from 2020 to 2050. After this period, the coefficients estimated in the past 30 years using a regression analysis could largely miss an adequate representation of the economic structure and therefore damages, inflationary risks and therefore interest rates.

4. Outputs

The outputs prepared in this analysis are presented in the following table.

Partners and Acknowledgement

The CVF and V20 Secretariat

The CVF and V20 secretariat, Global Center on Adaptation and Aroha

The Climate Vulnerable Forum (CVF) is the international forum for countries most threatened by climate change. Composed of 58 members[44] from Africa, Asia, the Caribbean, Latin America and the Pacific, it represents some 1.5 billion people worldwide. It was founded in November 2009 by the Maldives at Male', together with 10 other countries. The Forum is led by a rotating chair for an ordinary period of two years, with Ghana currently chairing for the period 2022-2024. Ghana is the second African nation to lead the CVF after Ethiopia.

Established in Lima, in October 2015, The Vulnerable Twenty Group (V20) of Ministers of Finance of the CVF is a dedicated cooperation initiative of economies systemically vulnerable to climate change. It works through dialogue and action to strengthen economic and financial responses to climate change.

The CVF and V20 is presided over by the Republic of Ghana for the period 2022-24. The CVF and V20 Secretariat is hosted by the Global Center on Adaptation (GCA), an international organization with headquarters in Rotterdam, the Netherlands, working as its Managing Partner and with secretariat operations carried out in partnership with Aroha, an international non-governmental organization based in Geneva, Switzerland.

Science Consortium

Climate Analytics

Climate Analytics (CA) is an international non-profit climate science and policy institute, established in 2008. Being headquartered in Berlin (Germany), CA has regional offices in New York (USA), Lomé (Togo), Perth (Australia), Port of Spain (Trinidad & Tobago), and Kathmandu (Nepal), as well as staff and associates across Europe, South America, Australia, Africa and Asia. The organisation's main mission is to **synthesise and advance scientific knowledge in the area of climate change** as well as to **Vulnerability** and on this basis to provide support in updating reports.

Our science experts, who will contribute to the CVM, are experienced in cross-cutting research **analysing impacts, risks and co-benefits to understand the full implications of climate change**. Based on these, we support government and non-government stakeholders in identifying priority areas of adaptation planning and investment. Our work hereby focuses on understanding the effects of climate change on **livelihood realities and development perspectives** of especially vulnerable population groups. As the main contributor to several **scientific reports issued by the World Bank and UNEP on mitigation and adaptation**, Climate Analytics has for instance significantly contributed to a better understanding about what still needs to be done to win the battle against climate change and what the consequences of inaction would be.

Climate Analytics (CA) would like to thank the following company team members: Dr. Carl-Friedrich Schleussner and Dr. Alexander Nauels for their invaluable insight into the Paris Agreement and 1.5C compatible pathways; Emily Theokritoff for her assistance with the GAMI database; and Tessa Möller for her assistance with data analysis of the biophysical indicators. The CA team would also like to thank its experts in regional offices around the world for their assistance in the development and execution of the country case studies. Finally, the team thanks Dr. Katja Freieler and Dr. Matthias Mengel of the Potsdam Institute for Climate Research for their insight into the ISIMIP3 data protocol. The Mercator Research Institute for the Global Commons and Climate Change (MCC) thanks Shruti Nath for sharing data and expertise on the attribution of temperature and precipitation trends to human influence on the climate.

Mercator Research Institute for the Global Commons and Climate Change

The **Mercator Research Institute for the Global Commons and Climate Change (MCC)** is a scientific think tank in Berlin, Germany that combines high-level economic and social science analyses with a structured approach at the science-policy interface. We provide solution-oriented policy portfolios for climate mitigation, for governing the global commons in general, and for enhancing the many aspects of human well-being. MCC explores solutions, advises policy-makers, and fosters open (deliberative) debate across society with a focus on fair access to natural and social commons, both for today's and future generations.

Global Data Lab

The **Global Data Lab (GDL)** is a data and research center at Radboud University in the Netherlands which develops databases, indicators, and instruments for monitoring and analyzing the status and progress of societies. GDL has built one of the largest existing databases for low and middle income countries (LMICs), with data on more than 35 million persons in 135+ countries. From this database indicators at subnational (e.g. provincial) level are constructed for a broad range of fields, including demographics, education, wealth, poverty, gender, public services, health and human development. These indicators are made freely available to the global community through the GDL website www.globaldatalab.org. Major instruments developed by GDL are the Subnational Human Development Index (SHDI), the International Wealth Index (IWI) and the GDL Vulnerability Index (GVI).

CMF Climate Media Factory

The **Climate Media Factory (CMF)** is a **media, consulting and concept agency** in Potsdam (Germany). For ten years CMF has been **shaping societal discourses** about the future via **innovative media**. To do this, CMF brings narrative, creative and scientific expertise to the table. CMFs work is transdisciplinary, the company emerged from a media laboratory of the Potsdam Institute for Climate Impact Research and the Babelsberg Film University. CMF is a both service provider and, but also a partner for research and innovation projects.

The **handling, curationing and visualisation of scientific data** to facilitate informed decision-making processes via web applications has emerged as one focus of research and media products in recent years. But the CMF portfolio also includes animations, project films, video platforms, MOOCs and much more besides interactive web applications for decision-makers.

The Lancet Countdown

Tracking Progress on Health and Climate Change is a multi-disciplinary, international research collaboration monitoring the links between health and climate change. The Lancet Countdown works to produce robust scientific evidence, and to ensure that health is at the centre of how governments understand and respond to climate change. With a global network and regional centres in high and low-middle income countries, it brings together almost 300 researchers from 100 academic institutions and UN agencies in every continent. The collaboration produces annual global and regional reports, with updates on over 40 indicators monitoring the health impacts of climate change, and the health opportunities of accelerated climate action. Its findings provide decision-makers with high-quality evidence to help guide a response to climate change that prioritises human health and wellbeing, and delivers a thriving future to present and future generations.

finres

finres is a science startup that supports public and private investors in understanding, evaluating climate risks to design profitable and robust investment strategies. The team is composed offrom researchers, data scientists and former staff from international financial institutions. finres also trains governments at the integration of climate risks in macroeconomic decision-making tools and policies.

Abbreviations

% - Percentage

1.5°C – One point five degrees Celsius

2°C – Two degrees Celsius

ASALs - Arid and semi-arid lands

CIDs - Climatic impact-drivers

CMIP6 - Coupled Model Intercomparison 6

CO_2 - Carbon dioxide

Covid-19 - Coronavirus disease

CPI - Consumer Price Index

CVF - Climate Vulnerable Forum

CVM3 - Climate Vulnerability Monitor, Third Edition

GCM: global climate model

GCMs - Global Climate Models

GDP – Gross Domestic Product

GHG - Greenhouse gas

GVI – GDL Vulnerability Index

IM – Impact Models

IPCC - Intergovernmental Panel on Climate Change

IPCC AR6 - Intergovernmental Panel on Climate Change Sixth Assessment Report

IPCC AR6 WG1 Ch5 - Intergovernmental Panel on Climate Change Sixth Assessment Report, Working Group one, Chapter five

IPCC AR6 WGI SPM - Intergovernmental Panel on Climate Change Sixth Assessment Report, Working Group one, Summary for Policymakers

IPCC AR6 WGII - Intergovernmental Panel on Climate Change Sixth Assessment Report, Working Group two

IPCC AR6 WGIII SPM - Intergovernmental Panel on Climate Change Sixth Assessment Report, Working Group three, Summary for Policymakers

ISIMIP3 - Intersectoral Impact Model Intercomparison Project 3

K- Kelvin

kg m^2 s^{-1} - Kilograms per square meter

kgm^{-2}- Kilogram per square metre

km – Kilometre

km^2 - Square kilometre

m s^{-1} - Meters per second

m^3 s^{-1} – Cubic Metre per second

OECD - Organisation for Economic Co-operation and Development

PWHL: percentage work hours lost

rainf – Rainfall

RX5-day - Heavy precipitation over a five day period

snowf – Snowfall

SPEI - Standardized Precipitation-Evapotranspiration Index

SSP – Shared Socioeconomic Pathway

SSP1 - Shared Socioeconomic Pathway 1

SSP126 – Shared Socioeconomic Pathway 1-2.6. See Glossary for definition

SSP3 - Shared Socioeconomic Pathway 3

SSP370 – Shared Socioeconomic Pathway 3-7.0. See Glossary for definition

SSPs - Shared Socioeconomic Pathways

t / ha – Tonnes per hectare

t ha^{-1} (dry matter) - Tonnes of dry matter per hectare

TCs – Tropical cyclones

UK - United Kingdom of Great Britain and Northern Ireland

UNDP – United Nations Development Programme

UNU-EHS - United Nations University, Institute for Environment and Human Security

USD - United States dollar

W: Watts

Glossary

1.5°C scenario: In line with the temperature limit specified in the Paris Agreement, the report assesses impacts in a scenario that assumes temperatures stabilise around a median warming of 1.5°C, based on results out of the SSP1-2.6 scenario in the near-term (2030).

Acclimation: process of the body adjusting to new climate conditions

Adaptation finance: Adaptation finance refers to the financial resources devoted to addressing adaptation to climate change by all public and private actors from global to local scales, including international financial flows to developing countries to assist them in addressing climate change.

Adaptation gap: The difference between actually implemented adaptation and a societally set goal, determined largely by preferences related to tolerated climate change impacts and reflecting resource limitations and competing priorities (UNEP, 2014; UNEP, 2018).

Adaptation: Adjustments in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts. These adjustments include changes in processes, practices, and structures, and can be incremental in a single system or structure, or substantive over several structures and systems, known as transformational adaptation.

Adaptive capacity: The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences (MA, 2005).

Anthropogenic forcing: Drivers of climate change which are caused by humans (such as greenhouse gases).

Attribution: This is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assessment of confidence.

Baseline: a point or period used for comparison
Baseline: The scenario used as starting or reference point for a comparison between two or more scenarios. For this report, the baseline refers to the 1995 – 2014 time period.

Below 2°C scenario: This scenario is based on results for the SSP1-2.6 scenario, which leads to a best estimate of 1.8°C by the end of century.

Biodiversity loss: This refers to the loss (extinction, relocation or decline) of the variability among living organisms from all sources including, among other things, terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems (UN, 1992).

Climate change: A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.

Climate driver: A changing aspect of the climate system that influences a component of a human or natural system.

Climate extreme: This includes extreme weather (or extreme climate event)and refers to the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable.

Climate mitigation: A human intervention to reduce emissions or enhance the sinks of greenhouse gases.

Climate model: A qualitative or quantitative representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes and accounting for some of its known properties.

Climate stimuli: Climate change stimuli are described in terms of "changes in mean climate and climatic hazards," and adaptation may be warranted when either of these changes has significant consequences (Downing et al., 1997).

Climate system: The global system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere and the interactions between them.

Climate variability: Deviations of some climate variables from a given mean state (including the occurrence of extremes, etc.) at all spatial and temporal scales beyond that of individual weather events. Variability may be intrinsic, due to fluctuations of processes internal to the climate system (internal variability), or extrinsic, due to variations in natural or anthropogenic external forcing (forced variability).

Climate-smart agriculture: a set of agricultural practices that seek to simultaneously increase productivity, improve resilience, and reduce emissions

Climate: In a narrow sense, climate is usually defined as the average weather -or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities- over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization (WMO). The relevant quantities are most often surface variables such as temperature, precipitation and wind.

Coupled Model Intercomparison Project (CMIP): A climate modelling activity from the World Climate Research Programme (WCRP) which coordinates and archives climate model simulations based on shared model inputs by modelling groups from around the world. The CMIP3 multi-model data set includes projections using Special Report on Emissions Scenarios (SRES) scenarios. The CMIP5 data set includes projections using the Representative Concentration Pathways (RCP). The CMIP6 phase involves a suite of common model experiments as well as an ensemble of CMIP-endorsed Model Intercomparison Projects (MIPs).

Crop yield potential: maximum yield that could be achieved with no limitations on water or nutrients

Ecosystem: A functional unit consisting of living organisms, their non-living environment and the interactions within and between them.

Emission scenario: A plausible representation of the future development of emissions of substances that are radiatively active (e.g., greenhouse gases (GHGs) or aerosols) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change, energy and land use) and their key relationships.

End-of-century: Refers to a 20-year time period (2081-2100), centered around the year 2090.

Endemic: also known as baseline levels, refers to the amount of a certain disease that is constantly or usually present in an area or population

Environmental suitability: the environmental conditions (e.g., temperature, precipitation, water salinity) under which a disease can survive and be transmitted

Epidemic: a substantial increase in the number of cases of a particular disease above what is considered usual (endemic) for that area and population

Exposure-response function: the relationship between the magnitude of exposure to a certain substance or condition and the associated magnitude of the outcome of interest

Food security: A situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life.

Food system: All the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socio-economic and environmental outcomes (HLPE, 2017). [Note: While there is a global food system (encompassing the totality of global production and consumption), each location's food system is unique, being defined by that place's mix of food produced locally, nationally, regionally or globally.]

Glacier: A perennial mass of ice, and possibly firn and snow, originating on the land surface by accumulation and compaction of snow and showing evidence of past or present flow. A glacier typically gains mass by accumulation of snow and loses mass by ablation.

Global circulation patterns: Refers to the world-wide system of winds by which the necessary transport of heat from tropical to polar latitudes is accomplished.

Global warming: Global warming refers to the increase in global surface temperature relative to a baseline reference period, averaging over a period sufficient to remove interannual variations (e.g., 20 or 30 years). A common choice for the baseline is 1850–1900 (the earliest period of reliable observations with sufficient geographic coverage), with more modern baselines used depending upon the application.

Governance: The structures, processes and actions through which private and public actors interact to address societal goals. This includes formal and informal institutions and the associated norms, rules, laws and procedures for deciding, managing, implementing and monitoring policies and measures at any geographic or political scale, from global to local.

Greenhouse gas (GHG): Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of radiation emitted by the Earth's ocean and land surface, by the atmosphere itself and by clouds. This property causes the greenhouse effect. Water vapour (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4) and ozone (O3) are the primary GHGs in the Earth's atmosphere. Human-made GHGs include sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs), chlorofluorocarbons (CFCs) and perfluorocarbons (PFCs); several of these are also O3-depleting (and are regulated under the Montreal Protocol).

Gross domestic product (GDP): The sum of gross value added, at purchasers' prices, by all resident and non-resident producers in the economy, plus any taxes and minus any subsidies not included in the value of the products in a country or a geographic region for a given period, normally one year. GDP is calculated without deducting for depreciation of fabricated assets or depletion and degradation of natural resources.

Hazard: The potential occurrence of a natural or human-induced physical event or trend 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.

Heatwaves: A period of abnormally hot weather, often defined with reference to a relative temperature threshold, lasting from two days to months. Heatwaves and warm spells have various and, in some cases, overlapping definitions.

Human systems: Human systems include social, economic and institutional structures and processes. Related to industry, settlement and society, these systems are diverse and dynamic, expressed at the individual level through livelihoods. Any system in which human organisations and institutions play a major role. Often, but not always, the term is synonymous with society or social system. Systems such as agricultural systems, urban systems, political systems, technological systems and economic systems are all human systems in the sense applied in this report.

Human-induced climate change: 'A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods' (UNFCCC).

Hydrological cycle: The cycle in which water evaporates from the ocean and the land surface, is carried over the Earth in atmospheric circulation as water vapour, condenses to form clouds, precipitates over the ocean and land as rain or snow, which on land can be intercepted by trees and vegetation, potentially accumulating as snow or ice, provides runoff on the land surface, infiltrates into soils, recharges groundwater, discharges into streams and, ultimately, flows into the oceans as rivers, polar glaciers and ice sheets, from which it will eventually evaporate again.

Incidence: the frequency or occurrence of new cases of a disease or other event

International Health Regulations (IHR): a legal framework designed to outline the obligations of countries to manage public health issues and emergencies that may impact other countries

Length of transmission season: the number of months or weeks with conditions suitable for transmission of an infectious disease

Loss and Damage, and losses and damages: Research has taken Loss and Damage (capitalised letters) to refer to political debate under the United Nations Framework Convention on Climate Change (UNFCCC) following the establishment of the Warsaw Mechanism on Loss and Damage in 2013, which is to 'address loss and damage associated with impacts of climate change, including extreme events and slow onset events, in developing countries that are particularly vulnerable to the adverse effects of climate change.' Lowercase letters (losses and damages) have been taken to refer broadly to harm from (observed) impacts and (projected) risks and can be economic or non-economic (Mechler et al., 2018).

Mid-term: Refers to a 20 year time period (2041-2060), centered around the year 2050.

Natural forcing: Drivers of climate change which occur independently of human actions (such as volcanic eruptions).

Natural systems: The dynamic physical, physicochemical and biological components of the Earth system that would operate independently of human activities.

Near-term: Refers to a 20 year time period (2021-2040), centred around the year 2030.

No climate action scenario: This scenario is based on SSP3-7.0 results, this higher warming scenario would lead to a median warming of 3.6°C by the end of century, currently above the estimated temperature that current climate policies would achieve.

Person-days: the sum total of days considered in a study considering both the number of people included and the amount of time contributed by each one (e.g., if 100 people are each included for 5 days, there would be 500 person-days)

Person-hours: the sum total of hours considered in a study considering both the number of people included and the amount of time contributed by each one (e.g., if 100 people are each included for 10 hours, there would be 1,000 person-hours)

Pre-industrial times: The multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial global mean surface temperature (GMST).

Projection: A potential future evolution of a quantity or set of quantities, often computed with the aid of a model.

R_0: the basic reproduction number, which represents the expected number of secondary infections resulting from one single primary infected person case in a totally susceptible population

Ratoon: Ratooning is a practice of harvesting a second crop from the stubble of a first crop.

Re-emerging diseases: diseases that were previously a serious public health issue in a certain place or globally, then decreased significantly, and have since become a serious issue again

Shared Socio-economic Pathways (SSPs): A set of illustrative emissions scenarios that cover a range of possible future development of anthropogenic drivers of climate change. They include scenarios with high and very high GHG and CO2 emissions, scenarios with intermediate GHG emissions and CO2 emissions remaining around current levels until the middle of the century, and scenarios with very low and low GHG emissions and CO2 emissions declining to net zero around or after 2050, followed by varying levels of net negative CO2 emissions. Emissions vary between scenarios depending on socio-economic assumptions, levels of climate change mitigation and, for aerosols and non-methane ozone precursors, air pollution controls.

Small Island Developing States (SIDS): as recognised by the United Nations Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States (OHRLLS), are a distinct group of developing countries facing specific social, economic and environmental vulnerabilities (UN-OHRLLS, 2011). They were recognised as a special case for both their environment and their development at the Rio Earth Summit in Brazil in 1992. Fifty-eight countries and territories are presently classified as SIDS by the UN OHRLLS, with 38 being UN member states and 20 being Non-UN Members or Associate Members of the Regional Commissions (UN-OHRLLS, 2018).

Socioeconomic determinants of health: non-medical factors, including but not limited to education, social class, income, and housing, that impact human health

Solastalgia: an emerging concept to describe the distress that people feel due to climate degradation

SSP1: Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation). A set of low and very low emissions scenarios corresponding to 1.5°C to 2°C of warming, relative to pre-industrial times, by 2100. In this pathway, the world shifts gradually toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Inequality is reduced both across and within countries, and consumption is oriented to low material growth, and lower resource and energy intensity. SSP1 envisions relatively optimistic trends for human development, with substantial investments in education and health, rapid economic growth, and well-functioning institutions.

SSP126: A scenario with low GHG emissions and CO2 emissions declining to net zero after 2050, followed by net negative CO2 emissions. This scenario leads to below 2°C by the end of the 21st century. It is referred to in the CVM3 as the “below 2°C scenario”.

SSP3: Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation). A set of high emissions pathways corresponding to 3.6°C of warming, relative to pre-industrial times, by 2100. In this pathway, there is resurgent nationalism, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. The SSP3 pathway is pessimistic regarding future economic and social development: economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized countries and high in developing countries.

SSP370: A scenario with with high and very high GHG emissions, and CO2 emissions that roughly double from current levels by 2100. This scenario to approximately 3.6°C by the end of the 21st century. It is referred to in the CVM3 as the No-climate-action Scenario.

Surveillance: ongoing, regular monitoring, collection, and analysis of public health conditions and outcomes that is used to prevent and control disease

Tropical cyclones: The general term for a strong, cyclonic-scale disturbance that originates over tropical oceans. Distinguished from weaker systems (often named tropical disturbances or depressions) by exceeding a threshold wind speed. A tropical storm is a tropical cyclone with one-minute average surface winds between 18 and 32 m s−1. Beyond 32 m s−1, a tropical cyclone is called a hurricane, typhoon or cyclone, depending on geographic location.

Urbanization: Urbanisation is a multi-dimensional process that involves at least three simultaneous changes: (1) land-use change: transformation of formerly rural settlements or natural land into urban settlements, (2) demographic change: a shift in the spatial distribution of a population from rural to urban areas and (3) infrastructure change: an increase in provision of infrastructure services including electricity, sanitation, etc. Urbanisation often includes changes in lifestyle, culture and behaviour, and thus alters the demographic, economic and social structure of both urban and rural areas (based on World Urbanization Prospects 2018; IPCC 2014; Stokes and Seto, 2019).

Vector-borne diseases: Illnesses caused by parasites, viruses and bacteria that are transmitted by various vectors (e.g., mosquitoes, sandflies, triatomine bugs, blackflies, ticks, tsetse flies, mites, snails and lice) (UNEP 2018).

Vulnerability index: A metric characterising the vulnerability of a system. A climate vulnerability index is typically derived by combining, with or without weighting, several indicators assumed to represent vulnerability.

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.

Water security: 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-borne diseases: Illnesses transmitted through contact with, or consumption of, unsafe or contaminated water (UNEP 2018).

Dry weather and drought conditions
by Brian Scantlebury
Link: https://stock.adobe.com/fr/images/dry-weather-and-drought-conditions/324114873

Endnotes

[1] https://public.wmo.int/en/resources/united_in_science

[2] The Climate Action Tracker estimates global warming will reach 2.1°C by 2100 if all additional pledges, targets, and policies are fully implemented by all countries globally. Its central estimate for a scenario of current policies and action is a warming of 2.7°C by 2100, with an upper estimate of 3.6°C for a higher, but plausible, sensitivity of the climate system to increasing concentrations of greenhouse gases.

[3] https://www.mdpi.com/2071-1050/12/17/6935/htm#

[4] Where references are made to CVF member states/countries in this CVM3 report they refer to the 55 nations membership of the CVF over the period November 2021-October 2022. Since October 2022, the CVF has numbered 58 member states.

[5] The G20 contracted by 3.2% in 2020 but rebounded by 6.1% in 2021 (versus 2019 growth of 2.8%) for a net 2.9% absolute loss of growth equivalent to over 50% of 2020-21 GDP growth potential (based on 2019 levels): https://www.oecd.org/newsroom/g20-gdp-growth-fourth-quarter-2021-oecd.htm ; https://www.oecd.org/sdd/na/g20-gdp-growth-Q4-2020.pdf

[6] https://www.v-20.org/resources/publications/climate-vulnerable-economies-loss-report

[7] https://reliefweb.int/report/vanuatu/post-disaster-needs-assessment-tropical-cyclone-pam-march-2015

[8] https://unctad.org/topic/least-developed-countries/list

[9] https://www.unep.org/resources/adaptation-gap-report-2021

[10] https://unfccc.int/topics/science/workstreams/periodic-review#eq-1of

[11] https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/

[12] https://www.isimip.org/protocol/3/

[13] Exposure is defined as the presence of people; livelihoods; species or ecosystems; environmental functions, services and resources; infrastructure; or economic, social or cultural assets in places and settings that could be adversely affected (IPCC 2021, p. 201).

[14] https://thecvf.org/members/

[15] Tropical cyclones have not been assessed directly for the CVM3, and these findings are based on additional literature

[16] https://www.undp.org/publications/towards-multidimensional-vulnerability-index

[17] https://cvi-heritage.org/about

[18] https://unfccc.int/topics/adaptation-and-resilience/the-big-picture/what-do-adaptation-to-climate-change-and-climate-resilience-mean

[19] Note that these results are based on temperature-based assessments and differ from the scenarios used throughout this report. Tropical cyclones have not been assessed directly for the CVM3, and these findings are based on additional literature.

[20] https://www.isimip.org/protocol/3/

[21] https://www.isimip.org/protocol/3/

[22] Source: https://climateknowledgeportal.worldbank.org/country/philippines/vulnerability

[23] https://public.emdat.be/data - aggregate data from 2012-2022 for Philippines;

[24] Flooding – cascading effects. Source: https://www.pagasa.dost.gov.ph/learning-tools/floods#:~:text=A%20really%20big%20flood%20can,in%20industry%2C%20commerce%20and%20trade.

[25] Source: https://newsinfo.inquirer.net/1477903/only-87-of-ph-population-registered-with-philhealth-around-50m-subsidized-by-govt

[26] Source: https://data.worldbank.org/indicator/SH.XPD.OOPC.CH.ZS?locations=PH

[27] Source: https://businessmirror.com.ph/2019/06/19/the-health-insurance-gap-in-the-philippines/

[28] https://www.isimip.org/protocol/3/

[29] https://www.irri.org/our-work/impact-challenges/climate-change-sustainability

[30] https://www.fao.org/faostat/en/#home

[31] https://www.fao.org/land-water/databases-and-software/crop-information/wheat/en/

[32] Full citation: https://www.imf.org/en/Publications/WP/Issues/2016/12/31/Taylor-Visits-Africa-43447

[33] Full citation: https://www.sciencedirect.com/science/article/pii/S0264999317315596

[34] For full citation: https://documents1.worldbank.org/curated/en/893151624478783247/pdf/Neutral-Real-Interest-Rates-in-Inflation-Targeting-Emerging-and-Developing-Economies.pdf

[35] https://www.nature.com/articles/s41558-021-01168-6 (https://static-content.springer.com/esm/art%3A10.1038%2Fs41558-021-01168-6/MediaObjects/41558_2021_1168_MOESM2_ESM.csv)

[36] https://databank.worldbank.org/source/world-development-indicators

[37] https://hdr.undp.org/data-center

[38] http://wdi.worldbank.org/table/WV.1

[39] https://info.worldbank.org/governance/wgi/

[40] http://wdi.worldbank.org/table/WV.1

[41] https://www.isimip.org/protocol/3/

[42] The analysis will only be conducted for the countries satisfying socioeconomic and climate data availability.

[43] Our approach differs because (1) EM-DAT database is partial in low- and middle-income countries and (2) EM-DAT data are only available for the past and would prevent our ability to project the potential consequences of changing weather patterns on inflation in the near- to mid-term future.

[44] Current CVF/V20 Member countries: Afghanistan, Bangladesh, Barbados, Benin, Bhutan, Burkina Faso, Cambodia, Chad, Colombia, Comoros, Costa Rica, Côte d'Ivoire, Democratic Republic of the Congo, Dominican Republic, Ethiopia, Eswatini, Fiji, The Gambia, Ghana, Grenada, Guatemala, Guinea, Guyana, Haiti, Honduras, Kenya, Kiribati, Kyrgyzstan, Nicaragua, Lebanon, Liberia, Madagascar, Malawi, Maldives, Marshall Islands, Mongolia, Morocco, Nepal, Niger, Palau, Palestine, Papua New Guinea, Philippines, Rwanda, Saint Lucia, Samoa, Senegal, South Sudan, Sri Lanka, Sudan, Tanzania, Timor-Leste, Tunisia, Tuvalu, Uganda, Vanuatu, Viet Nam and Yemen. However, where references are made to CVF member states/countries in this CVM3 report they refer to the 55 nations membership of the CVF over the period November 2021-October 2022.

Bibliography

---. "Climate Change Impact Assessment of Food- and Waterborne Diseases." Critical Reviews in Environmental Science and Technology, vol. 42, no. 8, 2012, pp. 857–90, doi:10.1080/10643389.2010.534706.

---. "Climate Change and the Rising Infectiousness of Dengue." *Emerging Topics in Life Sciences*, vol. 3, no. 2, 2019, pp. 133–42, doi:10.1042/ETLS20180123.

---. Report of the Member States Working Group on Strengthening WHO Preparedness and Response to Health Emergencies to the Special Session of the World Health Assembly. 2021.

---. Sixth Assessment Report, Climate Change 2022. 2022.

---. World Malaria Report 2021. 2021.

An, Ruopeng, et al. "Projecting the Influence of Global Warming on Physical Activity Patterns: A Systematic Review." Current Obesity Reports, vol. 9, no. 4, 2020, pp. 550–61, doi:10.1007/s13679-020-00406-w.

Andrijevic, Marina, Jesus Crespo Cuaresma, Raya Muttarak, et al. 'Governance in Socioeconomic Pathways and Its Role for Future Adaptive Capacity'. Nature Sustainability, vol. 3, no. 1, 1, Jan. 2020, pp. 35–41. www.nature.com, https://doi.org/10.1038/s41893-019-0405-0.

Andrijevic, Marina, Jesus Crespo Cuaresma, Tabea Lissner, et al. 'Overcoming Gender Inequality for Climate Resilient Development'. Nature Communications, vol. 11, no. 1, 1, Dec. 2020, p. 6261. www.nature.com, https://doi.org/10.1038/s41467-020-19856-w.

Ara Begum, Rita, et al. "Point of Departure and Key Concepts." Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by H.-O. Pörtner et al., IPCC, 2022, Cambridge University Press, Cambridge, pp. 121-196, doi:10.1017/9781009325844.003

Aumentado, C., Cerro, B. R., Olobia, L., Suy, L. L., Reyes, A., Kusumawathie, P. H. D., Sagrado, M., Hall, J. L., Abeyasinghe, R., Foxwell, A. R., & Vestergaard, L. S. (2015). The prevention and control of dengue after Typhoon Haiyan. *Western Pacific Surveillance and Response Journal*, 6(Suppl 1), 60–65. https://doi.org/10.5365/wpsar.2015.6.3.hyn_018

Baarsch, F., J. R. Granadillos, W. Hare, M. Knaus, M. Krapp, M. Schaeffer, and H. Lotze-Campen. 2020. "The Impact of Climate Change on Incomes and Convergence in Africa." World Development 126. doi: 10.1016/j.worlddev.2019.104699.

Balch, Jennifer K., et al. "Human-Started Wildfires Expand the Fire Niche across the United States." Proceedings of the National Academy of Sciences of the United States of America, vol. 114, no. 11, 2017, pp. 2946–51, doi:10.1073/pnas.1617394114.

Baylis, P., et al. "Weather Impacts Expressed Sentiment." PLoS One, 2018/04/26, vol. 13, no. 4, 2018, p. e0195750, doi:10.1371/journal.pone.0195750.

Beguería, Santiago, et al. "Standardized Precipitation Evapotranspiration Index (SPEI) Revisited: Parameter Fitting, Evapotranspiration Models, Tools, Datasets and Drought Monitoring." International Journal of Climatology, vol. 34, no. 10, 2014, pp. 3001–23, doi:10.1002/joc.3887.

Bernard, Thomas E., and Mehdi Pourmoghani. "Prediction of Workplace Wet Bulb Global Temperature." Applied Occupational and Environmental Hygiene, vol. 14, no. 2, 1999, pp. 126–34, doi:10.1080/104732299303296.

Berry, Helen L., et al. "The Case for Systems Thinking about Climate Change and Mental Health." Nature Climate Change, vol. 8, no. 4, 2018, pp. 282–90, doi:10.1038/s41558-018-0102-4.

Bezner Kerr, Rachel, et al. „Food, Fibre, and Other Ecosystem Products." Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate, edited by H.-O. Pörtner et al., IPCC, 2022, Cambridge University Press, Cambridge, pp. 713-906, doi:10.1017/9781009325844.007

Birkmann, Jörn, and UNU-EHS Expert Working Group on Measuring Vulnerability, editors. Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies. Second edition, United Nations University Press, 2013.

Bisbis, Mehdi Benyoussef, et al. 'Potential Impacts of Climate Change on Vegetable Production and Product Quality – A Review'. Journal of Cleaner Production, vol. 170, Jan. 2018, pp. 1602–20. ScienceDirect, https://doi.org/10.1016/j.jclepro.2017.09.224.

Boisvert, Linette N., et al. 'Intercomparison of Precipitation Estimates over the Southern Ocean from Atmospheric Reanalyses'. Journal of Climate, vol. 33, no. 24, Dec. 2020, pp. 10627–51. DOI.org (Crossref), https://doi.org/10.1175/JCLI-D-20-0044.1.

Borunda, Alejandra. "The Science Connecting Wildfires to Climate Change." National Geographic, 2020, p. 1, https://www.nationalgeographic.com/science/article/climate-change-increases-risk-fires-western-us.

Bouwer, L. M., & Wouter Botzen, W. J. (2011). How Sensitive arre US Hurricane Damages to Climate? Comment on a Paper by W.D. Nordhaus. Climate Change Economics, 02(01), 1–7. https://doi.org/10.1142/S2010007811000188

Briggs, David. Briggs 2021 A Global Downscaled Age Structure Data Set for Assessing Human Impacts of Climate Change, 1970-2100. 2021, doi:10.13140/RG.2.2.32206.38723.

Brooks, N., Adger, W. N., & Kelly, P. M. (2005). The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. Global Environmental Change, 15(2), 151– 163. https://doi.org/http://dx.doi.org/10.1016/j.gloenvcha.2004.12.006

Brown, C., Meeks, R., Ghile, Y., & Hunu, K. (2013). Is water security necessary? An empirical analysis of the effects of climate hazards on national-level economic growth. Philosophical Transactions of the Royal Society, 371, 1–19.

Burke, Marshall, Solomon M. Hsiang, and Edward Miguel. 2015. "Global Non-Linear Effect of Temperature on Economic Production." Nature (1):1–16. doi: 10.1038/nature15725.

Burke, Susie E. L., et al. "The Psychological Effects of Climate Change on Children." Current Psychiatry Reports, vol. 20, no. 5, Current Medicine Group LLC 1, May 2018, pp. 1–8, doi:10.1007/S11920-018-0896-9/TABLES/1.

Callaghan, Max, et al. 'Machine-Learning-Based Evidence and Attribution Mapping of 100,000 Climate Impact Studies'. Nature Climate Change, vol. 11, no. 11, Nov. 2021, pp. 966–72. www.nature.com, https://doi.org/10.1038/s41558-021-01168-6.

Caminade, Cyril, et al. "Impact of Recent and Future Climate Change on Vector-Borne Diseases." Annals of the New York Academy of Sciences, vol. 1436, no. 1, 2019, pp. 157–73, doi:10.1111/nyas.13950.

Campbell, Lindsay P., et al. "Climate Change Influences on Global Distributions of Dengue and Chikungunya Virus Vectors." Philosophical Transactions of the Royal Society B: Biological Sciences, vol. 370, no. 1665, 2015, pp. 1–9, doi:10.1098/rstb.2014.0135.

Campbell, Sharon, et al. "Heatwave and Health Impact Research: A Global Review." Health and Place, vol. 53, 2018, pp. 210–18, doi:10.1016/j.healthplace.2018.08.017.

Capone, Roberto, et al. "Food System Sustainability and Food Security: Connecting the Dots." Journal of Food Security, vol. 2, no. 1, 2014, pp. 13–22, doi:10.12691/jfs-2-1-2.

Cardona, Omar-Dario, et al. 'Determinants of Risk: Exposure and Vulnerability'. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, edited by Christopher B. Field et al., 1st ed., Cambridge University Press, 2012, pp. 65–108. DOI.org (Crossref), https://doi.org/10.1017/CBO9781139177245.005.

Caretta, Martina A., et al. "Water." Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by H.-O. Pörtner et al., IPCC, 2022, Cambridge University Press, Cambridge, pp. 551-712, doi:10.1017/9781009325844.006

Casanueva, A., et al. 'Variability of Extreme Precipitation over Europe and Its Relationships with Teleconnection Patterns'. Hydrology and Earth System Sciences, vol. 18, no. 2, Feb. 2014, pp. 709–25. hess.copernicus.org, https://doi.org/10.5194/hess-18-709-2014.

Casanueva, Ana, et al. "Escalating Environmental Summer Heat Exposure—a Future Threat for the European Workforce." Regional Environmental Change, vol. 20, no. 2, 2020, doi:10.1007/s10113-020-01625-6.

Chalmers, Samuel, and Ollie Jay. "Australian Community Sport Extreme Heat Policies: Limitations and Opportunities for Improvement." Journal of Science and Medicine in Sport, vol. 21, no. 6, 2018, pp. 544–48, doi:10.1016/j.jsams.2018.01.003.

Chambers, Jonathan. "Global and Cross-Country Analysis of Exposure of Vulnerable Populations to Heatwaves from 1980 to 2018." Climatic Change, vol. 163, no. 1, 2020, pp. 539–58, doi:10.1007/s10584-020-02884-2.

Chen, Mengni, et al. "The Link between Climate Change, Food Security and Fertility: The Case of Bangladesh." PLoS ONE, vol. 16, no. 10 October, 2021, doi:10.1371/journal.pone.0258196.

Chersich, Matthew Francis, et al. "Associations between High Temperatures in Pregnancy and Risk of Preterm Birth, Low Birth Weight, and Stillbirths: Systematic Review and Meta-Analysis." The BMJ, vol. 371, 2020, doi:10.1136/bmj.m3811.

Choruma, Dennis Junior, et al. 'Simulating the Impacts of Climate Change on Maize Yields Using EPIC: A Case Study in the Eastern Cape Province of South Africa'. Agriculture, vol. 12, no. 6, 6, June 2022, p. 794. www.mdpi.com, https://doi.org/10.3390/agriculture12060794.

Chuwah, Clifford, et al. 'Global Impacts of Surface Ozone Changes on Crop Yields and Land Use'. Atmospheric Environment, vol. 106, Apr. 2015, pp. 11–23. ScienceDirect, https://doi.org/10.1016/j.atmosenv.2015.01.062.

Cianconi, Paolo, et al. "The Impact of Climate Change on Mental Health: A Systematic Descriptive Review." Frontiers in Psychiatry, vol. 11, Frontiers Media SA, Mar. 2020, p. 74, doi:10.3389/FPSYT.2020.00074/BIBTEX.

Ciavarella, Andrew, et al. "Prolonged Siberian Heat of 2020 Almost Impossible without Human Influence." Climatic Change, vol. 166, no. 1–2, 2021, doi:10.1007/s10584-021-03052-w.

CIESIN. Global One-Eighth Degree Population Base Year and Projection Grids Based on the SSPs, v1.01 (2000–2100). 2021.

CIESIN, FAO, & CIAT. (2005). Gridded Population of the World, Version 3 (GPWv3): Population Count Grid. NASA Socioeconomic Data and Applications Center (SEDAC).

Cinco, T. A., de Guzman, R. G., Ortiz, A. M., Delfino, R. J., Lasco, R. D., Hilario, F. D., Juanillo, E. L., Barba, R., & Ares, E. D. (2016). Observed trends and impacts of tropical cyclones in the Philippines. *International Journal of Climatology*, *36*(14), 4638–4650. https://doi.org/10.1002/joc.4659

Coleman, J. Climate Change Made Devastating Early Heat in India and Pakistan 30 Times More Likely. 2022.

Colón-González, Felipe J., et al. "Projecting the Risk of Mosquito-Borne Diseases in a Warmer and More Populated World: A Multi-Model, Multi-Scenario Intercomparison Modelling Study." The Lancet Planetary Health, vol. 5, no. 7, 2021, pp. e404–14, doi:10.1016/S2542-5196(21)00132-7.

Cooley, Sarah, et al. "Ocean and Coastal Ecosystems and their Services." Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by H.-O. Pörtner et al., IPCC, 2022, Cambridge University Press, Cambridge, pp. 379-550, doi:10.1017/9781009325844.005

Costello, Anthony, et al. "Managing the Health Effects of Climate Change." The Lancet, vol. 373, no. 9676, 2009, pp. 1693–733, doi:10.1016/s0140-6736(09)60935-1.

Crichton, D. (1999). The Risk Triangle. Natural Disaster Management.

Crombach, Lamar, and Jeroen Smits. 'The Demographic Window of Opportunity and Economic Growth at Sub-National Level in 91 Developing Countries'. Social Indicators Research, vol. 161, no. 1, May 2022, pp. 171–89. Springer Link, https://doi.org/10.1007/s11205-021-02802-8.

Cruz, J., et al. "Effect of Extreme Weather Events on Mental Health: A Narrative Synthesis and Meta-Analysis for the UK." Int J Environ Res Public Health, 20201119th ed., vol. 17, no. 22, 2020, doi:10.3390/ijerph17228581.

Cunsolo Willox, Ashlee, et al. "Examining Relationships between Climate Change and Mental Health in the Circumpolar North." Regional Environmental Change, vol. 15, no. 1, Springer Verlag, Jan. 2015, pp. 169–82, doi:10.1007/S10113-014-0630-Z/FIGURES/1.

Cunsolo, Ashlee, and Neville R. Ellis. "Ecological Grief as a Mental Health Response to Climate Change-Related Loss." Nature Climate Change, vol. 8, no. 4, 2018, p. 275.

Cutter, Susan L., et al. 'Social Vulnerability to Environmental Hazards*'. Social Science Quarterly, vol. 84, no. 2, 2003, pp. 242–61. Wiley Online Library, https://doi.org/10.1111/1540-6237.8402002.

Dao, Francois, et al. "Burden of Malaria in Children under Five and Caregivers' Health-Seeking Behaviour for Malaria-Related Symptoms in Artisanal Mining Communities in Ghana." Parasites and Vectors, vol. 14, no. 1, 2021, doi:10.1186/s13071-021-04919-8.

Dasgupta, Shouro, and Elizabeth J. Z. Robinson. "Attributing Changes in Food Insecurity to a Changing Climate." Scientific Reports, vol. 12, no. 1, 2022, doi:10.1038/s41598-022-08696-x.

Deeb, Reem, et al. "Impact of Climate Change on Vibrio Vulnificus Abundance and Exposure Risk." Estuaries and Coasts, vol. 41, no. 8, 2018, pp. 2289–303, doi:10.1007/s12237-018-0424-5.

DeJong, D. N., Ingram, B. F., & Whiteman, C. H. (1996). A Bayesian Approach to Calibration. Journal of Business & Economic Statistics, 14(1), 1–9. https://doi.org/10.1080/07350015.1996.10524625

De Perez, Erin Coughlan, et al. "Global Predictability of Temperature Extremes." Environmental Research Letters, vol. 13, no. 5, 2018, doi:10.1088/1748-9326/aab94a.

Dell, M., Jones, B. F., & Olken, B. A. (2012). Temperature Shocks and Economic Growth: Evidence from the Last Half Century. American Economic Journal: Macroeconomics, 4(3), 66–95. https://doi.org/10.1257/mac.4.3.66

Di Napoli, Claudia, et al. "Verification of Heat Stress Thresholds for a Health-Based Heat-Wave Definition." Journal of Applied Meteorology and Climatology, vol. 58, no. 6, 2019, pp. 1177–94, doi:10.1175/JAMC-D-18-0246.1.

DiSera, Laurel, et al. "The Mosquito, the Virus, the Climate: An Unforeseen Réunion in 2018." GeoHealth, vol. 4, no. 8, 2020, doi:10.1029/2020GH000253.

Du, D., Zhao, X., & Huang, R. (2017). The impact of climate change on developed economies. Economic Letters. https://doi.org/10.1111/j.15740862.2009.00379.x

Dujardin, Sébastien, et al. 'Mobile Phone Data for Urban Climate Change Adaptation: Reviewing Applications, Opportunities and Key Challenges'. Sustainability, vol. 12, no. 4, 4, Jan. 2020, p. 1501. www.mdpi.com, https://doi.org/10.3390/su12041501.

Eastin, Joshua. 'Climate Change and Gender Equality in Developing States'. World Development, vol. 107, July 2018, pp. 289–305. ScienceDirect, https://doi.org/10.1016/j.worlddev.2018.02.021.

Ebi, Kristie L., et al. 'Extreme Weather and Climate Change: Population Health and Health System Implications'. Annual Review of Public Health, vol. 42, Apr. 2021, pp. 293–315. PubMed

Central, https://doi.org/10.1146/annurev-publhealth-012420-105026.

Ebi, Kristie L., et al. "Hot Weather and Heat Extremes: Health Risks." The Lancet, vol. 398, no. 10301, 2021, pp. 698–708, doi:10.1016/S0140-6736(21)01208-3.

Effect of Climate Change on Spring Wheat Yields in North America and Eurasia in 1981-2015 and Implications for Breeding | PLOS ONE. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0204932. Accessed 5 Oct. 2022.

Emanuel, K. (2005). Increasing destructiveness of tropical cyclones over the past 30 years. Nature, 436(7051), 686–688. https://doi.org/10.1038/nature03906

FAO, et al. The State of Food Security and Nutrition in the World 2020. Transforming Food Systems for Affordable Healthy Diets. 2020, doi:10.4060/ca9692en.

Fernandez, Ana, et al. "Flooding and Mental Health: A Systematic Mapping Review." PLOS ONE, vol. 10, no. 4, Public Library of Science, Apr. 2015, p. e0119929, doi:10.1371/JOURNAL.PONE.0119929.

Fleig, A. K., et al. 'Attribution of European Precipitation and Temperature Trends to Changes in Synoptic Circulation'. Hydrology and Earth System Sciences, vol. 19, no. 7, July 2015, pp. 3093–107. DOI.org (Crossref), https://doi.org/10.5194/hess-19-3093-2015.

Flouris, Andreas D., et al. "Workers' Health and Productivity under Occupational Heat Strain: A Systematic Review and Meta-Analysis." The Lancet Planetary Health, vol. 2, no. 12, 2018, pp. e521–31, doi:10.1016/S2542-5196(18)30237-7.

Ford, James D. "Indigenous Health and Climate Change." American Journal of Public Health, vol. 102, no. 7, 2012, pp. 1260–66, doi:10.2105/AJPH.2012.300752.

Gallo, F., Daron, J., Macadam, I., Cinco, T., Villafuerte, M., Buonomo, E., Tucker, S., Hein-Griggs, D., & Jones, R. G. (2018). High-resolution regional climate model projections of future tropical cyclone activity in the Philippines. *International Journal of Climatology*, *39*(3), 1181–1194. https://doi.org/10.1002/joc.5870

Gething, Peter W., et al. "A New World Malaria Map: Plasmodium Falciparum Endemicity in 2010." Malaria Journal, vol. 10, 2011, doi:10.1186/1475-2875-10-378.

Gomme, P., & Rupert, P. (2007). Theory, measurement and calibration of macroeconomic models. Journal of Monetary Economics, 54(2), 460–497. https://doi.org/10.1016/j.jmoneco.2005.09.005

Gopalkrishnan, Narayan. "Cultural Diversity and Mental Health: Considerations for Policy and Practice." Frontiers in Public Health, vol. 6, 2018, p. 179.

Grover-Kopec, Emily K., et al. "Web-Based Climate Information Resources for Malaria Control in Africa." Malaria Journal, vol. 5, 2006, doi:10.1186/1475-2875-5-38.

Gubler, D. "Dengue, Urbanization and Globalization: The Unholy Trinity of the 21st Century." International Journal of Infectious Diseases, vol. 16, 2012, p. e2, doi:10.1016/j.ijid.2012.05.009.

Habibi, Peymaneh, et al. "The Impacts of Climate Change on Occupational Heat Strain in Outdoor Workers: A Systematic Review." Urban Climate, vol. 36, 2021, doi:10.1016/j.uclim.2021.100770.

Hallegatte, Stephane, Jean-Charles Hourcade, and Philippe Ambrosi. 2007. "Using Climate Analogues for Assessing Climate Change Economic Impacts in Urban Areas." Climatic Change 82(1–2):47–60. doi: 10.1007/s10584-006-9161-z.

Hansson, Sten, et al. 'Communication-Related Vulnerability to Disasters: A Heuristic Framework'. International Journal of Disaster Risk Reduction, vol. 51, Dec. 2020, p. 101931. ScienceDirect, https://doi.org/10.1016/j.ijdrr.2020.101931.

Hayes, Katie, and Blake Poland. "Addressing Mental Health in a Changing Climate: Incorporating Mental Health Indicators into Climate Change and Health Vulnerability and Adaptation Assessments." International Journal of Environmental Research and Public Health 2018, Vol. 15, Page 1806, vol. 15, no. 9, Multidisciplinary Digital Publishing Institute, Aug. 2018, p. 1806, doi:10.3390/IJERPH15091806.

Hayes, Katie, et al. "Climate Change and Mental Health: Risks, Impacts and Priority Actions." International Journal of Mental Health Systems, vol. 12, no. 1, BioMed Central Ltd., June 2018, pp. 1–12, doi:10.1186/S13033-018-0210-6/METRICS.

Heaney, Alexandra K., et al. "Climate Change and Physical Activity: Estimated Impacts of Ambient Temperatures on Bikeshare Usage in New York City." Environmental Health Perspectives, vol. 127, no. 3, 2019, pp. 37002-1-037002-10, doi:10.1289/EHP4039.

Heinen, A., Khadan, J., & Strobl, E. (2018). The Inflationary Costs of Extreme Weather in Developing Countries. The Economic Journal, February. https://doi.org/10.1111/ecoj.12581

Helldén, Daniel, et al. 'Climate Change and Child Health: A Scoping Review and an Expanded Conceptual Framework'. The Lancet Planetary Health, vol. 5, no. 3, Mar. 2021, pp. e164–75. ScienceDirect, https://doi.org/10.1016/S2542-5196(20)30274-6.

Hempel, S., Frieler, K., Warszawski, L., Schewe, J., & Piontek, F. (2013). A trendpreserving bias correction: the ISI-MIP approach. Earth System Dynamics, 4(2), 219–236. https://doi.org/10.5194/esd-4-219-2013

Hickman, Caroline, et al. "Climate Anxiety in Children and Young People and Their Beliefs about Government Responses to Climate Change: A Global Survey." The Lancet Planetary Health, vol. 5, no. 12, Elsevier BV, 2021, pp. e863–73, doi:10.1016/s2542-5196(21)00278-3.

Honda, Yasushi, et al. "Heat-Related Mortality Risk Model for Climate Change Impact Projection." Environmental Health and Preventive Medicine, vol. 19, no. 1, 2014, pp. 56–63, doi:10.1007/s12199-013-0354-6.

Hope, Kempe Ronald. "Climate Change and Poverty in Africa." International Journal of Sustainable Development and World Ecology, vol. 16, no. 6, 2009, pp. 451–61, doi:10.1080/13504500903354424.

Institute for Environment and Sustainability (Joint Research Centre), et al. Climate Resilient Development Index: Theoretical Framework, Selection Criteria and Fit for Purpose Indicators. Publications Office of the European Union, 2015. Publications Office of the European Union, https://data.europa.eu/doi/10.2788/07628.

Institute for Health Metrics and Evaluation (IHME) Global Health Data Exchange (GHDx). Global Burden of Disease. 2021.

International Labour Organization. ILOSTAT Database. International Labour Organization, 2022.

IPCC. "Annex II: Glossary". Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by H.-O. Pörtner et al., IPCC, 2022c, Cambridge University Press, Cambridge, pp. 2897-2930, doi:10.1017/9781009325844.029

IPCC. "Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects." Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, 2014, edited by Christopher B. Field et al., Cambridge University Press, Cambridge, 1132 pp, doi:10.1017/CBO9781107415379

IPCC. "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change", edited by Valérie Masson-Delmotte et al., IPCC, 2021a, Cambridge University Press, Cambridge, doi:10.1017/9781009157896

IPCC. "Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change", edited by H.- O. Pörtner et al., IPCC, 2022b, Cambridge University Press, Cambridge, 3056 pp., doi:10.1017/9781009325844.

IPCC. 2012. "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation." A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, edited by C. B. Field et al., IPCC, 2012, Cambridge University Press, Cambridge, 582 pp, doi:10.13140/2.1.3117.9529

IPCC. "Summary for Policymakers." Climate Change 2021: The Physical Science Basis.

Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by L. Masson-Delmotte, V. et al., IPCC, 2021b, Cambridge University Press, Cambridge, pp. 3-32, doi:10.1017/9781009157896.001

IPCC. "Summary for Policymakers." Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by P.R. Shukla et al., IPCC, 2022a, Cambridge University Press, Cambridge, pp. 3-33, doi: 10.1017/9781009157926.001

Jan Van Oldenborgh, Geert, et al. "Attribution of the Australian Bushfire Risk to Anthropogenic Climate Change." Natural Hazards and Earth System Sciences, vol. 21, no. 3, 2021, pp. 941–60, doi:10.5194/nhess-21-941-2021.

Jones, B., and B. C.O'Neill. Global One-Eighth Degree Population Base Year and Projection Grids Based on the SSPs, v1.01 (2000 – 2100). doi:https://doi.org/10.1088/1748-9326/11/8/084003.

Jones, Matthew W., et al. "ScienceBrief Review: Climate Change Increases the Risk of Wildfires." Critical Issues in Climate Science, 2020, https://tyndall.ac.uk/sites/default/files/wildfires_briefing_note.pdf%0Ahttps://sciencebrief.org/briefs/wildfires.

Kc, Samir, and Wolfgang Lutz. 'The Human Core of the Shared Socioeconomic Pathways: Population Scenarios by Age, Sex and Level of Education for All Countries to 2100'. Global Environmental Change, vol. 42, Jan. 2017, pp. 181–92. ScienceDirect, https://doi.org/10.1016/j.gloenvcha.2014.06.004.

Ken Parsons. "Human Thermal Environments: The Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort and Performance." *Applied Ergonomics*, Third Ed., vol. 25, no. 6, 2014.

Khabarov, Nikolay, et al. "Forest Fires and Adaptation Options in Europe." Regional Environmental Change, vol. 16, no. 1, 2016, pp. 21–30, doi:10.1007/s10113-014-0621-0.

Kitoh, A., & Endo, H. (2019). Future changes in precipitation extremes associated with tropical cyclones projected by large-ensemble simulations. *Journal of the Meteorological Society of Japan. Ser. II*, *97*(1), 141–152. https://doi.org/10.2151/jmsj.2019-007

Kjellstrom, Tord, et al. "Estimating Population Heat Exposure and Impacts on Working People in Conjunction with Climate Change." *International Journal of Biometeorology*, vol. 62, no. 3, 2018, pp. 291–306, doi:10.1007/s00484-017-1407-0.

Klawa, M., & Ulbrich, U. (2003). A model for the estimation of storm losses and the identification of severe winter storms in Germany. In Natural Hazards and Earth System Sciences (Vol. 3). http://www.destatis.de/indicators/d/d

Kollanus, Virpi, et al. "Mortality due to Vegetation Fire–Originated PM2.5 Exposure in Europe—Assessment for the Years 2005 and 2008." Environmental Health Perspectives, vol. 125, no. 1, Jan. 2017, pp. 30–37, doi:10.1289/EHP194.

Kunawotor, M. E., Bokpin, G. A., Asuming, P. O., & Amoateng, K. A. (2021). The Impacts of Extreme Weather Events on Inflation and the Implications for Monetary Policy in Africa. Progress in Development Studies, 22(2), 130–148. https://doi.org/10.1177/14649934211063357

Laframboise, N., & Loko, B. (2012). Natural Disasters: Mitigating Impact, Managing Risks (WP/12/245).

Lange, S. (2019). Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0). Geoscientific Model Development, 12(7), 3055–3070. https://doi.org/10.5194/gmd-12-30552019

Lange, S., Menz, C., Gleixner, S., Cucchi, M., Weedon, G. P., Amici, A., Bellouin, N., Müller Schmied, H., Hersbach, H., Buontempo, C., & Cagnazzo, C. (2021). WFDE5 over land merged with ERA5 over the ocean (W5E5 v2.0). ISIMIP Repository. https://doi.org/10.48364/ISIMIP.342217

Lavell, Allan, et al. 'Climate Change: New Dimensions in Disaster Risk, Exposure, Vulnerability, and Resilience'. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, edited by Christopher B. Field et al., 1st ed., Cambridge University Press, 2012, pp. 25–64. DOI.org (Crossref), https://doi.org/10.1017/CBO9781139177245.004.

Lawrance, Emma, et al. "The Impact of Climate Change on Mental Health and Emotional Wellbeing: Current Evidence and Implications for Policy and Practice." Briefing Paper No 36. Grantham Institute, 2021.

Lawrence, Judy, et al. "Australasia." Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Valérie Masson-Delmotte et al., IPCC, 2021, Cambridge University Press, Cambridge, pp. 1581-1688, doi:10.1017/9781009325844.013

Lemke, Bruno, and Tord Kjellstrom. "Calculating Workplace WBGT from Meteorological Data: A Tool for Climate Change Assessment." Industrial Health, vol. 50, no. 4, 2012, pp. 267–78, doi:10.2486/indhealth.MS1352.

Lenzen, Manfred, et al. "Economic Damage and Spillovers from a Tropical Cyclone." Natural Hazards and Earth System Sciences, vol. 19, no. 1, 2019, pp. 137–51, doi:10.5194/nhess-19-137-2019.

Liu-Helmersson, Jing, Mikkel Quam, et al. "Climate Change and Aedes Vectors: 21st Century Projections for Dengue Transmission in Europe." *EBioMedicine*, vol. 7, 2016, pp. 267–77, doi:10.1016/j.ebiom.2016.03.046.

Liu-Helmersson, Jing, Åke Brännström, et al. "Estimating Past, Present, and Future Trends in the Global Distribution and Abundance of the Arbovirus Vector Aedes Aegypti under Climate Change Scenarios." *Frontiers in Public Health*, vol. 7, no. JUN, 2019, doi:10.3389/fpubh.2019.00148.

Liu-Helmersson, Jing, Hans Stenlund, et al. "Vectorial Capacity of Aedes Aegypti: Effects of Temperature and Implications for Global Dengue Epidemic Potential." *PLoS ONE*, vol. 9, no. 3, 2014, doi:10.1371/journal.pone.0089783.

Liu, Jingwen, et al. "Is There an Association between Hot Weather and Poor Mental Health Outcomes? A Systematic Review and Meta-Analysis." Environment International, vol. 153, 2021, doi:10.1016/j.envint.2021.106533.

Liu, Yujie, et al. "Modelling the Impacts of Climate Change and Crop Management on Phenological Trends of Spring and Winter Wheat in China." Agricultural and Forest Meteorology, vol. 248, 2018, pp. 518–26, doi:10.1016/j.agrformet.2017.09.008.

Luedeling, Eike. "Interpolating Hourly Temperatures for Computing Agroclimatic Metrics." *International Journal of Biometeorology*, vol. 62, no. 10, 2018, pp. 1799–807, doi:10.1007/s00484-018-1582-7.

Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation — IPCC. https://www.ipcc.ch/report/managing-the-risks-of-extreme-events-and-disasters-to-advance-climate-change-adaptation/. Accessed 5 Oct. 2022.

Martinez-Urtaza, Jaime, et al. "Genomic Variation and Evolution of Vibrio Parahaemolyticus ST36 over the Course of a Transcontinental Epidemic Expansion." mBio, vol. 8, no. 6, 2017, doi:10.1128/mBio.01425-17.

Martyr-Koller, Rosanne, et al. 'Loss and Damage Implications of Sea-Level Rise on Small Island Developing States'. Current Opinion in Environmental Sustainability, vol. 50, June 2021, pp. 245–59. ScienceDirect, https://doi.org/10.1016/j.cosust.2021.05.001.

Marx, Werner, et al. "Heat Waves: A Hot Topic in Climate Change Research." Theoretical and Applied Climatology, vol. 146, no. 1–2, 2021, pp. 781–800, doi:10.1007/s00704-021-03758-y.

Masson-Delmotte, V., et al. "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change." IPCC, 2021, 2021.

Mattos, Leonora M., et al. 'Chapter 19 - Climate Changes and Potential Impacts on Quality of Fruit and Vegetable Crops'. Emerging Technologies and Management of Crop Stress Tolerance, edited by Parvaiz Ahmad and Saiema Rasool, Academic Press, 2014, pp. 467–86. ScienceDirect, https://doi.org/10.1016/B978-0-12-800876-8.00019-9.

McElroy, Sara, et al. "Extreme Heat, Preterm Birth, and Stillbirth: A Global Analysis across 14 Lower-Middle Income Countries." Environment International, vol. 158, 2022, doi:10.1016/j.envint.2021.106902.

McGrath, Justin M., et al. 'An Analysis of Ozone Damage to Historical Maize and Soybean Yields in the United States'. Proceedings of the National Academy of Sciences, vol. 112, no. 46, Nov. 2015, pp. 14390–95. pnas.org (Atypon), https://doi.org/10.1073/pnas.1509777112.

Mendelsohn, R. (2016). Measuring Weather Impacts Using Panel Data. American Economic Association 2017 Conference, 22.

Middleton, Jacqueline, et al. "Indigenous Mental Health in a Changing Climate: A Systematic Scoping Review of the Global Literature." Environmental Research Letters, vol. 15, no. 5, IOP Publishing, Apr. 2020, p. 53001, doi:10.1088/1748-9326/AB68A9.

Mitchell, Daniel, et al. "Attributing Human Mortality during Extreme Heat Waves to Anthropogenic Climate Change." Environmental Research Letters, vol. 11, no. 7, 2016, doi:10.1088/1748-9326/11/7/074006.

Mora, Camilo, et al. "Over Half of Known Human Pathogenic Diseases Can Be Aggravated by Climate Change." Nature Climate Change, vol. 12, no. 9, 2022, pp. 869–75, doi:10.1038/s41558-022-01426-1.

Moses Mozart Dzawu, and Paul Wallace. 2015. "As Deadly Floods Subside, Ghana's Borrowing Costs Are Rising." Bloomberg, June 19.

Muhling, Barbara A., et al. "Projections of the Future Occurrence, Distribution, and Seasonality of Three Vibrio Species in the Chesapeake Bay under a High-Emission Climate Change Scenario." GeoHealth, vol. 1, no. 7, 2017, pp. 278–96, doi:10.1002/2017GH000089.

Mullins, J. T., and C. White. "Temperature and Mental Health: Evidence from the Spectrum of Mental Health Outcomes." J Health Econ, 2019/10/08, vol. 68, 2019, p. 102240, doi:10.1016/j.jhealeco.2019.102240.

Muñoz-Sabater, Joaquín, et al. "ERA5-Land: A State-of-the-Art Global Reanalysis Dataset for Land Applications." *Earth System Science Data*, vol. 13, no. 9, 2021, pp. 4349–83, doi:10.5194/essd-13-4349-2021.

Muñoz Sabater, J. *ERA5-Land Hourly Data from 1981 to Present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS).* 2019, doi:https://doi.org/10.24381/cds.e2161bac.

Muttarak, Raya, and Wolfgang Lutz. 'Is Education a Key to Reducing Vulnerability to Natural Disasters and Hence Unavoidable Climate Change?' Ecology and Society, vol. 19, no. 1, Mar. 2014. www.ecologyandsociety.org, https://doi.org/10.5751/ES-06476-190142.

Nakano, Hiroshi, et al. 'Breaking Rice Yield Barrier with the Ratooning Method under Changing Climatic Conditions: A Paradigm Shift in Rice-Cropping Systems in Southwestern Japan'. Agronomy Journal, vol. 112, no. 5, 2020, pp. 3975–92. Wiley Online Library, https://doi.org/10.1002/agj2.20309.

Nazarian, Negin, et al. "Project Coolbit: Can Your Watch Predict Heat Stress and Thermal Comfort Sensation?" Environmental Research Letters, vol. 16, no. 3, 2021, doi:10.1088/1748-9326/abd130.

Nazrul Islam and John Winkel. Climate Change and Social Inequality. 2017.

Neo Khanyile, and Paul Wallace. 2015. "Floods Expose Ghana's Fiscal Woes as Currency Plunges to Record." Bloomberg, June 4.

Nordhaus, W. D. (2006). Geography and macroeconomics: new data and new findings. Proceedings of the National Academy of Sciences of the United States of America, 103(10), 3510–3517. https://doi.org/10.1073/pnas.0509842103

Nordhaus, W. D. (2010). The Economics of Hurricanes and Implications of Global Warming. Climate Change Economics, 01(01), 1–20. https://doi.org/10.1142/S2010007810000054

Obradovich, N., et al. "Empirical Evidence of Mental Health Risks Posed by Climate Change." Proc Natl Acad Sci U S A, 2018/10/10, vol. 115, no. 43, 2018, pp. 10953–58, doi:10.1073/pnas.1801528115.

Obradovich, Nick, and James H. Fowler. "Climate Change May Alter Human Physical Activity Patterns." Nature Human Behaviour, vol. 1, no. 5, 2017, doi:10.1038/s41562-017-0097.

OBrien, L. V., et al. "Drought as a Mental Health Exposure." Environmental Research, vol. 131, Academic Press, May 2014, pp. 181–87, doi:10.1016/J.ENVRES.2014.03.014.

Osunla, Charles A., and Anthony I. Okoh. "Vibrio Pathogens: A Public Health Concern in Rural Water Resources in Sub-Saharan Africa." International Journal of Environmental Research and Public Health, vol. 14, no. 10, 2017, doi:10.3390/ijerph14101188.

Otto, Friederike E. L., et al. Climate Change Likely Increased Extreme Monsoon Rainfall, Flooding Highly Vulnerable Communities in Pakistan. p. 36.

Owen Landeg. "Flooding and Public Health in a Changing Climate." Hydrometeorological Extreme Events and Public Health, 2022.

Park, Jacob. "How Can We Pay for It All? Understanding the Global Challenge of Financing Climate Change and Sustainable Development Solutions." Journal of Environmental Studies and Sciences, vol. 12, no. 1, 2022, pp. 91–99, doi:10.1007/s13412-021-00715-z.

Parker, M. (2018). The Impact of Disasters on Inflation. Economics of Disasters and Climate Change, 2(1), 21–48. https://doi.org/10.1007/s41885-017-0017-y

Parmesan, Camille, et al. "Terrestrial and Freshwater Ecosystems and their Services." Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by H.-O. Pörtner et al., IPCC, 2022, Cambridge University Press, Cambridge, pp. 197-377, doi:10.1017/9781009325844.004

Parveen, Salina, et al. "Seasonal Distribution of Total and Pathogenic Vibrio Parahaemolyticus in Chesapeake Bay Oysters and Waters." International Journal of Food Microbiology, vol. 128, no. 2, 2008, pp. 354–61, doi:10.1016/j.ijfoodmicro.2008.09.019.

Périard, Julien D., et al. "Exercise under Heat Stress: Thermoregulation, Hydration, Performance Implications, and Mitigation Strategies." Physiological Reviews, vol. 101, no. 4, 2021, pp. 1873–979, doi:10.1152/physrev.00038.2020.

Perkins-Kirkpatrick, S. E., and S. C. Lewis. "Increasing Trends in Regional Heatwaves." Nature Communications, vol. 11, no. 1, 2020, doi:10.1038/s41467-020-16970-7.

Philip, S. Y., et al. "Rapid Attribution Analysis of the Extraordinary Heatwave on the Pacific Coast of the US and Canada June 2021." Earth System Dynamics Discussions, vol. 2021, 2021, pp. 1–34, doi:10.5194/esd-2021-90.

Pielke, R. A., Joel, G. J., Landsea, C. W., Collins, D., Saunders, M. A., & Musulin, R. (2008). Normalized Hurricane Damage in the United States: 1900–2005. Natural Hazards Review, 9(1), 29–42. https://doi.org/10.1061/(ASCE)1527-6988(2008)9:1(29)

Piguet, Etienne, et al. "Migration and Climate Change: An Overview." Refugee Survey Quarterly, vol. 30, no. 3, Oxford Academic, Sept. 2011, pp. 1–23, doi:10.1093/RSQ/HDR006.

Pindyck, R. S. (2013). Climate Change Policy: What Do the Models Tell Us? Journal of Economic Literature, 51(3), 860–872. https://doi.org/10.1257/jel.51.3.860

Portmann, Felix T., et al. "MIRCA2000-Global Monthly Irrigated and Rainfed Crop Areas around the Year 2000: A New High-Resolution Data Set for Agricultural and Hydrological Modeling." *Global Biogeochemical Cycles*, vol. 24, no. 1, 2010, p. n/a-n/a, doi:10.1029/2008gb003435.

Pörtner, Hans-Otto, et al. „Technical Summary." Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by H.-O. Pörtner et al., IPCC, 2022, Cambridge University Press, Cambridge, pp. 37-118, doi:10.1017/9781009325844.002

Prahl, B. F., Rybski, D., Burghoff, O., & Kropp, J. P. (2015). Comparison of storm damage functions and their performance. Natural Hazards and Earth System Sciences, 15(4), 769–788. https://doi.org/10.5194/nhess-15-7692015

Qin, Yue, et al. 'Agricultural Risks from Changing Snowmelt'. Nature Climate Change, vol. 10, no. 5, May 2020, pp. 459–65, https://doi.org/10.1038/s41558-020-0746-8.

Rahman, Rezaur, and Mashfiqus Salehin. 'Flood Risks and Reduction Approaches in Bangladesh'. Disaster Risk Reduction Approaches in Bangladesh, edited by Rajib Shaw et al., Springer Japan, 2013, pp. 65–90. Springer Link, https://doi.org/10.1007/978-4-431-54252-0_4.

Recent Climate and Air Pollution Impacts on Indian Agriculture | PNAS. https://www.pnas.org/doi/full/10.1073/pnas.1317275111. Accessed 5 Oct. 2022.

Reid, Colleen E., and Melissa May Maestas. "Wildfire Smoke Exposure under Climate Change: Impact on Respiratory Health of Affected Communities." Current Opinion in Pulmonary Medicine, vol. 25, no. 2, 2019, pp. 179–87, doi:10.1097/MCP.0000000000000552.

Riahi, Keywan, et al. 'The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview'. Global Environmental Change, vol. 42, Jan. 2017, pp. 153–68. ScienceDirect, https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Rocklöv, Joacim, et al. "Assessing Seasonal Risks for the Introduction and Mosquito-Borne Spread of Zika Virus in Europe." EBioMedicine, vol. 9, 2016, pp. 250–56, doi:10.1016/j.ebiom.2016.06.009.

Rocklöv, Joacim, Mikkel Brandon Quam, et al. "Assessing Seasonal Risks for the Introduction and Mosquito-Borne Spread of Zika Virus in Europe." *EBioMedicine*, vol. 9, 2016, pp. 250–56, doi:10.1016/j.ebiom.2016.06.009.

Rocklöv, Joacim, Yesim Tozan, et al. "Using Big Data to Monitor the Introduction and Spread of Chikungunya, Europe, 2017." *Emerging Infectious Diseases*, vol. 25, no. 6, 2019, pp. 1041–49, doi:10.3201/eid2506.180138.

Rodney, Rachael M., et al. "Physical and Mental Health Effects of Bushfire and Smoke in the Australian Capital Territory 2019–20." Frontiers in Public Health, vol. 9, 2021.

Romanello, Marina, Alice McGushin, et al. "The 2021 Report of the Lancet Countdown on Health and Climate Change: Code Red for a Healthy Future." The Lancet, vol. 398, no. 10311, 2021, pp. 1619–62, doi:10.1016/S0140-6736(21)01787-6.

Romanello, Marina, Claudia Di Napoli, et al. "The 2022 Report of the Lancet Countdown on Health and Climate Change: Health at the Mercy of Fossil Fuels." Lancet, vol. 399, 2022.

Romanello et al. "The 2022 Report of The Lancet Countdown on Health and Climate Change." *The Lancet*, 2022.

Rossetto, T., & Elnashai, A. (2003). Derivation of vulnerability functions for European-type RC structures based on observational data. Engineering Structures, 25(10), 1241–1263. https://doi.org/http://dx.doi.org/10.1016/S0141-0296(03)00060-9

Salamati Nia, Seyed Payam, and Udayangani Kulatunga. "Safety and Security of Hospitals during Natural Disasters: Challenges of Disaster Managers." International Journal of Safety and Security Engineering, vol. 7, no. 2, 2017, pp. 234–46, doi:10.2495/SAFE-V7-N2-234-246.

Salm, Melissa, et al. "Defining Global Health: Findings from a Systematic Review and Thematic Analysis of the Literature." BMJ Global Health, vol. 6, no. 6, 2021, doi:10.1136/bmjgh-2021-005292.

Sawyer, Dave, Ryan Ness, Caroline Lee, and Sarah Miller. 2022. Damage Control: Reducing the Costs of Climate Impacts in Canada. Ottowa, Canada.

Sacks, William J., et al. "Crop Planting Dates: An Analysis of Global Patterns." *Global Ecology and Biogeography*, vol. 19, no. 5, 2010, pp. 607–20, doi:10.1111/j.1466-8238.2010.00551.x.

Sacks, William J., and Christopher J. Kucharik. 'Crop Management and Phenology Trends in the U.S. Corn Belt: Impacts on Yields, Evapotranspiration and Energy Balance'. Agricultural and Forest Meteorology, vol. 151, no. 7, July 2011, pp. 882–94. ScienceDirect, https://doi.org/10.1016/j.agrformet.2011.02.010.

Saint Ville, Arlette, et al. "Food Security and the Food Insecurity Experience Scale (FIES): Ensuring Progress by 2030." *Food Security*, vol. 11, no. 3, 2019, pp. 483–91, doi:10.1007/s12571-019-00936-9.

Schipper, E. Lisa F., et al. "Climate Resilient Development Pathways." Climate Change 2022: Impacts, Adaptation, and Vulnerability." Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by H.-O. Pörtner et al., IPCC, 2022, Cambridge University Press, Cambridge, pp. 2655-2807, doi:10.1017/9781009325844.027

Schlenker, W., & Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. Proceedings of the National Academy of Sciences, 106(37), 15594–15598. https://doi.org/10.1073/pnas.0906865106

Semenza, Jan C. "Cascading Risks of Waterborne Diseases from Climate Change." Nature Immunology, vol. 21, no. 5, Nature Research, May 2020, pp. 484–87, doi:10.1038/s41590-020-0631-7.

Semenza, Jan C., and Jonathan E. Suk. "Vector-Borne Diseases and Climate Change: A European Perspective." FEMS Microbiology Letters, vol. 365, no. 2, 2018, doi:10.1093/femsle/fnx244.

Seneviratne, Sonia I., et al. 'Investigating Soil Moisture–Climate Interactions in a Changing Climate: A Review'. Earth-Science Reviews, vol. 99, no. 3, May 2010, pp. 125–61. ScienceDirect, https://doi.org/10.1016/j.earscirev.2010.02.004.

Seventy-Fourth World Health, assembly. WHO's Work in Health Emergencies: Strengthening Preparedness for Health Emergencies: Implementation of the International Health Regulations (2005). no. A74/9 Add.1, 2021.

Shiferaw, Bekele, et al. 'Crops That Feed the World 6. Past Successes and Future Challenges to the Role Played by Maize in Global Food Security'. Food Security, vol. 3, no. 3, Aug. 2011, p. 307. Springer Link, https://doi.org/10.1007/s12571-011-0140-5.

Sofiev, Mikhail. "Chapter 21 - Wildland Fires: Monitoring, Plume Modelling, Impact on Atmospheric Composition and Climate." Developments in Environmental Science, edited by R. Matyssek et al., vol. 13, Elsevier, 2013, pp. 451–72.

Son, Ji-Young, et al. 'Temperature-Related Mortality: A Systematic Review and Investigation of Effect Modifiers'. Environmental Research Letters, vol. 14, no. 7, July 2019, p. 073004. Institute of Physics, https://doi.org/10.1088/1748-9326/ab1cdb.

Snow, Robert W., et al. "The Prevalence of Plasmodium Falciparum in Sub-Saharan Africa since 1900." *Nature*, vol. 550, no. 7677, 2017, pp. 515–18, doi:10.1038/nature24059.

Sports Medicine Australia. *Extreme Heat Policy*. 2021.

Stanaway, Jeffrey D., et al. "The Global Burden of Dengue: An Analysis from the Global Burden of Disease Study 2013." The Lancet Infectious Diseases, vol. 16, no. 6, 2016, pp. 712–23, doi:10.1016/S1473-3099(16)00026-8.

Stanke, Carla, Marko Kerac, et al. "Health Effects of Drought: A Systematic Review of the Evidence." PLoS Currents, vol. 5, 2013.

Stanke, Carla, Virginia Murray, et al. "The Effects of Flooding on Mental Health: Outcomes and Recommendations from a Review of the Literature." PLoS Currents, vol. 4, Public Library of Science, May 2012, p. e4f9f1fa9c3cae-e4f9f1fa9c3cae, doi:10.1371/4f9f1fa9c3cae.

Strobl, E. (2012). The economic growth impact of natural disasters in developing countries: Evidence from hurricane strikes in the Central American and Caribbean regions. Journal of Development Economics, 97(1), 130–141. https://doi.org/https://doi.org/10.1016/j.jdeveco.2010.12.002

Sultana, Farhana. 'Climate Change, COVID-19, and the Co-Production of Injustices: A Feminist Reading of Overlapping Crises'. Social & Cultural Geography, vol. 22, no. 4, May 2021, pp. 447–60. DOI.org (Crossref), https://doi.org/10.1080/14649365.2021.1910994.

Sun, Qiaohong, et al. "Global Heat Stress on Health, Wildfires, and Agricultural Crops under Different Levels of Climate Warming." Environment International, vol. 128, 2019, pp. 125–36, doi:10.1016/j.envint.2019.04.025.

Syed, Sarah, et al. "Extreme Heat and Pregnancy Outcomes: A Scoping Review of the Epidemiological Evidence." International Journal of Environmental Research and Public

Health, vol. 19, no. 4, 2022, doi:10.3390/ijerph19042412.

Székely, Miklós, et al. "The Pathophysiology of Heat Exposure." Temperature, vol. 2, no. 4, 2015, p. 452, doi:10.1080/23328940.2015.1051207.

Tasdik Hasan, M., et al. "Exploring Mental Health Needs and Services among Affected Population in a Cyclone Affected Area in Costal Bangladesh: A Qualitative Case Study." International Journal of Mental Health Systems, vol. 14, no. 1, 2020, doi:10.1186/s13033-020-00351-0.

Taylor, John B. 1993. "Discretion versus Policy Rules in Practice: Two Critical Points. A Comment." Carnegie-Rochester Conference Series on Public Policy 39:195–214. doi: 10.1016/0167-2231(93)90010-T.

Taylor, John B. 1993. Discretion versus Policy Rules in Practice. Vol. 39.

The World Bank. *World Bank Official Boundaries*. 2022.

Thomas, Adelle, et al. 'Climate Change and Small Island Developing States'. Annual Review of Environment and Resources, vol. 45, Oct. 2020. ResearchGate, https://doi.org/10.1146/annurev-environ-012320-083355.

Thomas, Kimberley, et al. 'Explaining Differential Vulnerability to Climate Change: A Social Science Review'. WIREs Climate Change, vol. 10, no. 2, 2019, p. e565. Wiley Online Library, https://doi.org/10.1002/wcc.565.

Thomas, Melissa K., et al. "Food Insecurity and Its Impact on Body Weight, Type 2 Diabetes, Cardiovascular Disease, and Mental Health." Current Cardiovascular Risk Reports, vol. 15, no. 9, 2021, doi:10.1007/s12170-021-00679-3.

Thompson, R., et al. "Associations between High Ambient Temperatures and Heat Waves with Mental Health Outcomes: A Systematic Review." Public Health, vol. 161, 2018, pp. 171–91.

Tong, S., and K. Ebi. 'Preventing and Mitigating Health Risks of Climate Change'. Environmental Research, vol. 174, July 2019, pp. 9–13. ScienceDirect, https://doi.org/10.1016/j.envres.2019.04.012.

Trinanes, Joaquin, and Jaime Martinez-Urtaza. "Future Scenarios of Risk of Vibrio Infections in a Warming Planet: A Global Mapping Study." The Lancet Planetary Health, vol. 5, no. 7, 2021, pp. e426–35, doi:10.1016/S2542-5196(21)00169-8.

United Nations Development Program (technical authors: Kjellstrom T, Otto M, Lemke B, Hyatt O, Briggs D, Freyberg C, Lines L). "Climate Change and Labour: Impacts of Heat in the Workplace." Climate Vulnerable Forum Secretariat, 2016, http://www.undp.org/content/undp/en/home/librarypage/climate-and-disaster-resilience-/tackling-challenges-of-climate-change-and-workplace-heat-for-dev.html.

Vicedo-Cabrera, A. M., et al. "The Burden of Heat-Related Mortality Attributable to Recent Human-Induced Climate Change." Nature Climate Change, vol. 11, no. 6, 2021, pp. 492–500, doi:10.1038/s41558-021-01058-x.

Vicente-Serrano, S. M., & López-Moreno, J. I. (2005). Hydrological response to different time scales of climatological drought: an evaluation of the Standardized Precipitation Index in a mountainous Mediterranean basin. Hydrology and Earth System Sciences, 9(5), 523–533. https://doi.org/10.5194/hess-9-523-2005

Vins, Holly, et al. "The Mental Health Outcomes of Drought: A Systematic Review and Causal Process Diagram." International Journal of Environmental Research and Public Health, vol. 12, no. 10, MDPI AG, Oct. 2015, pp. 13251–75, doi:10.3390/ijerph121013251.

Wang, Zengmiao, et al. "The Relationship between Rising Temperatures and Malaria Incidence in Hainan, China, from 1984 to 2010: A Longitudinal Cohort Study." The Lancet Planetary Health, vol. 6, no. 4, 2022, pp. e350–58, doi:10.1016/S2542-5196(22)00039-0.

Watkiss, P., et al. "Climate Change: The Cost of Inaction and the Cost of Adaptation." EEA Technical Report, no. 13, 2007.

Watts, Nick, et al. 'The 2020 Report of The Lancet Countdown on Health and Climate Change: Responding to Converging Crises'. The Lancet, vol. 397, no. 10269, Jan. 2021, pp. 129–70. DOI.org (Crossref), https://doi.org/10.1016/S0140-6736(20)32290-X.

World Bank. (2022). World Development Indicators. http://databank.worldbank.org/data/reports.aspx?source=world development-indicators

World Food Summit. Food and Agriculture Organization of the United Nations (FAO). Rome Declaration on World Food Security. 1996.

World Health Organization. Dengue and Severe Dengue: Key Facts. Jan. 2022.

World Health Organization. *2021 WHO Health and Climate Change Global Survey Report*. 2021.

Xu, Rongbin, et al. "Wildfires, Global Climate Change, and Human Health." New England Journal of Medicine, vol. 383, no. 22, 2020, pp. 2173–81, doi:10.1056/nejmsr2028985.

Xu, Zhiwei, et al. "The Impact of Heat Waves on Children's Health: A Systematic Review." *International Journal of Biometeorology*, vol. 58, no. 2, 2014, pp. 239–47, doi:10.1007/s00484-013-0655-x.

Zachariah et al. Without Human-Caused Climate Change Temperatures of 40°C in the UK Would Have Been Extremely Unlikely. 2022.

Zachariah, Arulalan, Krishna AchutaRao, et al. Climate Change Made Devastating Early Heat in India and Pakistan 30 Times More Likely. Sept. 2022, pp. 5768–84. DOI.org (Crossref), https://onlinelibrary.wiley.com/doi/10.1002/joc.7560.

Zachariah, Mariam, Robert Vautard, et al. Without Human-Caused Climate Change Temperatures of 40oC in the UK Would Have Been Extremely Unlikely. p. 26.

Zachariah, Mariam, Sjoukje Philip, et al. Climate Change Increased Heavy Rainfall, Hitting Vulnerable Communities in Eastern Northeast Brazil. p. 31.

Zeng, Wu, et al. "Impact of a Nonfatal Dengue Episode on Disability-Adjusted Life Years: A Systematic Analysis." American Journal of Tropical Medicine and Hygiene, vol. 99, no. 6, 2018, pp. 1458–65, doi:10.4269/ajtmh.18-0309.

Zhou, Yongjin, et al. 'Border Effect on Ratoon Crop Yield in a Mechanized Rice Ratooning System'. Agronomy, vol. 12, no. 2, 2, Feb. 2022, p. 262. www.mdpi.com, https://doi.org/10.3390/agronomy12020262.

BOTTOM LINE

The main finding of this report is that climate change impacts generate loss and damage that are creating crises for society, human health and development globally. The asymmetric impact of climate change deepens global inequalities and injustice, though nobody is spared. In the near-term, the world should brace for a rapid escalation in climatic shocks. Absent of climate action, end-of-century impacts dwarf climate shocks to-date, while limiting warming to 1.5°C will prevent a potentially massive expansion in climate impacts beyond 2030. Accelerated adaptation action and efforts to address loss and damage will be essential to managing the climate crisis. Finally, increased investments in knowledge and data will continue to prove crucial to further refining understanding of the nature of this crisis and effective response strategies going forwards.

3rd Edition

CVM3

Data Explorer
www.v-20.org/climatevulnerabilitymonitor

Climate Vulnerable Forum
@V20Group | @TheCVF
Climate Vulnerable Forum
Climate Vulnerable Forum (CVF)
& Vulnerable Twenty Group (V20)