UNDERSTANDING THE SHORT AND LONG-TERM IMPACTS **OF CLIMATE EXTREMES**

SLICE

Short- and Long-Term Impacts of Climate Extremes

Identifying key impact channels and effective strategies for long-term economic development under climate change

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UNDERSTANDING THE SHORT AND LONG-TERM IMPACTS **OF CLIMATE EXTREMES**

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Contents

Floods, tropical cyclones, heatwaves, and droughts cause not only substantial direct damages, but also have the potential to deteriorate socio-economic development perspectives in the short and in the long-term.

The SLICE project – funded by the German Federal Ministry of Education and Research – has been working to understand how climate extremes impact socio-economic development, assessing impacts both on the macro level as well as on the household level for the focus countries Nigeria, Malawi and the Philippines.

Key findings

Exposure to extreme events and direct damages increase substantially with climate change

- The number of people exposed to **tropical cyclones** every year could increase by 26% (33 million people) in a world that warms by 2°C from pre-industrial levels, assuming present-day population. If populations increase, this changes as, global population is projected to peak around mid-century and decline thereafter. A middle-of-the-road socio-economic scenario, reaching about 3-4°C of warming by the end of the 21st century and factoring in population growth would see an increased exposure of 41% (52 million people). A stronger mitigation scenario, where warming is limited to 2°C at the end of the 21st century, limits this increase to 20% (25 million people). Cumulatively, stronger mitigation could save over 1.8 billion people from tropical cyclone exposure throughout the 21st century (Geiger *et al.*, 2021).
- Globally, **flood vulnerability** has decreased in the period 1980-2010. However, economic damages still increase over the years because this vulnerability reduction was overtaken by the increase of exposed assets due to economic growth. In Eastern Asia, Latin America, Russia and Central Asia climate change has contributed to an increase in flood damages (Sauer *et al.*, 2021).
- Analyses in Malawi and Nigeria show that regional impacts from climate change on the water regime differ depending on the context. In several areas of Nigeria, **flood risk** is projected to increase through augmented surface runoff and extreme precipitation, increasing exposed urban areas and infrastructure to riverine floods. In Malawi, flood risk is likely to be increased through more heavy precipitation events, but decreasing runoff is projected to threaten water availability. Accounting for projected population growth, both countries are projected to fall below the threshold of **water scarcity** in the future. These compound risk projections call for urgent water conservation actions to support infrastructure and rainfed agriculture. The frequency of very hot days and **heat-related mortality** is also projected to substantially increase in both countries.

- In the Philippines, climate change projections show an increase in runoff and **extreme precipitation** across the entire country. The share of total population and infrastructure exposed to floods, which is already very high today, is projected to further increase over the next decades. Average tropical cyclone intensity and tropical cyclone precipitation are projected to increase. At the same time, water availability adjusted for population growth is projected to decline and heat-related deaths are projected to increase.

There are substantial short-term and long-term impacts of extremes on socio-economic development

- Extreme weather events such as tropical cyclones and river floods can **reduce economic growth** of affected countries for more than a decade. The growth losses increase disproportionately with disaster intensity. We find that in the historical period 1971—2014 and across all affected countries, growth losses from severe tropical cyclones and river floods may have accumulated to 6.5% and 5.0% over 15 years. Ongoing intensification of extreme weather events in frequency and intensity due to climate change may therefore substantially reduce the development prospects of disaster-prone developing countries (Krichene *et al.*, 2021).
- Accounting for tropical cyclone impacts significantly increases the **Social Cost of Carbon** for major emitting countries prone to tropical cyclones such as: Japan (+39.8%), China (+8.1%), the US (+6.3%), and globally (+2.1%), when compared to the estimates currently used for policy evaluations. The benefits of climate policies could therefore be substantially underestimated. Adequately accounting for the damages of extreme weather events in policy evaluation is key to prevent a critical lack of climate action (Krichene *et al.*, 2022).
- **Tropical cyclones** affect poorer populations disproportionately. Our study finds that food-poor households in the Philippines are significantly affected through negative impacts on wage earnings (particularly from agricultural salaries) as well as a reduction in total food and non-food expenditures, suggesting limited resources to cope with income losses (Schleypen, J., Plinke, C., Geiger, T., 2023). Well-being losses are largest for poor households in the Philippines. However, incomplete recoveries between recurrent climate extremes cause the largest relative increase in well-being losses for middle-income households (Sauer et al., 2023).
- In Malawi, exposure to **drought** increases the likelihood of a household to report drought-related food insecurity. Drought exposure is also negatively impacting the health of children, even at moderate drought levels. Impacts increase in severity with increasing drought intensity and duration of exposure. Smallholder farmers in Malawi are especially vulnerable, with more pronounced negative health impacts for children at moderate drought intensities, compared to non-smallholder farmers (Zimmer *et al.*, 2023)
- There is no full 'catch-up' of drought-exposed children over time in Malawi: children that have been exposed to severe drought in their early childhood (aged below 2 years) but

not afterward in childhood still exhibit significant negative health impacts years after the exposure, compared non-exposed children indicating longer-term health impacts (Zimmer *et al*., 2023)

- In Nigeria, extreme weather events are more than doubling the risk of harvest failure due to flooding. Facilitating education as a resilience strategy can enable household members to diversify their income sources and adapt to a changing climate (Berger, 2023).

We identify multiple coping and adaptation strategies - but all have limitations

- The global food system is susceptible to systemic shocks. Weather-induced simultaneous **production failures** in multiple main production regions (multi-breadbasket failures or conflicts), can be substantially amplified by uncoordinated unilateral policy responses such as export restrictions. International cooperation and leadership is needed to mitigate overlapping crisis situations as the developing crisis triggered by the Russian invasion of Ukraine and overlapping with Covid-19 related economic downturns (Falkendal *et al*., 2021; Kuhla *et al*., 2023).
- Better national climate risk insurance could compensate for future increases in **hurricane damages** with global warming in developed countries such as the US, if warming is limited to 1.5°C. However, national insurance schemes are not sufficient for strongly exposed Small Island Developing States such as Haiti. For these states, national and international mechanisms and institutions will need to provide concessional climate finance and expertise in climate adaptation. Multilateral institutions such as the United Nations' Green Climate Fund will need to be further strengthened to ensure that they have both the financial resources and the effective governance, to fulfill their mandates (Otto *et al*., 2023).
- In the Philippines, we find that households partially rely on remittances or cash coming from abroad for coping with **tropical cyclone impacts**. However, these financial flows only come with a delay. As an immediate solution to a loss in income due to tropical cyclones, households reallocate their budget in favor of housing repairs over health and educational expenditures. Food-poor households, who already earn less than the amount required for the minimum nutritional needs, resort to in-kind food consumption rather than those bought with cash (Schleypen, J., Plinke, C., Geiger, T., 2023).
- For Malawi, the most commonly reported active coping strategy for households is relying on their own savings to cope with a **drought shock**, as well as receiving help from family and friends. However, savings may be run down over time or simply not available for poorer households. Involuntary changes in eating patterns, family members taking up work, receiving unconditional help from the government or NGOs as well as selling livestock or assets are also relevant coping strategies for drought exposure, though so far they are reported less frequently by households in Malawi (Zimmer *et al*., 2023).

Key terms and definitions

Following the definitions of the IPCC's Sixths Assessment Report (AR6) (IPCC, 2021)

- "**Hazard** is defined as 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."
- "**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."
- "**Vulnerability** in this report [following AR6] is defined as the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt."
- **"Adaptation** is defined, in human systems, as the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities. In natural systems, adaptation is the process of adjustment to actual climate and its effects; human intervention may facilitate this." "Adaptation plays a key role in reducing exposure and vulnerability to climate change."
- **"Resilience** in this report [following AR6] is defined as the capacity of social, economic and ecosystems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure as well as biodiversity in case of ecosystems while also maintaining the capacity for adaptation, learning and transformation. Resilience is a positive attribute when it maintains such a capacity for adaptation, learning, and/or transformation."
- **"Representative Concentration Pathways (RCP)"** define the scenarios that include time series of emissions and concentrations of the full set of greenhouse gases (GHGs), aerosols and chemically active gases, as well as land use/land cover leading to specific radiative forcing characteristics. **RCP2.6:** (Strong mitigation scenario) radiative forcing peaks at approximately 3 W m–2 and then declines to be limited at 2.6 W m–2 in 2100. **RCP6.0:** Intermediate stabilization pathway in which radiative forcing is limited at approximately 6.0 W m–2 in 2100 (IPCC, 2021).
- **"Shared Socio-economic Pathway (SSP)"** are scenarios of projected socio-economic global changes up to 2100 (Rogelj et al., 2018).

Preface

The aim of the project "Short- and Long-Term Impacts of Climate Extremes (SLICE)" was to gain a deeper understanding of the channels through which climate variability and climate change impact on societies and economies. By assessing these impact channels on the household as well as on the macroeconomic level, we were able to quantify the socio-economic impacts of extreme weather events and to assess the effectiveness and limitations of different coping and adaptation strategies.

This Synthesis Report first provides an overview of the insights of the SLICE project for the different analyzed extreme event types. It summarizes the insights of the project related to different impact channels, coping and adaptation strategies and factors affecting resilience. To reflect differences in timing and persistence of impacts and related implications, the key SLICE findings for short-term impacts and long-term impacts are synthesized throughout the report. We also summarize methodological advancements achieved under the SLICE project and discuss 'Lessons Learnt'. The last section of this Synthesis Report concludes and synthesizes policy implications.

Insights by extreme event type

Tropical Cyclones

Already in today's climate, tropical cyclones (TCs) are one of the most damaging categories of extreme weather events. They expose on average 150 million people annually (Geiger, Frieler and Bresch, 2018). Beneath substantial direct damages, tropical cyclone strikes can also reduce economic growth of countries for over a decade (Krichene *et al.*, 2021). In tropical cyclone prone countries, the long-term effects of recurrent tropical cyclones accumulate over time and can have a more adverse impact on these countries' economic development than the direct losses in the wake of an event.

Risks related to hazard and exposure

Under global warming, the frequency of the most intense TCs is projected to increase. To quantify the associated population exposure, we combine TC simulations with an impact model to quantify country-level population exposure to TC winds for different magnitudes of global mean surface temperature increase and future population distributions. We estimate an annual global TC exposure increase of 26% (33 million people) for a 1 °C increase in global mean surface temperature, assuming present-day population (Fig. 1).

The timing of warming matters when additionally accounting for population change, with global population projected to peak around mid-century and decline thereafter. A middle-of-the-road socio-economic scenario combined with 2 °C of warming around 2050 increases exposure by 41% (52 million).

A stronger mitigation scenario reaching 2 °C around 2100 limits this increase to 20% (25 million). Rapid climate action therefore avoids interference with peak global population timing and limits climate-change-driven exposure. Cumulatively, over 1.8 billion people could be saved by 2100 (Geiger *et al.*, 2021).

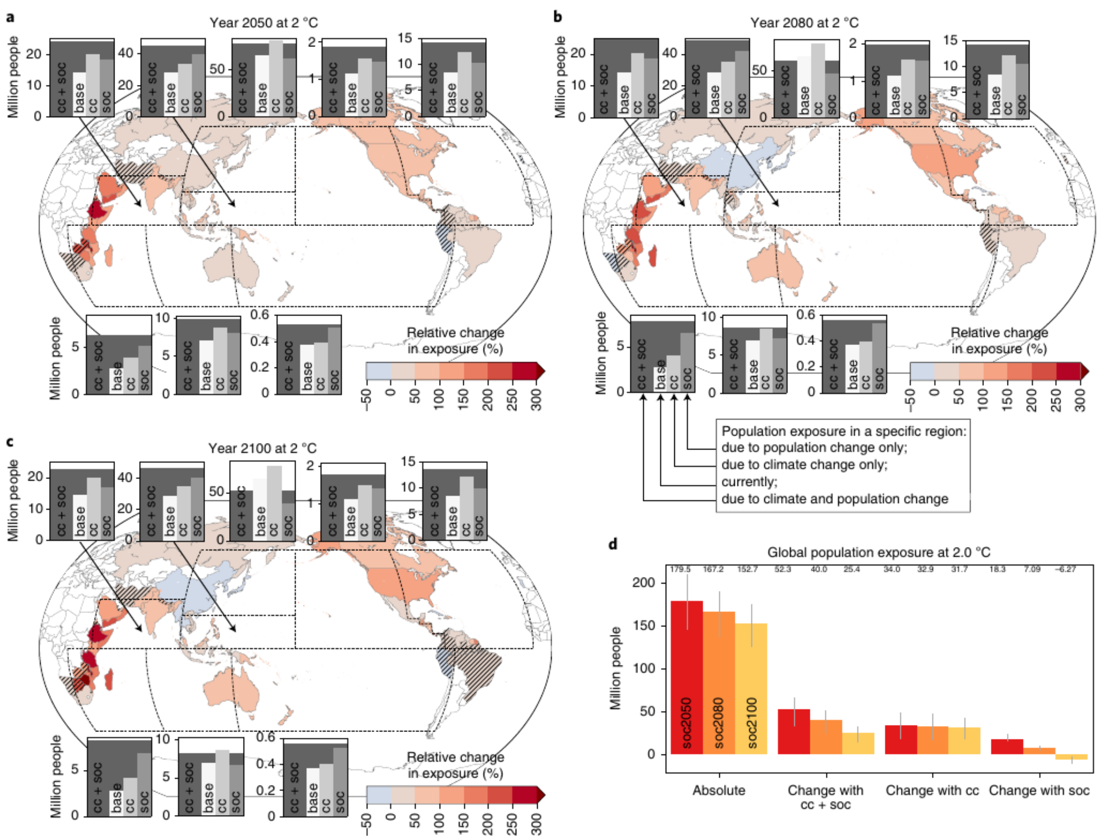

Figure 1 Population exposure for different base years of socio-economic development and 2 °C of warming. a—c, Maps displaying the mean relative change in country-specific population exposure between the baseline (2015, 1 °C) and 2 °C of warming for different base years (2050, a; 2080, b; and 2100, c) under socio-economic development according to a middle-of-the-road scenario. Hatching indicates countries where fewer than three model realizations agree on the sign of the change. The map insets show modeled absolute population exposure (in millions of people) for eight different regions separated by drivers of change (base, 1 °C warming with 2015 population patterns; cc, 2 °C warming with 2015 population patterns; soc, 1 °C warming with SSP2-based population patterns; cc + soc, 2 °C warming with SSP2-based population patterns). d, Globally aggregated absolute exposure and exposure change with respect to the baseline separated into the drivers of change for different base years (2050, red; 2080, orange; and 2100, yellow). Whiskers indicate the exposure range due to the different model realizations (courtesy (Geiger et al., 2021)).

Insights on socio-economic impacts and vulnerability

There is a strongly non-linear increase of growth losses with disaster intensity. The vulnerability of growth to tropical cyclones strongly varies from country to country, and differences in vulnerability cannot be explained by the development level of countries. In the historical period, 1980-2014, we find, for instance, average growth losses to accumulate in the US, Japan, and the Philippines to about 0.01%, 0.08%, and 0.13% percent per-year, respectively Fig. 2.

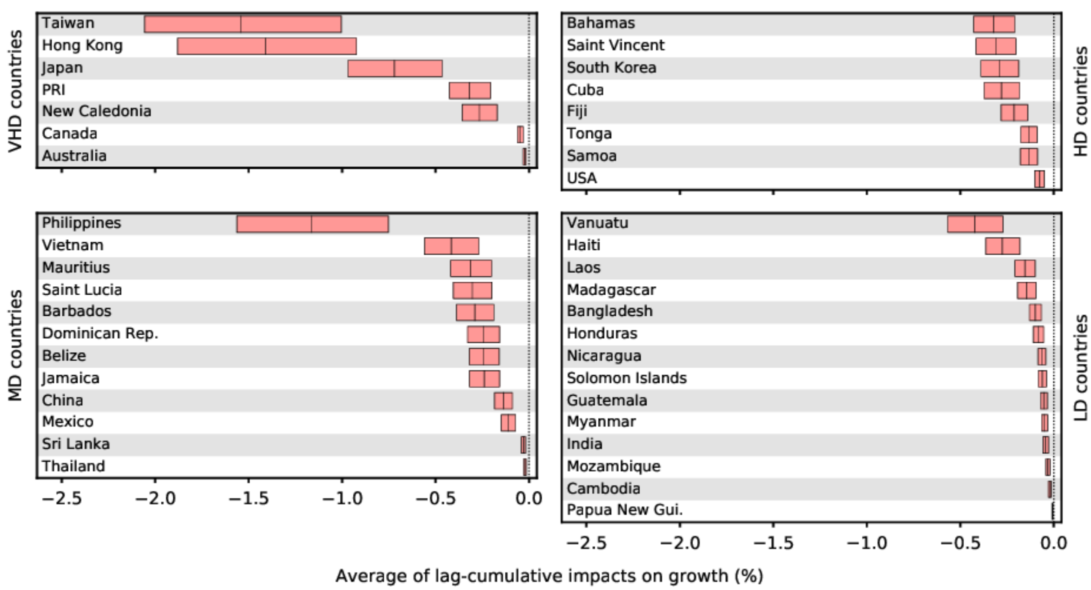

Figure 2 Average annual growth losses of countries in the historical period. Average annual tropical cyclone-induced growth losses for very high developed (VHD), high developed (HD), medium developed (MD) and least developed (LD) countries (according to the inequality-adjusted human development index. Black vertical lines and boxes indicate median losses and 66% confidence intervals, respectively, and red and gray colors denote statistically significant and non-significant results, respectively. Modified from (Krichene et al., 2022).

The intensification of tropical cyclones under global warming also renders it more likely that long-term growth impacts of subsequent events overlap, which increases cumulative future growth losses. Unfortunately, current policy evaluations do not account for these long-term effects of tropical cyclones (and extreme weather events in general). This may lead to a substantial underestimation of climate damages and to a critical underestimation of the benefits of mitigation and adaptation measures.

Combining our TC simulations with the empirical regression model, we derive, for the first time, temperature-dependent tropical cyclone damage functions for 41 TC-affected countries that account for the persistence of TC damages in the economic system. These damage functions allow assessing the increase in damages with global warming (Fig. 3), and are critical for the climate integrated assessment community to include the damages of TCs in climate mitigation and adaptation policy evaluations.

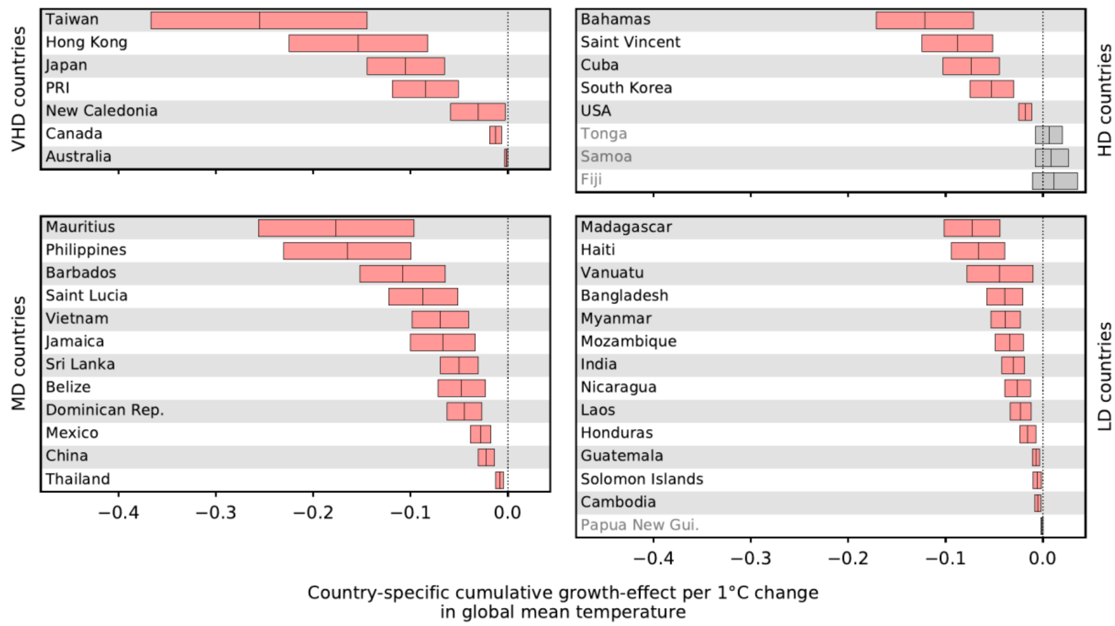

Figure 3 Marginal damages of tropical cyclones. Tropical cyclone-induced country-level growth rate changes per degree of global mean temperature change for very high developed (VHD), high developed (HD), medium developed (MD) and least developed (LD) countries (according to the inequality-adjusted human development index). Black vertical lines and boxes indicate median losses and 66% confidence intervals, respectively, and red and gray colors denote statistically significant and non-significant results, respectively. Courtesy (Krichene et al. 2022).

The novel TC-damage modeling framework allows us to estimate two complementary metrics of high policy relevance: i) the discounted annual damage (DAD) and ii) the contribution of tropical cyclones to the social cost of carbon (SCC). The DAD is a measure for the additional future economic burdens of countries induced by climate change. It reveals adaptation needs and allows the development of tailored evidence-based National Adaptation Plans (NAPs). They are computed over the period 2021–2100 as the discounted difference of the national GDP trajectories with and without the change in tropical cyclone activity under additional warming.

Our DAD analysis reveals that differences in income among countries must not be neglected when estimating and comparing the adaptation challenges of countries. In per-capita terms, absolute DADs are highest for strongly exposed high-income countries such as Taiwan, Japan, and the US.

However, when DAD is measured relative to average household income, the damages for the small island developing state of Mauritius but also for the lower-middle-income countries of the Philippines and Vietnam become comparably large. For an average household, these reach from about one to 10 days of income lost per year, largely depending upon assumptions on discounting.

The SCC measures the monetized value of the damages to society caused by an incremental metric tonne of CO2 emissions and is a key metric informing climate policy. Used by governments and other decision-makers in benefit–cost analysis for over a decade, SCC estimates draw on climate science, economics, demography and other disciplines. We find that accounting for TC impacts significantly increases the SCC of the strongly affected major greenhouse gas emitters Japan (+68.9%), China (+11.5%), the US (+9.6%), and globally (+6.3%) compared to the estimates currently used for policy evaluations (Krichene et al. 2022).

Compared to the total global SCC, the contribution of tropical cyclones of 6.3% seems moderate. But the burden is almost entirely on only five countries: USA, Japan, China, India, and Taiwan contribute more than 75% of the tropical cyclone-induced SCC. In the case of Japan, the damages from tropical cyclones increase the national SCC by almost 70% (Fig. 4). Further, it is critical to keep in mind that these estimates only comprise the contributions of TCs, which affect only a limited set of countries. Other major categories of extreme weather events such as floods and droughts cause direct damages that are comparable to TC damages globally and also reduce the economic growth of the affected countries in the long term. This suggests that the benefits of climate policies could currently be substantially underestimated. Adequately accounting for the damages of extreme weather events in policy evaluation may therefore help to prevent a critical lack of climate action.

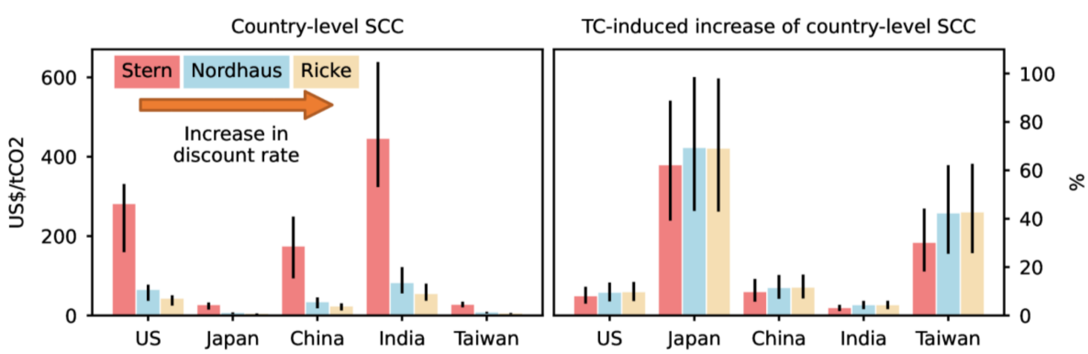

Figure 4 The social cost of carbon (SCC) from tropical cyclones. Median country-level SCC (left) and their tropical cyclone-induced increases (right) for the period 2021-2100 and for a middle of the road scenario for greenhouse gas emissions and economic growth (RCP6.0-SSP2), and three different values of the growth-adjusted discount rates used in the Stern review (Stern, 2008), for the standard calibration of Nordhaus's DICE model (Nordhaus, 2011), and by (Ricke et al., 2018) (color code). Black whiskers indicate the 66% confidence interval (16.7—83.3%). Courtesy (Krichene et al., 2022).

Box 1: Tropical Cyclones as compound events — How detrimental is extreme rainfall?

TCs affect households not only through strong winds, but also through storm surges and heavy rainfall, with the latter two leading to flooding, salinization of vegetation, erosion, and additional destruction of infrastructure (Bakkensen, Park and Sarkar, 2018; Kunze, 2020). There may be regions affected by all hazards, but also regions without stronger wind impacts but with rainfall or storm surge surge damages. The intensity of TCs is solely measured by its wind speed in commonly used categorizations of TCs. It naturally follows that in science wind speed is usually the only indicator representing a TC shock.

It has been a common assumption that wind speed, rainfall and storm surge during TCs are highly correlated. This led to the simplification of many models to omit TC-related precipitation and storm surge. Yet, a sound understanding of the additional damages caused by the co-hazards storm surge and rainfall is still missing.

In the Philippines, almost 50% of rainfall in the Northern and Southern Luzon are associated with TCs; while only 20% is associated with TCs in the Visayas region, and 4% in the Mindanao region where TC events are much less frequent (Cinco *et al.*, 2016).

Within the SLICE project we studied the effect of TC-induced rainfall on important socio-economic indicators in the Philippines using high-quality TC and rainfall data combined with household panel surveys (Schleypen, J., Plinke, C., Geiger, T., 2023).

Our study highlights that TC-associated extreme rainfall causes delayed income losses after the TCs, mainly through a decrease in agricultural income and salaries.

On the expenditure side, the presence of heavy rainfall during the strongest TC also causes a delayed reduced spending in cereals and meat, as well as an immediate reduction in spendings on education, and an extended increase in housing expenditures of one more year.

These results underline the importance of taking into account co-hazards individually, as their impacts as well as their transmission channels may differ.

Drought

Risks related to hazard and exposure

The IPCC's 6th Assessment Report (AR6) defines droughts as "periods of time with substantially below-average moisture conditions, usually covering large areas, during which limitations in water availability result in negative impacts for various components of natural systems and economic sectors" ((IPCC, 2021), Ch.11, p. 1570) summarizing definitions from the literature.

Different types of droughts can be identified depending on the affected systems and focus of measurement as well as time horizon with categories overlapping, spanning from meteorological droughts with (shorter term) precipitation deficits to agricultural droughts with soil moisture deficits and impacts on crop yields and ecological drought with trees dying from water stress to (longer term) hydrological droughts with water shortages and groundwater depletion ((IPCC, 2021), Ch.11).

The AR6 summary of policy makers concludes that man-made climate change has already contributed to increases in agricultural and ecological droughts in some regions and that it can be said with high confidence that every additional 0.5°C of warming causes discernible increases in the intensity and frequency of agricultural and ecological droughts in some regions. For meteorological and hydrological droughts, the AR6 states with medium confidence that frequency and intensity are projected to increase in some regions.

The SLICE Climate Risk Profiles provide an overview of the current as well as projected exposure to climate extremes like droughts for the SLICE focus countries Malawi, Nigeria and the Philippines. In the Philippines, droughts often occur in conjunction with El Nino events, with the reduction in water inflow and runoff into reservoirs regularly leading to water scarcity, severely impacting agricultural production, human health and the power sector (Plinke, C., Schleypen, J., Lange, S., 2021).

In Nigeria, droughts have historically played a stronger role in northern regions of the Sahel, with recent scientific literature suggesting an expansion of the Sahara desert by over 3000 square kilometres every year as well as warnings about lake Chad drying up (Berger, J., Zimmer, A., Plinke, C., Udechukwu, S., Lange, S., 2021; Plinke, C., Schleypen, J., Lange, S., 2021). While, in the recent past, single large scale drought events have happened less frequently in Nigeria, the general trend is moving towards an overall dryer climate in Nigeria making agricultural production more challenging (Berger, J., Zimmer, A., Plinke, C., Udechukwu, S., Lange, S., 2021).

For both the Philippines and Nigeria, however, projections for indicators related to droughts do not show a clear trend for increasing drought risk in the future, while modeling uncertainty is partly very high (Berger, J., Zimmer, A., Plinke, C., Udechukwu, S., Lange, S., 2021; Plinke, C., Schleypen, J., Lange, S., 2021).

Malawi is regularly exposed to drought events, having experienced eight major drought events in the past four decades. The southern part of Malawi and, to a lesser extent, the central regions of the country are particularly exposed to droughts, with El Nino years typically leading to erratic precipitation and prolonged dry spells (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Udechukwu, S., Lange, S., 2021). In 2015-2016, Malawi experienced a major drought event due to strong El Nino conditions, which affected large parts of the country, with an estimated 6.5 million Malawians - about 39% of the population - being affected (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Udechukwu, S., Lange, S., 2021).

Projections for Malawi indicate that surface runoff, i.e. the amount of water discharged through surface or subsurface streams, is expected to decrease substantially in several regions in the country while at the same time potential evapotranspiration, i.e. the total amount of water that would be lost through evaporation, is projected to increase strongly. In line with this, soil moisture is projected to decrease in Malawi.

While water management and access to clean drinking water is partly already a challenge today in Malawi, these trends are projected to contribute to increasing water stress. Especially when taking projected population growth into account, Malawi's water availability is projected to decrease by over 80% under different climate change scenarios by the year 2080, crossing the threshold for what is considered 'water scarcity' and coming close to the 'absolute water scarcity' threshold (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Udechukwu, S., Lange, S., 2021).

The share of drought exposed crop land area is also projected to increase in Malawi, which is concerning given Malawi's high dependence on agriculture and virtually all agricultural activity still being rainfed (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Udechukwu, S., Lange, S., 2021). Also for Nigeria and the Philippines, water stress is projected to increase when accounting for population growth (Berger, J., Zimmer, A., Plinke, C., Udechukwu, S., Lange, S., 2021; Plinke, C., Schleypen, J., Lange, S., 2021).

Insights on socio-economic impacts and vulnerability

Given the alarming projections for water availability and the recent exposure to major drought events, we have focused on Malawi for assessing the socio-economic impacts of droughts in the SLICE project.

Based on household survey data and biophysical gridded data for drought exposure, we first assess how past drought events of different severity levels have affected household food security in Malawi (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023). We find empirical evidence that agricultural households in Malawi that have been affected by a severe drought in the last 12 months prior to the surveys have a significantly higher propensity to report having been food insecure during this time, indicating that food insecurity is a relevant impact channel through which droughts affect agricultural households in Malawi.

In a second part of the analysis, we assessed whether drought exposure has negatively impacted child health in Malawi (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023). Combining child-level and household survey information with gridded biophysical time series data of drought conditions by months, we identify the exposure to drought over the lifetime of the surveyed children which are aged between 6-59 months at the time of the surveys. The lifetime of the surveyed children covers several larger drought events such as the major drought in 2005 (first survey wave) as well as the major drought event in 2015-2016 (second survey wave) as well as different smaller more local droughts and regional variation in drought intensity and duration.

We also find empirical evidence that drought exposure is negatively affecting child health, with negative impacts on the height-for-age score - an indicator for chronic malnutrition - being more severe for children exposed to higher drought intensity levels and longer durations of drought exposure over their lifetime, with significant negative impacts already found for more moderate drought intensity. Moreover, we find that children in smallholder farming households are more vulnerable and experience greater negative impacts from droughts compared to children of non-smallholder families (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023).

Beyond assessing which factors increase vulnerability or resilience to drought exposure, we explore drought effects at different periods of a child's development, including the long-term impacts of early childhood exposure to drought. We find that there is no full 'catch-up' of exposed children over time: children that have been exposed to severe drought in their early childhood (aged below 2 years) but not later in childhood still have a significantly lower height-for-age score than non-exposed children. This confirms the critical role of the first two life-years for the healthy development of a child and indicates that there are significant negative long-term impacts to children's health with children affected by early childhood exposure not fully recovering over time from the negative health im

pacts even years after exposure (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023). For children not affected in their early childhood but exposed to severe drought conditions between the age of 2 and 5 years, we also find a significantly lower height-for-age score compared to children that have never been exposed to severe drought, indicating that also drought exposure after the first two life years still has a negative impact on child health (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023).

Given the projected increasing risks for water scarcity in Malawi (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Udechukwu, S., Lange, S., 2021) and virtually all agriculture still being rainfed in Malawi, our findings raise strong concerns regarding future developments and child health prospects.

Floods

Risks related to hazard and exposure

The 6th Assessment Report of the IPCC (AR6) defines floods as "...the inundation of normally dry land… classified into types (e.g., pluvial floods, flash floods, river floods, groundwater floods, surge floods, coastal floods) depending on the space and time scales and the major factors and processes involved." (IPCC, 2021) The AR6 concludes with high confidence that "The frequency and magnitude of river floods have changed in the past several decades with high regional variations [...]. Anthropogenic climate change has increased the likelihood of extreme precipitation events and the associated increase in the frequency and magnitude of river floods." (IPCC, 2022).

The temporal evolution of flood extents is difficult to measure due to a lack of suitable data and is subject to various direct human influences, such as river engineering or forest cover. Therefore, it is extremely difficult to isolate drivers responsible for changes in flood indicators. The common proxy measures for flooding are runoff and river discharge indicators. On the global level there are no clear trends of changing river discharge (IPCC, 2021).

However, on the regional level trends in discharge (both increasing and decreasing) are clearly detectable. In a larger share of major global basins these trends are rather caused by climatic than by direct human influence such as river engineering.

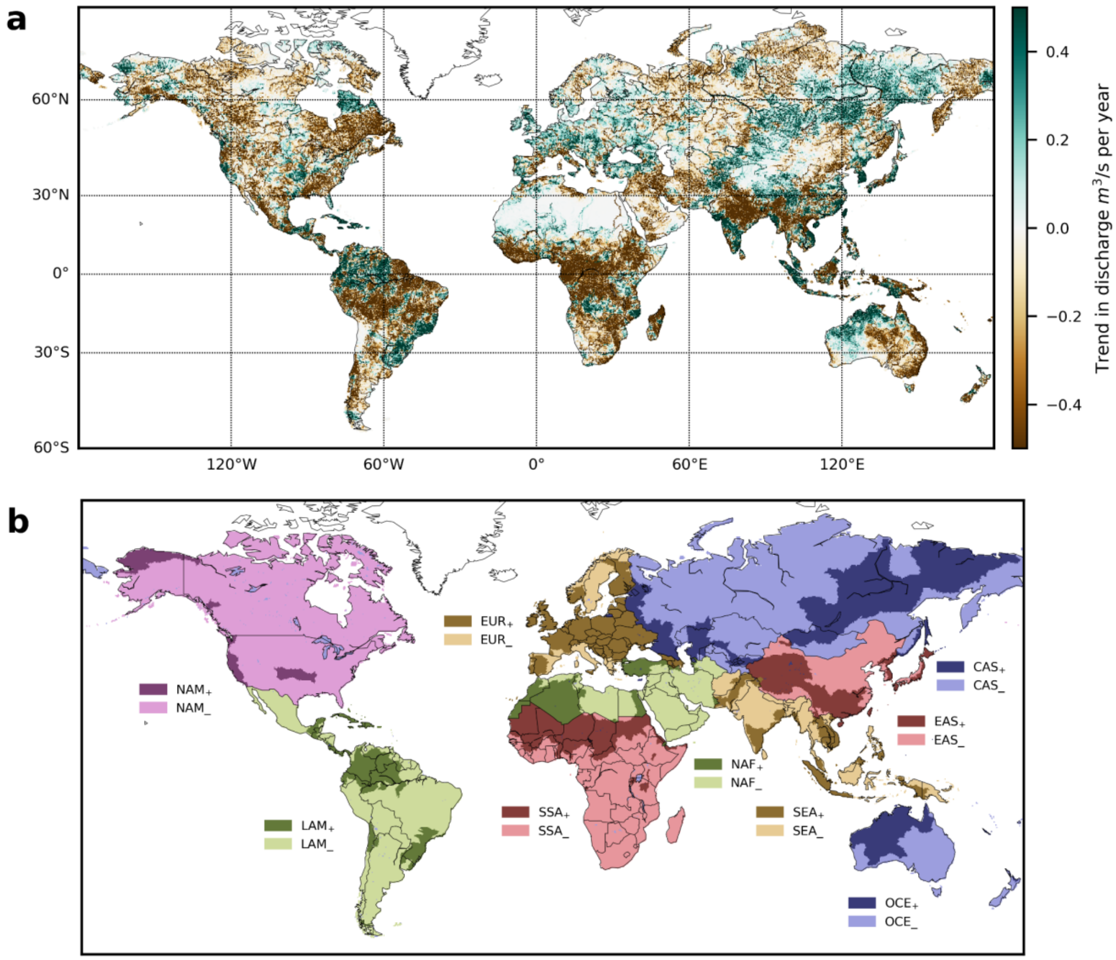

Figure 5 Discharge trends and definition of regions.a Absolute trends in annual maximum daily discharge in the time period 1971–2010. b Map of the nine geographical world regions: North America (NAM), Eastern Asia (EAS), Europe (EUR), Latin America (LAM), Central Asia & Russia (CAS), South & Sub-Saharan Africa (SSA), South & South-East Asia (SEA), North Africa & Middle East (NAF), Oceania (OCE) chosen according to geographical proximity and similarity of socio-economic structure. These regions are then further divided into subregions assembled of river basins with positive (R+, dark colors) and negative discharge trends (R–, light colors). Courtesy (Sauer et al., 2021).

A recent study based on discharge records shows that within Europe climate change has both increased and decreased river discharge (Blöschl *et al.*, 2019). Due to a lack of homogenous observational data on past river flows, in our study on global flood damage (Sauer *et al.*, 2021), we modeled maximum river discharge from 1971-2010 to estimate the underlying trends in river discharge on a 25 km resolution (Fig. 5 **a**). The results confirm the diverging trends in Europe, while they reveal similar patterns in the rest of the world with areas of significantly increasing discharge trends and others with significantly decreasing trends. The model allows to keep direct human influences on river basins at constant levels, so the trends shown in Fig. 5 **a** are purely climate-induced.

Box 2: Future drivers for flood risk in our focus countries Philippines, Malawi and Nigeria

Diverging trends in runoff also dominate in future projections. Risk profiles for Nigeria show that climate change is projected to increase surface runoff by 10 % in northern Nigeria, decreases runoff by 10 % in central Nigeria and does not change runoff in the south (Fig. 6).

Regionally, this leads to an increase in flood risk, augmented through increasing extreme precipitation. With flash floods due to excessive precipitation being one of the most devastating climate extremes in Nigeria, even small increases in extreme precipitation will have a major impact.

The projected changes pose a significant challenge to future infrastructure needs and flood risk management.

Also, in risk profiles for Malawi, heavy precipitation events are expected to increase, although numbers are subject to high model uncertainties.

In contrast, surface runoff is projected to decrease in several parts of Malawi with increasing GHG concentrations.

Considering the adverse trends in precipitation and water availability projections highlight the need for urgent water conservation actions, as 96% of current agricultural production is still rainfed.

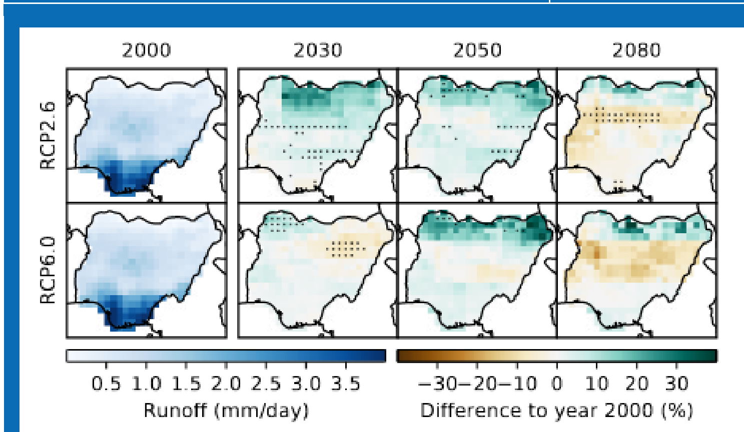

Figure 6 : Projections of runoff (water availability from precipitation) for Nigeria as percent difference to values in the year 2000 in mm per day. The left-most column displays historical values for the year 2000, the other columns display projections for the years 2030, 2050 and 2080. The upper row shows projections under RCP2.6, the lower row those obtained under RCP6.0. A dot in a grid cell indicates high agreement between the models and thus low uncertainty. Source: Climate Risk Profile: Nigeria

The climate risk profile created for the Philippines suggests a uniform increase of around 14% in surface runoff across the entire country by 2080 compared to the year 2000.

Heavy precipitation events are expected to increase in frequency and intensity. The event frequency is quantified to increase from 7 days in the year 2000 to about 8 days in 2030 and 9 days in 2050 (Fig. 7) in a scenario with moderate emissions (RCP2.6). The intensity of heavy precipitation events is expected to increase by 5 % in 2050. In scenarios with higher emissions (RCP 6.0), both frequency and intensity of heavy precipitation exceed levels in the scenario of moderate emissions.

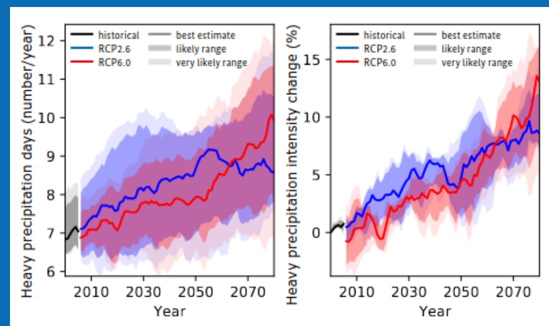

Figure 7 Projections of the number of days with heavy precipitation (left) and the change in heavy precipitation intensity (right) over the Philippines under different GHG emissions scenarios. Source: Climate Risk Profile: Philippines

The changes in flood exposure depend on the changes in flood extent and flood frequency. Additionally, they are driven by socio-economic variables such as population and economic growth. From 2000-2018 inundation areas observed by satellites and high-resolution population data showed a 20–24% increase of population exposed to river floods (Tellman *et al.*, 2021). Under future global warming of 2°C a global increase of exposed population of 100% is projected, with the largest increases in Egypt, Sudan, and the Netherlands (Lange *et al.*, 2020).

Box 3: Future flood exposure of population and infrastructure in our focus countries Philippines, Malawi and Nigeria

In our focus countries, increasing exposure of population to floods is one of the future key risks. In the Philippines, the share of the total population exposed to floods is already very high today and is projected to increase from 0.1 % in 2000 to 0.2 % in 2080 under RCP2.6, and to 0.5 % under RCP6.0 (Fig. 8). Infrastructure exposure illustrated with the example of major roads, is projected to increase under both emissions scenarios. Impassable roads and bridges may cause significant disruption and related social and economic impacts on health services, food and water supplies. The development of residential areas in low-lying areas can exacerbate the risk of flooding for households. Given the growing population, rapid urbanization and structural economic inequality, poor urban communities located in flood prone areas are disproportionately more vulnerable.

For the African focus countries Nigeria and Malawi, projections provide a mixed picture on the risk of future exposure of urban areas to river floods. On the one hand, we find an increase of the exposure of urban land areas to riverine floods that is projected to double from 2000 to 2080 independent of the emission scenario in Nigeria. However, projections for Nigeria involve large uncertainties, especially under RCP6.0. On the other hand, in Malawi best estimates do not project a significant change in the urban land area exposed to floods under both emission scenarios.

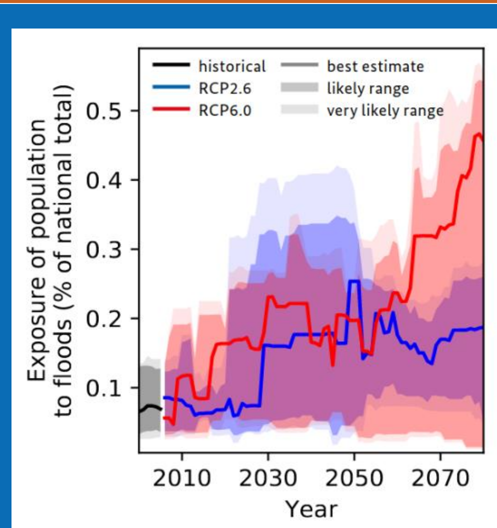

Figure 8: Projected exposure of population to river floods at least once per year for the Philippines for different GHG emissions scenarios. Source: Climate Risk Profile: Philippines

In Nigeria exposure of major roads to river floods is projected to almost double until 2080. The uncertainty of this measure is displayed in the span of the very likely range of 0.5 % to 1.6 % for RCP2.6 and 0.4 % to 2.4 % for RCP6.0 in 2080. This covers primarily extreme flooding events. Trends for smaller, but also devastating floods are not necessarily captured by this indicator.

This finding is relevant to assess indirect costs that occur due to flooding. For instance, regarding the exposure of farmers who need to transport their produce to the market, employees who have to reach their workplace or children who must commute to school.

Flood projections illustrating the exposure of infrastructure with the example of major roads in Malawi, show a high degree of uncertainty under both emission scenarios. Median values project a slight decrease of the share of major roads exposed to floods by 2080. At the same time, up to 2.7 % of major roads could be exposed to floods by 2080 (upper bound of the very likely range of RCP6.0) compared to 1.5 % in 2000.	

Insights on socio-economic impacts and vulnerability

It remains an open question to what extent the observed changes in climate and flood related indicators such as discharge have already induced long-term trends in economic damages caused by fluvial flooding. Besides climatic drivers and changing exposure, the vulnerability of a society crucially affects the socio-economic impact caused by floods. To understand the contribution of climate to changes in socio-economic impacts, the effects of each driver need to be isolated.

There are several studies that quantified the changes in exposure and vulnerability as drivers for changing trends in damage records. However, the contribution of climate to damage trends has rarely been addressed. Most studies did not find significant trends, after adjusting for economic- and population growth, that could be caused by changes in climate. Studies on economic damage are commonly done for economically homogeneous world regions, neglecting climate conditions. Interestingly, the discharge trend analyses suggest that within commonly defined world regions, e.g. in Europe, an aggregation of flood-induced damages across these regions would imply an aggregation over diverging signals of climate change, thereby, hiding its influence on the aggregated level. Therefore, in our work (Sauer *et al.*, 2021), we divide nine standard, socio-economically homogeneous world regions (R) into subregions R+ and R– comprising the river basins with positive and negative basin-average trends in discharge, respectively Fig. 5 b.

Observed damages from river floods have globally increased between 1980 and 2010 (Fig. 9 black frames), but the role of individual drivers, such as changes in climate, exposure and vulnerability is so far unclear. To disentangle and quantify the respective contributions of i) climate-induced changes, including flood extent and depth, ii) from changes in exposure of valuable assets, and iii) their vulnerability, we develop an impact model based on historical flood simulations and global gridded-GDP from ISIMIP.

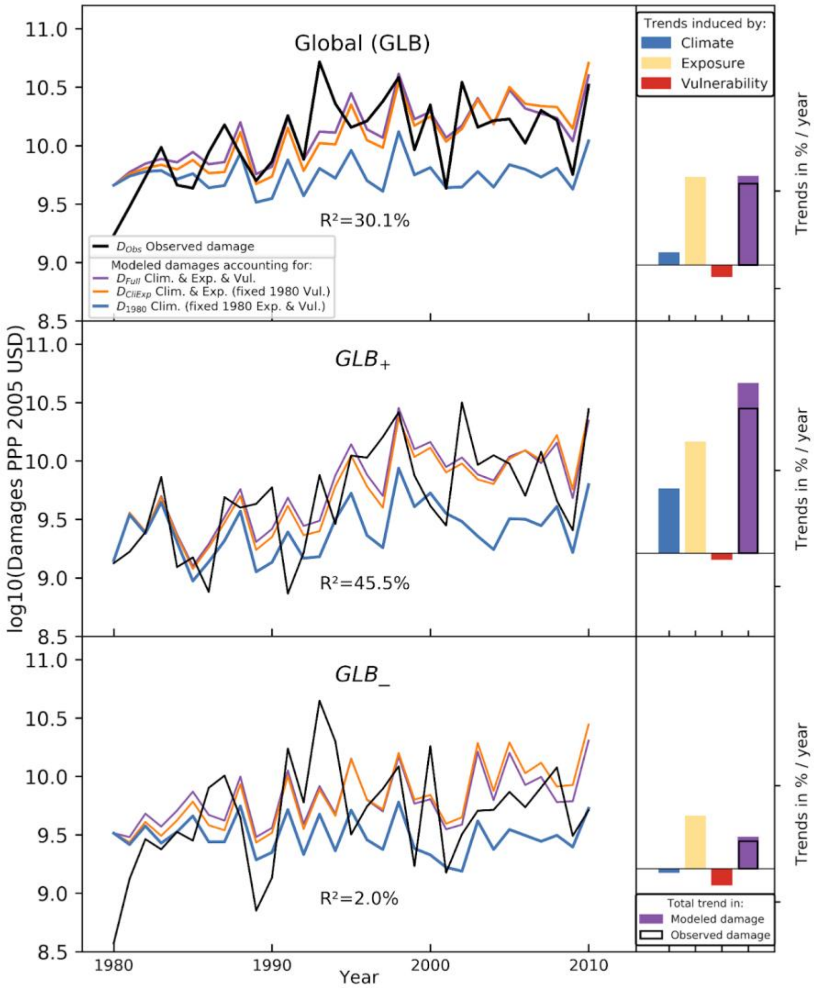

Figure 9 Observed and modeled time series of global river flood damages (1980-2010). Time series of observed damages from the NatCatService database (black) as well as modeled damages (multi-model median) when we run the model in three different modes: I) we let climate, exposure and vulnerability change over time (purple), II) we change climate and exposure (orange) keeping vulnerability at 1980 conditions, and III) we let only climate change and keep exposure and vulnerability on 1980-fixed levels. Bars indicate the relative trend in annual modeled (purple) and observed damages (black frames) and the individual contributions of each driver: climate (blue), exposure (yellow), vulnerability (red) relative to the recorded annual mean damage of the baseline period 1980-1995 (ISIpedia, 2021).

The increasing trend in damages that we see globally (Fig. 9) roughly corresponds to the increasing exposure, as the small increase caused by climate is compensated by a small vulnerability reduction (red bar). When we look at the small right panels in Fig. 9 we can also generally state that exposure increase was the driving force between 1980-2010 and that climate contributions were only minor in comparison (SSA is an exception, but here we have low confidence in the model). However, when dividing the world regions into subregions with homogeneous discharge trends (Fig. 5 b), climate-induced trends in damages become clearly detectable (Fig. 9 and Fig. 10).

In most regions e.g in Latin America and Eastern Asia, we see that climate has significantly increased damages in one subregion, but decreased damages in other regions. Considering only areas with increasing discharge trends R+, globally, as well as in South & South-East Asia, Central Asia, and Eastern Asia, the climate-induced trends are comparable or even larger than the trends induced by the socio-economic drivers.

The same holds true for the climate-induced trends in South & Sub-Saharan Africa, Oceania, and North Africa & Middle East, where however the explanatory power of the full model is considered too low ($R2 < 20\%$) to allow for an attribution of observed damages. In most regions with increasing discharge trends (R+), climate-induced trends are positive and often significant, but mostly negative and insignificant in the corresponding regions with decreasing discharge trends (R–) (Fig. 10). In some areas of Oceania climate has reduced damages significantly.

The contributions of climate to changes in damages are often insignificant and close to zero when we look only at the world regions as a whole or across the globe. Our work highlights that looking only at entire world regions (blue dots) hides effects of changing climate, as there are often underlying significantly reduced or increased trends in damages on a subregional level (Fig. 10).

Note, that vulnerability is usually assumed to decrease with time, as people learn to adapt. In regions such as Latin America and Eastern Asia the vulnerability reduction was indeed remarkable, but there are other world regions where it seems to have barely changed or even increased. Here we find that in some regions and subregion vulnerability has even increased, e.g in South & South-East Asia, but also in developed regions such as North America and Oceania (Sauer *et al.*, 2021).

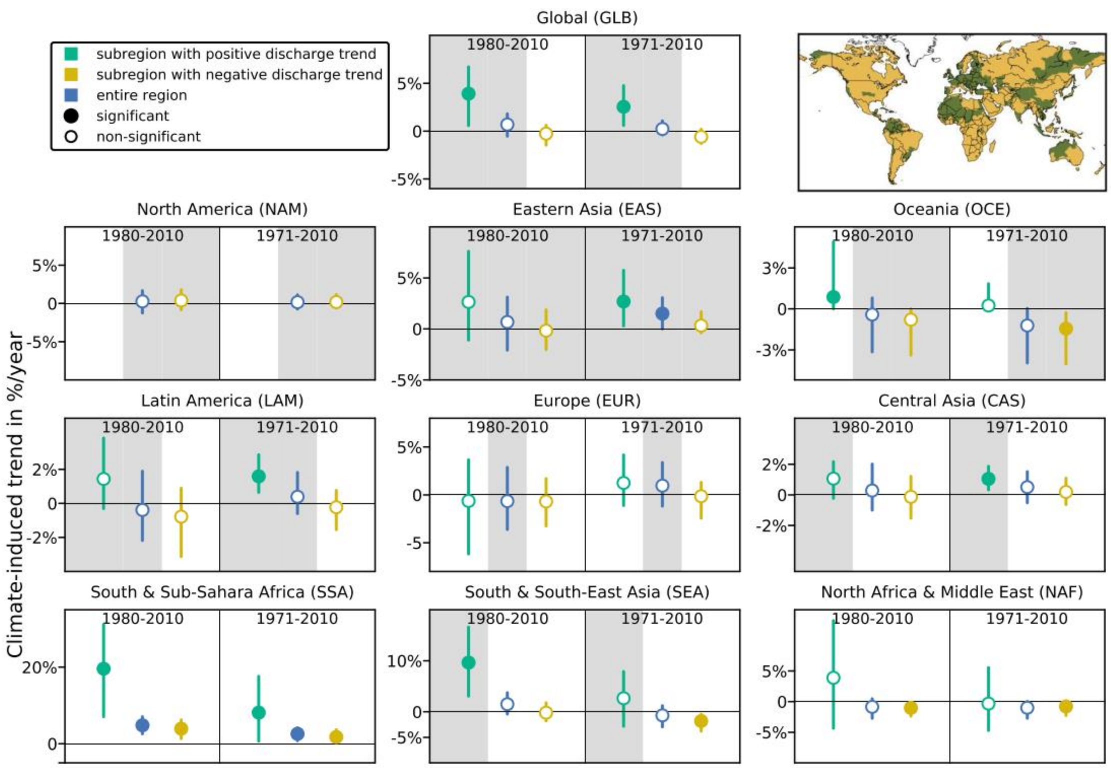

Figure 10 The climate contribution to the change in damages during the time periods 1971-2010 and 1980-2010. Shown are trends for each geographical world region (R) as well as in the subregions with positive (R+) and negative discharge trends (R–). Error bars indicate the 90% confidence interval of the Theil–Sen slope estimation. Symbols indicate the statistical significance of the climate trends at various levels. Climate-induced trends derived from simulated damages assuming fixed 1980 exposure are expressed relatively to the recorded annual mean damage of the baseline period 1980–1995 in the region or subregion. Gray background colors highlight the regions where the explained variance of the full model is higher than 20%. Modified from (Sauer et al., 2021).

Recurrent climate extremes

Impacts of extreme events are so far mostly researched and best understood for individual events. This approach has some shortcomings because many regions in the world experience multiple natural disasters within a short time period. There is a common narrative that these multi-shocks aggravate adverse impacts on society and may trap people in poverty.

On one hand, in frequently affected regions, such as the Philippines, there may not always be enough time for households to recover in-between recurrent events, causing additional adverse poverty effects.

On the other hand, recurrent events may cause less damage than multiple well-separated events, as assets that are already destroyed cannot be destroyed again, or they may be a trigger for adaptation reducing both direct and long-term impacts.

In the face of climate change increasing the likelihood of high event frequencies in many world regions (IPCC, 2019), it becomes more important to understand the effects of consecutive extreme events.

To improve our understanding of impacts related to consecutive disasters, in the framework of the SLICE project we developed two country case studies on the Philippines that investigate impacts of recurrent extreme events in the Philippines, ranked as the fourth most climate-affected country in the world (Eckstein, Künzel and Schäfer, 2021).

In our study on household impacts of tropical cyclones in the Philippines, we combined data on modeled windfields of observed tropical cyclones (TCs) and extreme precipitation with the Family Income and Expenditure Survey (FIES) (Schleypen, J., Plinke, C., Geiger, T., 2023). In order to measure the impact of tropical cyclones on households we take into account the wind speed of the most intense TC, as well as the presence of heavy precipitation and the number of TCs affecting the household in the same year. We find that the significant negative impact of the strongest TC on income is further aggravated by multiple TC occurrences, coming mainly from non-agricultural income.

However, the mechanisms through which multiple extremes aggravate poverty effects are poorly understood. Yet, there is no systematic way to assess the effects of incomplete recoveries compared to scenarios where undisturbed recovery is possible. In our second study focusing on consecutive extreme events (Sauer *et al.*, 2023), we aimed to improve our understanding on the different impact mechanisms of individual and recurrent disasters to quantify the effect of incomplete recovery. Therefore, we extended an agent-based household model that simulates household recoveries after a shock, using the global flood database (GFD) to reproduce the flood shocks between 2000-2018 from satellite observations.

To isolate the effect of incomplete recoveries we develop counterfactual scenarios where households either cannot be affected more than once by a flood, so other households are flooded instead (Counterfactual 1) or always have enough time to fully recover before they are hit by a subsequent disaster (Counterfactual 2).

Analyzing nationally aggregated effects, we find in our simulations for the Philippines that assets cannot be recovered completely between flood shocks (Fig. 11 **a**). Our results show a stronger accumulation of the damage to the stock of productive assets over time due to incomplete recoveries (cf. increasing spread between black and orange lines in Fig. 11 **a**) resulting in a relative increase of residual damage (damage that is not recovered) by around 50% in 2018.

A decade after the last event (2026) the relative increase in residual damage caused by incomplete recovery reaches even 100% underlining the relevance of incomplete recovery in the long run.

Nationally aggregated consumption losses basically follow the dynamics of the damage to productive assets. Incomplete recovery of multiply-affected households increases residual consumption losses by about 25% and accumulated well-being losses by around 50% in 2018 (Fig. 11 **b** and **c** purple line).

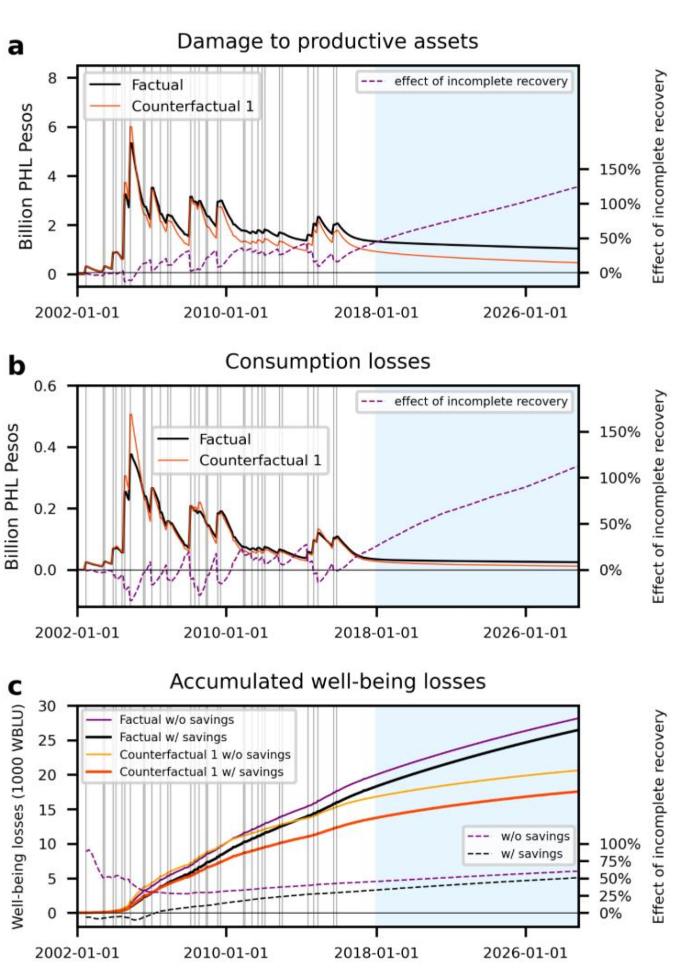

Figure 11 Nationally aggregated response dynamics to observed flood sequence. a Temporary evolution of the damage to the stock of productive assets, b consumption losses, and c accumulated well-being losses aggregated over all households to the national level for subsequent flood shock over the period 2000-2018 covered by the Global Flood Database (Tellman et al., 2021). The black and red line indicate the factual scenario where the same households can be affected by several floods and a counterfactual scenario where households are affected only once, respectively. Gray vertical lines indicate flood events as recorded in the Global Flood Database from January 1, 2002 to January 1, 2018 (white background). The recovery phase where no further shocks are recorded as the time period is no longer covered by the Global Flood Database is indicated in blue. Dash-dotted lines in c indicate the relative difference between the well-being losses for the factual and the respective counterfactual scenarios. Yellow and purple lines in c indicate scenarios where households do not have savings to mitigate consumption losses. Courtesy (Sauer et al., 2023).

While the damage to productive assets in the beginning of the time period is lower under incomplete recovery conditions because assets that are not recovered yet cannot be destroyed again, on the long run damaged assets and consumption losses accumulate stronger under incomplete recovery. The recovery time increases disproportionately when households' incomes fall close to or even under the subsistence line. In order to fulfill their basic needs these households have to reduce their recovery spendings.

Also on a national level, this leads to an accumulation of loss and damage compared to scenarios where each household has the opportunity to fully recover.

The modeling approach shows that long-term impacts on households are underestimated if recurrent events are treated like a cascade of individual events (Fig. 12). While direct asset damages are slightly reduced through incomplete recovery, consumption and well-being losses increase disproportionally under recurrent events.

Our simulations show that five events with overlapping socio-economic repercussions cause a direct asset damage of around four well-separated events, but the overall consumption losses of around 8 separated events and a total well-being loss of even 12 individual events (Fig. 12). These numbers represent the effects on average households, in the section on "Poverty and distributional implications" we show that there are great differences between income deciles.

The empirical study on TC impacts allows a more detailed evaluation on the underlying impact channels through which multiple TCs worsen or dampen the estimated effects of the single TC with the highest magnitude. On top of the negative immediate impact of the strongest TC, multiple TCs further reduce total income through non-agricultural income. On the expenditure side, multiple TCs cause a delayed reduction in human investments, such as health and education expenditures, thereby prolonging the negative spending in health expenses for another year. Furthermore, we find a dampening of expenditures in housing in the occurrence of multiple TCs. Overall, we conclude that experiencing multiple TCs in a year aggravates the situation, at least in terms of human investment, and no adaptation of households is observed (Schleypen, J., Plinke, C., Geiger, T., 2023).

Our model results suggest that recovery of households from recurrent floods often takes several years (Sauer *et al.*, 2023). Our empirical study suggests that Tropical Cyclone impacts based on wind intensity alone are short-lived and contained within the year of the TC, however, the presence of co-hazards such as extreme rainfall and multiple TC occurrences on top of the damages of the strongest wind speed contribute to the difficulty in recovering, thereby prolonging the impacts (Schleypen, J., Plinke, C., Geiger, T., 2023).

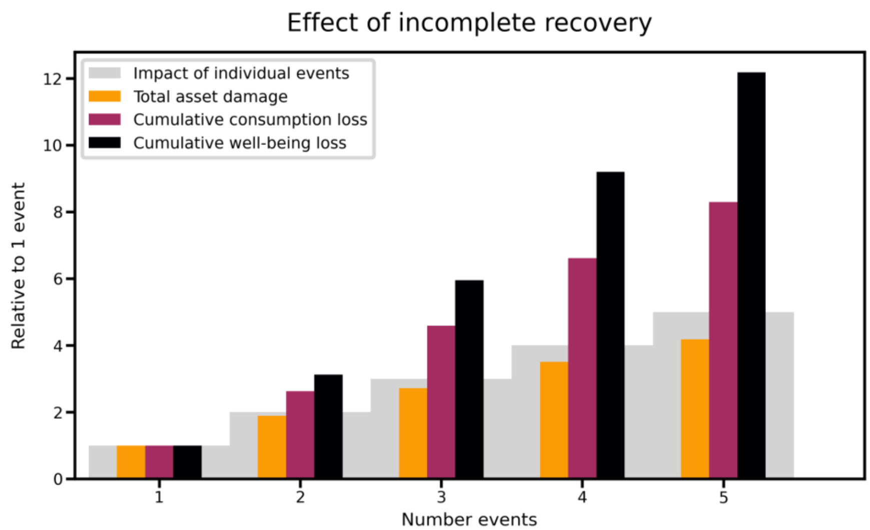

Figure 12 *Effect of incomplete recovery of households in dependence of the number of experienced flood events. Left column: Average cumulative direct asset damages (panel a), average cumulative consumption losses (panel b), and average cumulative well-being losses (panel c) for households in each income decile that are affected by 1-5 flood events in the period 1980-2018 covered by the Global Flood Database (Tellman et al., 2021) in the factual scenario. Middle column: Average increase in losses with the number of flood events that households experience relative to the average losses of households that are affected only by one flood event. Horizontal green lines indicate damages and losses that would occur if losses increased linearly with event number. Right column: Relative increase in average losses in the factual scenario where households may not recover between events compared to the counterfactual scenario 2 where full recovery is always possible. Absolute well-being losses are measured in well-being loss units (WBLU). Modified from (Sauer et al., 2023).*

These differences highlight the relevance of coping strategies, which are currently not considered in the model for flood recovery. The occurrence of multiple natural disasters has pushed the Philippines into advancing its disaster risk reduction management (DRRM). Currently, the Philippines is a recipient of grants on DRRM towards innovation, resilient cities, disaster risk finance, resilient recovery, resilient infrastructure, and resilience to climate change.

Our empirical results provide evidence that DRRM measures post-disaster are effective in containing the effects of the TC within a year. However, the results of both studies highlight the importance of considering the effect of recurrent events.

The agent-based model allows to investigate recovery dynamics, showing that the effects of recurring disasters and incomplete recovery are not additive, but that a given number of floods occurring within the recovery time of a previous one causes higher well-being and consumption losses than the same number of floods occurring with frequencies allowing full recovery in-between. The empirical approach confirms that multiple TCs aggravate impacts compared to single TCs and allows us to better understand the relevant channels.

Insights on impact channels

Extreme events can impact households or also the affected country overall through different impact channels. Below, we summarize the insights from the SLICE project for the key impact channels food security and poverty, health and (macro-)economic development impacts including impacts on economic growth.

Food security

One key impact channel through which climate-related extreme events, such as floods, droughts or tropical cyclones, can negatively affect household well-being is by damaging crops and generally agricultural production, in the worst case leading to harvest failure or deaths of livestock. This in turn can negatively affect food security, especially in countries where a large share of the population is dependent on agriculture for income or even relies on subsistence farming to feed the household.

Household level impacts

In Nigeria, the major flood of 2012 has led to harvest failure for many households. 3.6% of all surveyed households were affected by this flood alone. Looking into different levels of exposure to "wetter than usual" weather conditions in Nigeria over a period of 2007 to 2016 using the "Standardized Precipitation-Evapotranspiration Index" (SPEI) and the resulting impact on reported harvest failure, we find that exposure to "extremely wet" local weather conditions more than doubles the risk of a household to experience harvest failure (Berger, 2023).

This result is similar, albeit on a much higher level of absolute exposure, for households in high-risk regions, such as close to the main rivers (Berger, 2023). This is specifically concerning as the number of households residing in flood-prone areas in Nigeria has been growing over time with socio-economically disadvantaged households making up a large part of this group (Berger, 2023).

In Malawi, the major drought of 2015-2016 extending over a long duration also strongly affected the livelihoods of agricultural households. Analyzing household survey data for Malawi, we find that exposure to extreme drought has significantly increased the probability of a household to report food insecurity, i.e. households reporting having suffered from a situation where the household did not have enough food to feed its members (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023).

Food insecurity again can have wider implications for the health of household members, especially children as discussed in more detail in the section on "health".

In the Philippines, the negative impact of tropical cyclones on wages and agricultural salaries of food-poor households, or households whose earnings fall below the level required for basic nutritional needs, makes the support of in-kind contributions on food essential. Our results confirm a significant reduction in total food expenditure of food-poor households due to tropical cyclones, and an increase in the reliance on in-kind food support.

These results have important food security implications in terms of the reliability and the limited networks of family, friends, or government programs that this vulnerable group is able to access. In the absence of these networks, food-poor households would experience an even lower food consumption due to tropical cyclones (Schleypen, J., Plinke, C., Geiger, T., 2023).

Impacts on global food markets

The impact of systemic shocks can also have implications beyond the affected region. Also on a global level, our research identifies that shocks such as the COVID pandemic have substantially affected global food markets and related prices, and we can learn from analyzing such shocks, also with regard to climate-induced multi-breadbasket failures.

The concentration of production in few main producing regions such as the European Union, Ukraine, Russia, North America, Argentina and Brazil and resulting import dependencies of many low-income countries in Africa and Asia, renders the global food system fragile to systemic shocks from weather-induced production failures in breadbasket regions and unilateral uncoordinated policy responses such as export restrictions issued by main producing countries.

Only in the last 20 years, two major world food crises in 2007/08 and then again in 2010/11 have pushed tens of million additional people into food insecurity resulting in food riots mainly in African and Asian countries (Berazneva and Lee, 2013). There are long- and short-term drivers of these two recent world food price crises. The main long-term drivers are population growth, changing diets in emerging economies (Headey, 2011), low investments in Research and Development since the 1990s (von Braun, 2008), and an increase in biofuel production (Fraser et al., 2015; Gorter et al., 2013).

Whereas year-to-year weather variability and uncoordinated unilateral policy measures were singled out as the two main short-term drivers of these recent crises, multi-breadbasket failures – i.e. nearly simultaneous droughts affecting several major exporting countries – preceded both recent crises (Trostle et al., 2011).

Supply shortages and associated price hikes were amplified by export restrictions issued by several drought-affected main exporting countries as well as by precautionary buying of rich, import-dependent countries in an attempt to ensure domestic food security at the expense of food security in import-dependent regions such as the Horn of Africa (Challinor et al., 2018; Trostle et al., 2011).

Only recently, the Russian invasion of Ukraine has triggered sharp increases in global food prices, sparking concern that food-supply disruptions will spread globally: the Russian invasion of Ukraine. Together, Russia and Ukraine produce more than one-third of the wheat traded in international markets (FAOSTAT, 2021). Both countries grow a substantial amount of wheat on the highly fertile black earth soils of the Black Sea region.

We have developed several short-term scenarios on how the ongoing food crises could develop throughout the next trade year (TY) for wheat (July 2022—June 2023) (Fig. 13). Together, with a similar analysis for potential Covid-related food security risks (Falkendal *et al.*, 2021), this analysis provides suggestions for policymakers and other agricultural stakeholders on how systemic food security risks could be mediated, providing insights also for weather-related shocks.

Combining an analysis of the global wheat supply network (Puma *et al.*, 2015) with a global agricultural commodity price model including storage (Schewe, Otto and Frieler, 2017) allows us to consider two key metrics for food security risks.

On the one hand, *impaired supply* describes the reduction in supply resulting from production anomalies and export restrictions that countries have to cope with by either tapping into their reserves, filing additional demand requests to non-failing suppliers or, as a last resort, reducing their consumption. In essence, impaired supply provides an indication of how much the current global distribution of wheat would be changed.

On the other hand, world market (WM) price hikes impact consumers, especially the urban poor in low-income countries that have little means to insulate their domestic consumers from price volatility at world markets (e.g., costly strategic reserves).

Based on our analyses, a shock such as the war could undermine global food security to an extent comparable to the two preceding crises. Many import dependent countries in Africa and South-East Asia would be stripped off more than one quarter of their annual wheat supply and price hikes could reach the level of the 2007/08 crisis, the most severe event in recent history. The current crisis is unfolding at a time when many developing economies have not yet recovered from the COVID-19 pandemic, which financially constrains their response options.

Further, countries in the Horn of Africa such as Ethiopia and Kenya are additionally affected by a severe drought threatening the food security of 13 million people (UN, 2022). Also, Lebanon, Libya, and Tunisia – the three countries in Northern Africa that would be most severely affected by an Ukrainian export failure – already have to cope with multiple overlapping crises (CASCADES, 2022). All three are facing political instability aggravated by economic crises, while Lebanon and Libya have to handle large refugee inflows from Syria and Sub-Saharan Africa, respectively.

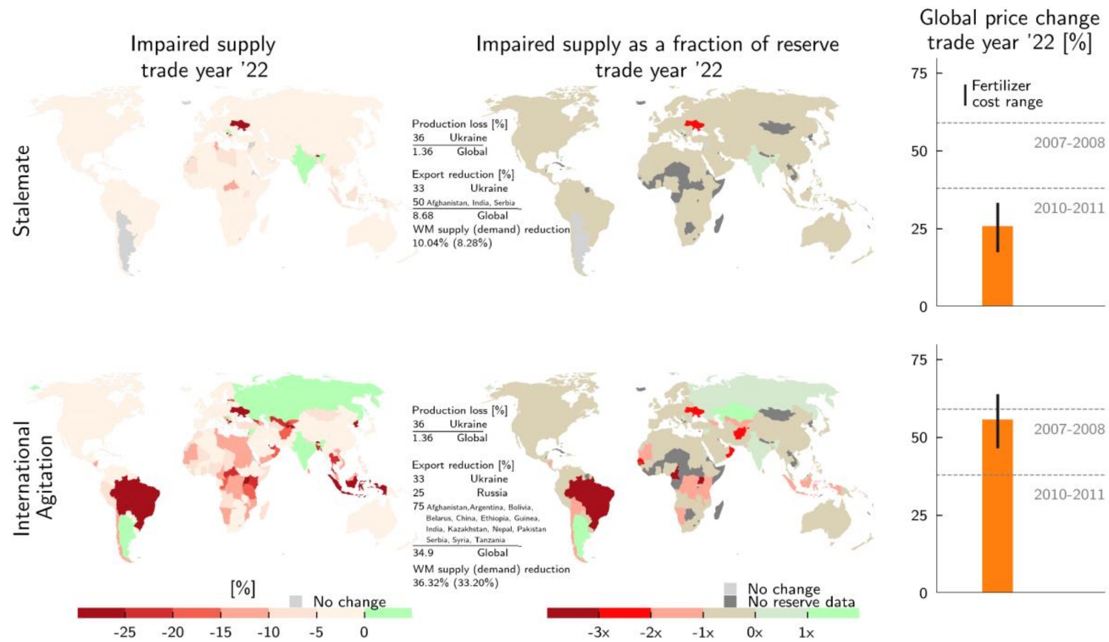

Figure 13 Food security impacts of the Russian Invasion of Ukraine. Two scenarios are considered for the international trade year for wheat (July 2022 until June 2023): Stalemate, an optimistic scenario where the regional conflict freezes and international cooperation can avoid escalating export restrictions of countries that are not directly affected by the war, and International Agitation, a less-optimistic scenario where international cooperation is not strong enough to avoid escalating export restrictions. Left: domestic impaired supply compared to baseline (left column) and to national reserves (right column). Right: estimated changes in the world market price (WM) for wheat. Black whiskers indicate price changes resulting from different fertilizer input prices (ranging between 1-3 times the current price levels). The dashed lines indicate price hikes during the 2007/08 and 2010/11 world food price crises. Courtesy (Kuhla et al., 2023).

The severity and complex multi-dimensional structure of the developing crisis require immediate and coordinated action by key food producing-countries and international institutions. Efforts must be focused on addressing both urgent humanitarian needs and the rapid, short-term structural changes in global supply and trade.

The centerpiece for humanitarian activities around food assistance is the World Food Program (WFP), which relies on financial support from donor countries. Indeed, financial need has increased dramatically not only due to the war but also in the wake of the COVID-19 pandemic.

Between 2019 and 2020 the number of people experiencing severe hunger globally increased rapidly from 650 to 758 million and the current crises could add 8-13 million in 2022 according to recent FAO estimates, with the strongest relative increases in Sub-Saharan Africa and Asia Pacific (FAO, 2022). These increases are qualitatively different from those of the 2007/08 and 2010/11 crises, which slowed the global decrease in the number of people experiencing severe hunger since 2004 but did not cause this trend to reverse globally.

Addressing the structural changes in the global food system is challenging. It is clear from our modeling that escalating export restrictions must be avoided. The key for avoiding such trade interventions is for countries to recognize that it is in their own self-interest to maintain stable global food prices (Cohen, 1998).

The costs of inaction could be especially high – both in the short term as hunger and social instability could rapidly spread – and in the long term as climate change increases in demand due to population growth and changing diets induce additional pressures on global food systems.

Poverty and distributional implications

Exposure to extreme weather events can have impacts on wealth including distributional implications pushing households into poverty or deepening existing poverty patterns.

Tropical-cyclone induced poverty dynamics in the Philippines

The effects of extreme events are disproportionately distributed to vulnerable groups such as the poor, who are already struggling with current conditions even without the presence of natural disasters. In the Philippines, we have analyzed the difference in tropical cyclone impacts on food-poor households (i.e. with earnings falling below the level required for basic nutritional needs) compared to the rest of the sample.

We find that there are impacts that only food-poor households experience, such as the reduction in wages and agricultural salaries, and the overall reduction in total food and total non-food expenditures. These additional impacts place food-poor households deeper into poverty, with slim resources for recovery (Schleypen, J., Plinke, C., Geiger, T., 2023).

Distributional long-term impacts of recurrent floods

We further employed our household resilience model (cf. Sec. “Household response to recurrent climate extremes”) to assess the poverty implications of recurrent — mostly tropical-cyclone induced floods — in the Philippines (Sauer *et al.*, 2023). We find that in absolute terms high income households perceive the largest asset damages, as they usually dispose over the largest asset stock (Fig. 14 **a**). Low-income households also experience the highest absolute consumption losses under individual disasters, while middle-income households have highest consumption losses under recurrent disasters (Fig. 14 **b**).

These dynamics can be explained by the high vulnerability of low-income households, which usually lose large parts of their asset stocks in a single disaster and have the longest recovery times (Fig. 14 **c**). Thus, individual disasters leave less asset stock that can be destroyed in subsequent disasters. In contrast, middle-income households usually manage to recover quickly from an individual flood, but multiple disasters with small recovery windows are likely to push them close to or even under the subsistence line, where recovery becomes slow and consumption losses accumulate rapidly.

Our results show that low-income households perceive the highest absolute well-being losses for both individual and recurrent disasters, as an additional drop in consumption at their already low consumption losses forces them to forgo very basic goods (Fig. 14 **d**). In general, socio-economic resilience describing the ratio of experienced asset damage to well-being loss, increases with income and is reduced by incomplete recovery (Fig. 14 **e**).

The negative net effect of incomplete recoveries is most pronounced for middle-income countries across all impact metrics except asset damages, as they recover well from individual disasters, but tend to fall below subsistence line and into poverty under recurrent floods. This underlines that development aid targeted at lifting people living just under poverty line slightly above it will be unsustainable in the face of climate change and increasing event frequencies.

Poverty implications of the 2012 flood in Nigeria

In Nigeria, our model results suggest that exposure to the major flood disaster of 2012 had multiple direct and indirect effects with impact on poverty headcount & poverty dynamics (Malafry, Otto and Piontek, 2023). Households are directly affected by the flood through asset destruction, such as damaged or destroyed housing and land improvements, livestock death, and farming equipment and durable goods' destruction.

Additionally, all households are indirectly affected by the general downturn in the aggregate economy associated with the climate disaster. We analyze both the changes in poverty and welfare-induced by asset loss, as well as the hardships imposed on the rest of the population due to diminished wages and public good provision.

Our modeling suggests there are also significant implications to indirectly affected households. The post-flood experience of households who were only at risk of transient poverty before the disaster now find themselves in a chronic spell and all the livelihood insecurities associated with such an experience. This response highlights the danger of focusing on aggregates, where a mere poverty headcount could be obscuring stark welfare implications that become apparent when intensity and duration are accounted for in post-disaster dynamics (Malafry, Otto and Piontek, 2023).

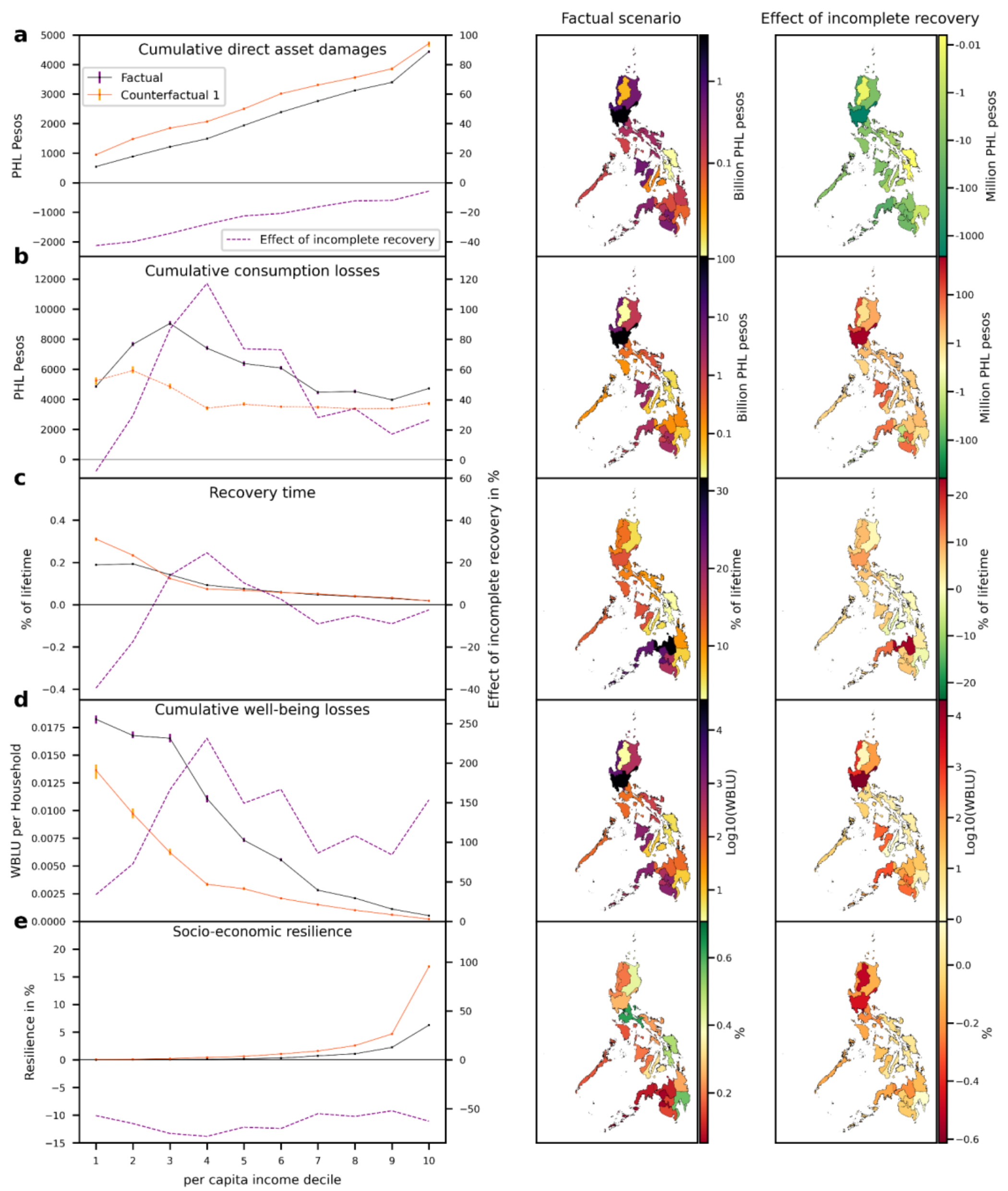

Figure 14 Distributional and regional impacts of recurrent flood shocks. Average cumulative direct asset damages (panel a), average cumulative consumption losses (panel b), average share of their lifetime flood affected households in the Philippines spend recovering their damaged assets from recurrent flood shocks as reported by the Global Flood Database (Tellman et al., 2021) over the period 2000-2018 (panel c), average cumulative well-being losses measured in well-being loss units (WBLU) (panel d) and average socio-economic resilience (panel e). Left column: National averages for each per-capita income decile of the population for the factual scenario where the same household can be affected multiple times (solid black lines) and the counterfactual scenario where each household can be affected at most once (solid orange lines). Absolute (left y-achses) and relative differences (right y-achses) between the factual and the counterfactual scenarios as they arise from incomplete recovery in between events in the factual scenario are denoted by dashed purple lines. Whiskers denote 90% uncertainty intervals as established from 25 runs with varying household selections. Middle column: Regionally differentiated variable values as obtained for factual scenario (color code). Right column: Same as middle column but for differences between factual and counterfactual scenarios. Courtesy (Sauer et al., 2023).

Health

Impacts from extreme events may for example show in changes to health expenditures to cope with the shock. For the Philippines, we find that wind damages related to Tropical Cyclones immediately reduce total income and expenditure on health. These decreases in health expenditures extend to another year if households are hit by more than one tropical cyclone in a year (Schleypen, J., Plinke, C., Geiger, T., 2023).

While food insecurity for short durations already puts households in very unpleasant situations, the implications get more severe if the health of household members is negatively affected from the exposure to extreme events. This is especially concerning for vulnerable household members such as children, as these are still in their development process and impact can have longer term implications for their development prospects.

Assessing the impacts of drought exposure on child health in Malawi for children aged up to 5 years (until their 6th birthday) living in agricultural households, we find that children that have been exposed to severe drought conditions over their lifetime have a significantly negative impact on their height-for-age (HAZ) score, which is a common metric for measuring chronic malnutrition or repeated exposure to food shortage (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023).

The negative impact on a child's HAZ increases the more months the child has been exposed to severe drought conditions over its lifetime, while already being measurable for more moderate drought intensity levels (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023). The negative impact on a child's HAZ is also increasing with drought intensity, showing even higher impacts for exposure to extreme drought conditions (Fig. 15).

These findings are specifically worrying in view of the projected water scarcity in view of climate change and population growth (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Udechukwu, S., Lange, S., 2021).

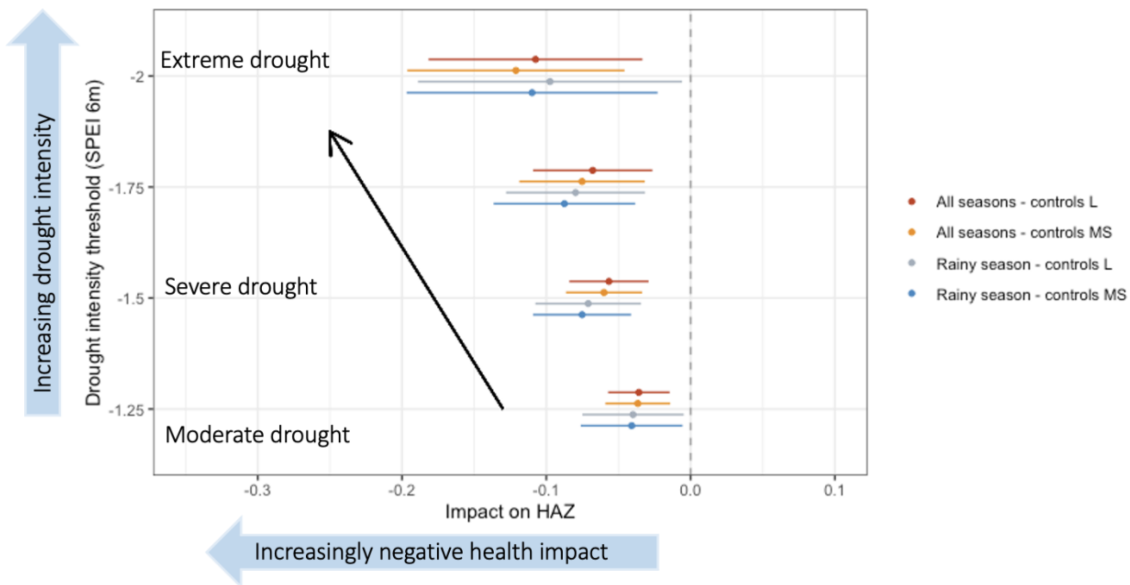

Figure 15 Negative impacts in child health increase with increasing drought intensity (Malawi). Courtesy: (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023)

We moreover identify a specific vulnerability of children in smallholder farming households in Malawi which typically engage in subsistence farming to feed their family, finding more pronounced negative health impacts for drought exposure especially for more moderate drought intensity levels (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023). Given that more moderate droughts typically get less political attention – both nationally as well as internationally in terms of aid and support measures – this finding can be considered very concerning.

We also assessed if there are longer-term impacts of drought exposure on child health (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023). We find that children that have been exposed to severe drought in their early childhood (aged 0-2 years) but not later in childhood still have a significantly lower HAZ than non-exposed children, meaning they do not fully recover even if their HAZ is measured years after their last drought exposure. The first two life years are typically considered especially critical for development of a child, determining long-term development prospects of a child.

Also for children not exposed in early childhood but exposed after the first two life years, i.e. when they are aged between two years and five years, we also find that exposure to severe drought conditions still significantly negatively affects a child's health, indicating the general vulnerability of young children to drought exposure related health impacts (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023).

The climate risk profiles for Nigeria, Malawi and the Philippines moreover identify an increasing projected exposure of the populations to heat risks, projecting heat-related mortality to increase for all three countries (Berger, J., Zimmer, A., Plinke, C., Udechukwu, S., Lange, S., 2021; Plinke, C., Schleypen, J., Lange, S., 2021; Zimmer, A., Plinke, C., Lehmann-Uschner, K., Udechukwu, S., Lange, S., 2021).

Economic development and growth

In recent years, empirical evidence has built up that extreme weather events such as floods, tropical cyclones, and droughts, do not only cause substantial direct damage but can also adversely impact economic development of the affected countries in the years after an event. These indirect economic losses can accumulate over more than a decade and the associated monetary losses can be much higher than the direct asset losses caused by the event.

Further, growth losses increase disproportionately with disaster intensity. In our study, we find that growth losses from severe tropical cyclones and fluvial floods accumulate to 6.5% and 5.0% over 15 years (Krichene *et al.*, 2021). The ongoing intensification of extreme weather events in frequency and intensity under global warming, may therefore substantially reduce the development prospects of disaster-prone developing countries.

There has been the narrative that economic development may always help to protect against natural disasters. We find that this does not hold true for tropical cyclones where the vulnerabilities of all development groups of affected countries (as classified by the inequality weighted human development indices) are similar. In contrast, we find that development may help protect against fluvial floods.

We systematically study the economic and non-economic transmission channels through which these events impact economic growth in the long-run. We find that mainly economic growth determinants act as transmission channels while non-economic determinants play only a minor role. Aggregate consumption (household consumption and government expenditure) fosters economic growth in the aftermath of tropical cyclones and fluvial floods (Krichene *et al.*, 2021).

Therefore, we may conclude that policies raising government spending in the aftermath of tropical cyclones and fluvial floods to stimulate private consumption can contribute to mitigating the adverse impacts on economic growth.

Furthermore, our findings suggest that investment generally amplifies growth losses, except for developing countries, in the aftermath of tropical cyclones. This — rather surprising — finding may be explained by the increase of public investment to finance disaster relief measures such as the reconstruction of destroyed infrastructure. These investments might crowd out productive private investment and increase public debt to unsustainable levels (Marto, Papageorgiou and Klyuev, 2018).

Coping strategies and factors affecting resilience and adaptation

Households or also countries affected by climate extremes may choose different strategies to cope with the impacts when affected or to adapt to anticipated climate events in advance. They may also exhibit different characteristics that make them more resilient or less resilient to impacts and improve chances of or speed of recovery. Below, we summarize the insights from the SLICE project for the different factors fostering or hindering resilience as well as the strategies to cope with or adapt to climate extremes.

Wealth

The SLICE project also investigated whether the level of wealth influences the resilience against impacts from extreme events, e.g. by allowing different coping strategies. This was analyzed on the macro-level, i.e. the economic development and income level of countries, as well as on the micro-level, i.e. the income and wealth level of households affected by extreme events.

On the **macroeconomic level**, we implemented a country-specific regression framework to assess how the observed impacts depend on the countries' development level. We find empirical evidence that a higher economic development level can help to prevent losses in economic growth caused by fluvial floods (Krichene *et al.*, 2021). However, for tropical cyclones we find that development *cannot* protect against economic growth losses from exposure (Krichene *et al.*, 2021).

On the **household level,** we have studied the factors affecting resilience and coping for different countries and extreme event types. For floods in Nigeria, we find that income risk, asset poverty and proximity to credit constraints determines the propensity of a household to suffer chronic poverty spells after flood impacts (Malafry, Otto and Piontek, 2023). Moreover, households in Nigeria with relatively low assets and poor income prospects are also vulnerable to increased poverty risk even if not directly affected by asset loss from the flood, due to the general downturn in the flood-stricken economy (Malafry, Otto and Piontek, 2023).

Our study on Philippine households (Schleypen, J., Plinke, C., Geiger, T., 2023) provides an important addition in our empirical model to existing scientific methodologies by acknowledging the heterogeneity of tropical cyclones impacts in terms of co-hazards (i.e., wind speed and extreme precipitation) and the additional effect of tropical cyclones frequency (i.e., multiple tropical cyclone occurrences in a year).

Our results suggest that i) the sudden outpour of rainfall during a tropical cyclone, which increases the risk of flooding, and ii) the recurrence of tropical cyclones, which limit recovery periods, have varying impacts on the different expenditures (i.e., particularly on health and education) and income categories (i.e., income from livestock, poultry, and construction sectors).

Moreover, we find that specific impacts are only experienced by food-poor households, thereby making it more difficult for this vulnerable group to recover back to pre-disaster conditions (Schleypen, J., Plinke, C., Geiger, T., 2023). For droughts in Malawi, we find lower negative impacts of exposure to severe drought on child health for children in households which possess a more advanced type of toilet facility - which is an indicator for a higher wealth level of the household (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023).

We find that the health of children in small-holder farming households in Malawi is more strongly negatively impacted when exposed to drought compared to non-smallholder farming households in case of moderate drought (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023). This implies that smallholder farming households that typically do subsistence farming for own-consumption may be less in the position to build up an economic “buffer” to deal with harvest decreases related to already moderate drought levels.

In the Philippines, we find that income is reduced for all households, however, total expenditures are only significantly reduced for food-poor households. While this may suggest evidence of consumption-smoothing in response to a reduction in income, we find that households, in general, tend to reallocate their total budget – an increase in the expenditure needed to rebuild their homes comes at the expense of human investments such as expenditures in health and education.

Furthermore, the food-poor households who already have very limited assets – both productive fixed assets and liquid assets – tend to rely on in-kind support for food. Even with this support, our study still finds a significant reduction in food-poor expenses in both total food and total non-food spending (Schleypen, J., Plinke, C., Geiger, T., 2023).

A commonly reported coping strategy to respond to exposure to drought shocks in Malawi is *relying on own sa*vings (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023). However, this requires that the household has a sufficiently high income or wealth level to build up savings for “hard times”, which is not the case for many very poor households. Households with lower wealth levels and limited possibilities to rely on savings can be expected to be more likely to have to revert to coping strategies relying more on external support or affecting their own basic needs (such as changing eating patterns).

Another commonly reported coping strategy for households in Nigeria and Malawi exposed to floods and droughts is to get support from relatives or friends. However, also this requires a certain level of economic wealth of the relatives or friends to be able to economically support others.

With an increasing frequency of extreme events as well as an increasing intensity of extreme events, this ability to support other households may also erode. In case none of these strategies are available or feasible, households in Nigeria frequently sell their livestock, which can be seen as a measure of last resort, since this livestock constitutes the livelihood of many agricultural households.

Education

We also find empirical evidence that education can increase the resilience against extreme events. For floods in Nigeria, we find that education functions as a resilience strategy against floods both by enabling households to shift from agriculture into other economic sectors and by facilitating an informed choice of residence towards safer regions of the country (Berger, 2023).

Households might be better able to adapt to changing conditions, such as by planting more climate-resilient crops (Berger, 2023). Extreme events can directly interfere in this development of resilience, however, by forcing households to take children out of school, eliminating their ability to get a good education.

For droughts in Malawi we find that the negative impact on child health for children exposed to severe drought conditions is lower for children with mothers with a higher education level or generally higher education level in the household when looking into a subsample of children, however, we do not find a significant impact of education in the full sample (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023).

Recovery assistance programs and international aid

Due to the number of Tropical Cyclones that frequent the Philippines, there are already a number of plans, policies, and programs that support disaster reduction and relief, as well as those directed towards poverty alleviation even without the occurrence of disasters. The results drawn from Philippine households suggest that food security in the aftermath of a tropical cyclone is aided by financial support from abroad (via remittances), as well as in-kind donations, particularly for food-poor households who suffer from a loss in already very low income. These measures rely on government provisions of disaster relief, as well as the households' own networks.

Despite these measures, we still find reductions in health and educational spending, which, we find, is consistent with local norms and realities (Lasco, Yu and David, 2022). For instance, due to the lack of coverage by health insurances, Filipinos tend to wait until their conditions are unbearable before seeking formal medical attention. Similarly, the incentive to strengthen education is lowered by interruptions such as the use of schools as evacuation centers, as well as the motivation of students given multiple disruptions and the resulting performances.

These observations suggest that the external assistance received from the households' networks is generally not allocated to expenditures on human investments, not only because of the limited availability, but also because of household preference and motivation (Schleypen, J., Plinke, C., Geiger, T., 2023).

In the case of the major flood event that happened in Nigeria in 2012, we have examined scenarios that involve the delivery of international aid. From the literature, we are able to identify what an average "aid surge" might be, both in terms of size and duration. Using this we examine the different ways in which this aid can be used – either given directly to the government to help with its public goods and services provision, or directly to the flood-affected households.

In the latter instance, direct aid greatly reduces the disaster's impact on poverty amongst those directly affected by the flood. This works to actually reduce the headcount of poverty, as the aid delivered is sufficient to raise poor households' consumption above the poverty line. However, this relief only lasts as long as the aid surge's duration (Malafry, Otto and Piontek, 2023).

While relying on own savings and receiving help from family and friends are the most commonly reported active coping strategies by Malawian households in response to being affected by a drought shock, receiving unconditional help from the government or NGOs as reported coping strategies for drought exposure are reported less frequently by households in Malawi (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023).

Climate risk insurance

Global warming is likely to increase the proportion of intense hurricanes in the North Atlantic (Knutson *et al.*, 2020). Our aim was to understand how strongly this may reduce economic growth of the United States of America (US) as a major tropical-cyclone prone economy and of Haiti as a strongly affected Small Island Developing State, and whether better insurance can compensate for these climate change-induced increases in growth losses.

To this end, we employ a novel event-based growth model to first estimate growth losses in a 35-years historical period 1980—2014 before estimating the increase in growth losses in a world that has warmed on average by +2°C compared to preindustrial levels and a world that has warmed on average by +2.7°C which corresponds to the median estimated warming level under currently implemented and enacted emission pledges of the countries (CAT, 2021).

There is substantial uncertainty on how hurricane climatology will change with global warming, and the magnitude of the effect strongly depends on the underlying methodology used to estimate this change (Knutson *et al.*, 2020). To account for these uncertainties, we use two loss estimates, one based on changes in the storms' wind-fields and the other based on changes in hurricane storm surge.

For the US, we estimate that hurricanes have induced growth losses of 0.024% in the historical period. Under global warming, we find a moderate increase of growth losses by 10% (for 2°C as well as 2.7°C) compared to the historical standard scenario for the wind field-based estimate but a strong increase by 146% (2.7°C: 522%) for the storm surge-based estimate.

We then test the efficiency of a compulsory non-profit hurricane insurance financed by a flat fee on all citizens, regardless of their individual risk (Kousky, 2019). This insurance scheme represents a precautionary savings mechanism where premiums accumulated in normal times are issued to affected households in the disaster aftermath. The discussed insurance scheme resembles tax financed and non-profit public insurance schemes already implemented in the US today such as United States National Flood Insurance Program (NFIP) managed by the Federal Emergency Management Agency (Michel-Kerjan, 2010), the Florida Hurricane Catastrophe Fund (FHCF), or the California Earthquake Authority (see (OECD, 2021) for a detailed review on catastrophe insurance programs in Organization for Economic Co-operation and Development countries).

However, since here we are interested in finding the upper limit for the share of climate-change induced losses that insurance can compensate for, the discussed insurance scheme is in two aspects more comprehensive than these existing insurance schemes: first, by assuming that all assets are insurable against hurricane risks, we exclude potential issues regarding the uninsurability of losses, e.g. in particularly disaster-prone locations. Second, by considering insurance to be compulsory, we exclude issues of limited insurance uptake by the population.

For the US, we find that to compensate for the additional global warming-induced growth losses, the historical insurance coverage of 50% would have to be substantially raised to 84% (2.7°C: 99%) according to the surge-based estimate, whereas a moderate increase to 58% for 2°C as well as 2.7°C would suffice according to the wind field-based estimate for the standard scenario (cf. columns 2 and 6 with columns 3 and 7 (2.7°C: 5 and 9) in the upper panel of Fig. 16).

The hurricane-induced growth losses for Haiti in the present climate are already one magnitude larger than those of the US (0.24%). One reason is that Haiti's disaster insurance market is much less developed and nearly all of the past hurricane losses were not insured (NatCatSERVICE, 2014). Further, already in the present climate Haiti is affected so strongly that even in the idealistic limit of full insurance coverage, it would still suffer growth losses comparable in magnitude to those of the US today (cf. upper with lower panel of Fig. 16), and hurricane impacts are projected to further aggravate for Haiti under continued climate change, at least according to the more pessimistic storm surge-based damage projection.

While our estimates on how climate change may impact on economic losses caused by hurricanes are subject to several sources of uncertainty, they nonetheless show that the mitigating effect of increased insurance coverage is of the same order of magnitude as the climate change-induced loss increase.

Though insurance premiums may increase under global warming by up to a factor of four, they likely will remain affordable for US consumers. This suggests that insurance can be a major building block of future climate change adaptation strategies, at least in developed countries. For developing countries the hurdles to adapt to climate change are much higher since they are often more strongly affected by — and more vulnerable to — climate change impacts and lack the financial means and strong institutions to implement comprehensive climate adaptation measures (Hallegatte *et al.*, 2016). To this end, our results stress the importance — for developing and developed countries alike — to complement insurance solutions with other measures to build resilience to extreme weather events such as investments into better housing standards and resilient infrastructure (Hallegatte, Rentschler and Walsh, 2018) or coping strategies such as managed retreat (Carey, 2020) in a risk-layering approach (Martinez-Diaz, Sidner and McClamrock, 2019). However, in contrast to rich developed countries of the Global North, strongly affected developing countries will be only able to successfully adapt to climate change impacts when national and international mechanisms and institutions providing concessional climate finance and expertise in climate adaptation such as the United Nations' Green Climate Fund are further strengthened by ensuring that they have both, the financial resources and the effective government, to fulfill their mandates.

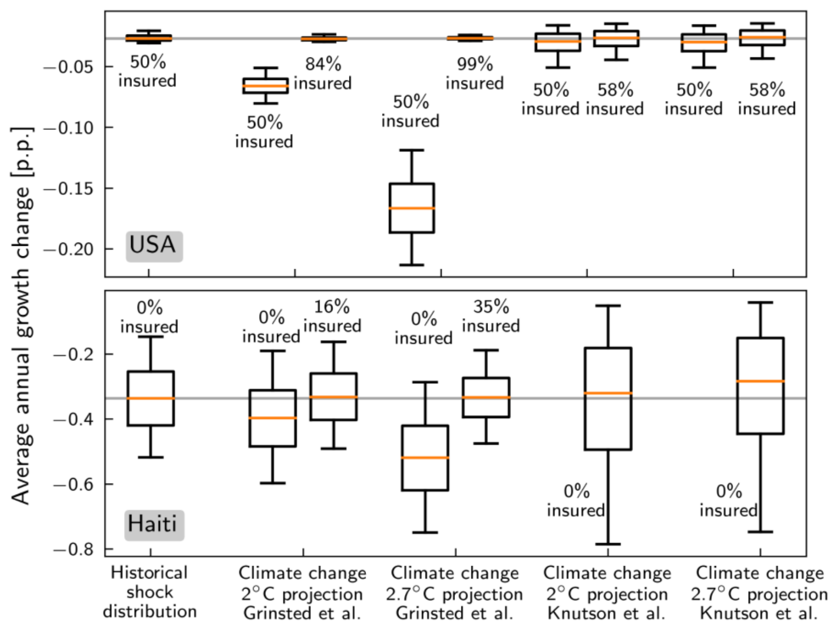

Figure 16 Projected impacts of hurricanes on economic growth in 2°C and 2.7°C worlds and the effectiveness of insurance as coping strategy for the US (upper panel) and Haiti (lower panel). Annual growth losses (relative to the corresponding unperturbed economies evolving on the balanced growth paths) as obtained for the historical shock distribution (0% insurance coverage, period 1980—2014; 1st column), for Paris-compatible +2°C warming above pre-industrial levels (2nd, 3rd, 6th, 7th column) and +2.7°C (4th, 5th, 8th, 9th column) climate change projections of growth losses are derived from two different methods to estimate climate change-induced changes in hurricane climatology by (Grinsted, Moore and Jevrejeva, 2013) and (Knutson et al., 2013). Growth losses are shown for insurance coverage in the historical period (2nd and 4th column). Additionally, for both estimates and warming levels, the insurance coverages that would be necessary to reduce growth losses to the historical level are shown (3rd, 5th, 7th, and 9th column). Orange lines, boxes, and whiskers indicate median loss estimates as well as the 25th—75th and 5th—95th percentile ranges, respectively. Courtesy (Otto et al., 2023).

Methodological advancements under SLICE

In the SLICE project we made substantial progress towards a better understanding of processes that determine climate short- and long-term impacts on society. Our work contributes relevant advances at several dimensions:

- the understanding of the channels through which climate variability and change impact on socio-economic development
- the understanding of the poverty implications of recurrent extreme weather events with overlapping socio-economic repercussions (recurrent events)
- Attribution of climate impacts
- Comprehensive impact assessment accounting for well-being and consumption losses in addition to asset losses
- Event-based temperature damage functions suited for integrated assessments weighing the costs of climate change (e.g., the Social Cost of Carbon) with the costs of climate mitigation measures

Process-based impact research must be based on reliable biophysical hazard indicators. In this context, the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP, www.isimip.org) provides impact model simulations that are comparable across sectors and time and permits to move impact modeling from the use of climate indicators (e.g. rainfall) to more explicit hazard indicators (e.g. flooded areas) that are more closely linked to impact formation.

In particular, this allowed us to disentangle the drivers of changes in past flood damage trends, by overlaying annual flooded areas derived from hydrological simulations forced by observational weather data (Jongman *et al.*, 2015; Tanoue, Hirabayashi and Ikeuchi, 2016) with annual global asset distributions. We are able for the first time to separate and quantify the contributions of climate from socio-economic drivers, by means of restricted models accounting only for observed changes in climate, while keeping socio-economic drivers such as river engineering, exposure and vulnerability levels at fixed levels (Sauer *et al.*, 2021).

Furthermore, we could improve our process understanding by disentangling the impacts of co-hazards like wind-speed and extreme precipitation during TC-events. The empirical analysis on the impacts of TCs on Philippine households provides empirical evidence in support of the inclusion of TC co-hazards (e.g.., extreme precipitation and vulnerability (i.e., locally-informed damage thresholds on wind speed and an analysis on food poor households). The research article (Schleypen, J., Plinke, C., Geiger, T., 2023) provides a novel methodological approach to incorporate these complexities, which resulted in impact estimates that disentangle the effects of each of the hazards, thereby providing more guidance for policy initiatives.

The main advancement of the Nigeria study on flooding is the direct link of weather anomalies with household survey data. While it usually has to be inferred from weather data whether a certain region or household was hit by an extreme event, quantifying the risk of actually being affected by the event according to the household facilitates a better understanding of climate impacts (Berger, 2023).

The development of an agent-based household model that allows us to simulate short- and long-term impacts of recurrent events provides critical insights into the recovery dynamics shaped under recurrent events. In particular, the development of counterfactuals that allowed us to compare impacts under full and under incomplete recovery is a novel contribution to the process-understanding in the field of recurrent extreme weather events (Sauer *et al.*, 2023). The flexibility of the model-set up is suitable to be easily extended for the investigation of both individual and national adaptation and coping efforts.

A notable advancement for the improvement of modeling approaches achieved within SLICE is the development of novel country-level temperature damage function for a large set of 41 tropical-cyclone affected countries that account for the persistence of damages in the economic system (Krichene *et al.*, 2022). These damage functions are of great interest for climate integrated assessment analysis (IAMs), weighing the costs of climate change (social cost of carbon) with the costs of mitigation efforts.

Standard monetary impact indicators often fall short to inform about impacts on basic services or the achievement and monitoring of the development goals.

In this context, the SLICE project encompasses a number of studies which provide impact metrics beyond initial asset damage, addressing e.g. food security, health and education. For the Philippines we were able to gain insights into the income effects caused by tropical cyclones, and the resulting responses of households in terms of expenditure patterns. In particular, we could resolve expenditure changes in the categories including among others education, health, food and housing.

Similarly, we differentiated between income losses by source of income (e.g., agricultural and non-agricultural income and wages) and type of recipient (i.e., food-poor or non-food-poor households). We have aimed to draw our empirical model closer to vulnerabilities locally, by adjusting the thresholds used in our wind index to capture damages incurred even at lower wind speeds, thereby representing the presence of weaker structures in communities (Schleypen, J., Plinke, C., Geiger, T., 2023).

For Malawi, we identified a special vulnerability of smallholder farming households with their children being more strongly affected in their health by exposure to drought compared to non-smallholder farming households (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023). While the applied econometric methodology of using interaction terms is well established, the vulnerability of smallholder farmers to droughts remains hidden in standard regression approaches (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023).

Likewise, by differentiating by age of exposure to drought, we identified a long-term effect of drought exposure on child health years after the exposure if a child was exposed in its first two life years (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023).

Lessons learnt

The SLICE project brings together empirical and model-based approaches. Each of them comes with drawbacks, advantages, limitations and challenges, which we briefly summarize in this section. Challenges faced during empirical work are mostly related to available data and their interpretation. In general, comprehensive and structured panel data would be the most suitable to assess long-term impacts on households.

These data sets are however rarely available, limiting the opportunities for this type of analysis to few countries, mostly developed countries. Even if household panel surveys are available for developing countries, as in the case of our focus countries Malawi, and Nigeria, the quality and lengths of the panel data is typically challenging, with i) very small sample size for panel data waves (Malawi), ii) panel attrition, households splitting and "sample refreshing" between waves leading to different households being surveyed over time (e.g. for Nigeria) limiting the usefulness of panel data, iii) surveyed information is partly inconsistent between panel waves, with survey questions changing between waves or modules being added or abandoned (Nigeria and Malawi), iv) there is contradicting household information across survey periods or also within survey waves (Nigeria, partly also Malawi) and v) surveyed data often only containing information on the last 12 months prior to the interview while the panel waves are 3 years apart. Available household surveys are moreover not tailored to the specific research question, lacking key information.

Additionally, we note that households are typically subject to several shocks including extreme events over time, so they may have additionally been exposed to extreme events prior to survey periods but information is not available. Therefore, the impacts of specific shocks are often difficult to disentangle. All in all, these difficulties make the empirical assessment of long-term impacts very challenging.

Model approaches aim to bridge the gaps of observational data and allow to include and exclude drivers of interest. At the same time, model validation is critical for the interpretation of model results, but difficult to achieve due to the lack of observational data. Especially, the validation of models used to assess the long-term effects of climate impacts is constrained by the lack of empirical understanding. For short-term impacts, such as asset damages, the global disaster databases NatCatSERVICE (NatCatSERVICE, 2014) and EM-DAT (EM-DAT 2020) are starting points for impact model validation, but still damage records are far from being complete, especially in early years of recording. Additionally, damage validation on a spatially explicit level is challenging, as the exact disaster locations are difficult to trace back.

A major challenge for the modeling of direct impacts poses the derivation of extreme events from physical indicators, as these are often threshold dependent. In the case of floods, these thresholds are basically defined by implemented protection standards, which need to be exceeded for flood formation. These protection standards are only known for a small number of provinces, while for the rest of the world these levels are estimated from policy standards or modeled in dependence of GDP per capita (Scussolini *et al.*, 2016).

Similarly, deriving droughts from physical indicators is challenging and thresholds for indicators such as the Standardized Precipitation-Evapotranspiration Index (SPEI) can be sensitive to definitions or outliers if available time series for historic weather data are short.

Many of our studies are based on spatially-explicit hazard indicators derived from impact models participating in the second simulation round of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP, www.isimip.org). Despite the large efforts of model intercomparison projects such as ISIMIP to make impact model simulations comparable across sectors and time, it remains challenging to generate continuous time series of impact indicators (e.g., flooded areas) for an extended historical period that span into the future.

The reason is that for the historical period, the impact models are driven by observed weather data while they are driven by global climate models for the future period. These differences require a model bias-correction that ensures an adequate representation of extremes in the projections. Therefore, a sophisticated bias correction is required for each impact indicator and each considered country or region. The best way to perform such a correction may differ between impact indicators and may depend upon the study design (e.g., it is better to correct flooded areas or flood affected people).

Insights for policy making and outlook

An increasing number of climate impact studies and climate impact economics studies stress the importance of comprehensively accounting for the impacts of extreme weather events when assessing the impact of climate change on societies and economies. Especially understanding and quantifying the short- and long-term impacts of extreme weather events is of utmost importance, which was a key objective of the SLICE project.

The results of the SLICE project add to our growing understanding on i) how the impacts of extreme weather events have been driven in the past and are changing under global warming and ii) on the economic and non-economic impact channel through which these events impact societies and economies as well as iii) analyzing coping strategies and factors affecting resilience and adaptation.

Beyond relevant contributions to the scientific literature, the insights from the SLICE project also contribute to several broader important policy debates relevant both on the international level for climate negotiations as well as on the local level informing policy makers how to act. These policy debates include the achievement of the Sustainable Development Goals (SDGs), the debate around Loss and Damage (L&D) and related equity questions as well as the critical role of adaptation and the limits to adapting to a changing climate.

The findings from the SLICE project moreover highlight the need for urgent action against climate change, underlining the importance of the "critical decade" ahead of us requiring strongly intensified mitigation efforts for avoiding the most severe impacts of climate change, as highlighted by the recent Sixth Assessment Report of the IPCC.

Insights relevant for the Sustainable Development Goals (SDGs)

We find that extreme weather events can have long-lasting adverse impacts on societies and economies. While developing countries are least responsible for historic emissions causing climate change, they often bear the highest costs due to climate impacts.

Quantifying this cost and assessing the changes in frequency and intensity of extreme events can identify at-risk groups and improve targeted policy intervention for the ones most in need. Our estimates show that, even when not accounting for population growth, globally 33 million additional people (26%) could be exposed to tropical cyclones in a +2°C world compared to the present climate (+26%) (Geiger *et al.*, 2021).

Our analyses for the Philippines (Schleypen, J., Plinke, C., Geiger, T., 2023) show that tropical cyclone impacts affect the poorer population disproportionately through affecting wage earnings and particularly agricultural salaries, having direct implications for SDG1 (no poverty) and SDG10 (reduced inequality), as well as through food-expenditure reductions affecting SDG2 (zero hunger). Moreover, while absolute well-being losses are largest for poor households in the Philippines, middle-income households also struggle with recovering from recurrent climate extremes, experiencing the largest relative losses in well-being (Sauer *et al.*, 2023).

Accounting for tropical cyclone impacts significantly increases the social cost of carbon (SCC) for major emitters which are also prone to tropical cyclones (Krichene *et al.*, 2022), highlighting the benefit of ambitious climate change mitigation policies linked to SDG13 (climate action). For floods, the increasing global exposure, which is undermining progress related to reducing vulnerability, is leading to increasing economic damages (Sauer *et al.*, 2021).

The negative impact on economic growth due to extreme events such as tropical cyclones or floods can persist for more than a decade with growth losses from severe tropical cyclones and fluvial floods accumulating to 6.5% and 5.0% of GDP over 15 years (Krichene *et al.*, 2021), implying severe long-term implications for SDG8 (economic growth) especially affecting development prospects of disaster prone developing countries.

The climate risks profiles from the SLICE project moreover identify water availability and water scarcity issues as a serious concern under climate change for the focus countries Malawi as well as Nigeria and also for the Philippines when accounting for projected population developments, which has direct implications for SDG6 (clean water and sanitation).

Also heat stress is identified as a growing risk under climate change for the SLICE focus countries, having direct implications for SDG3 (good health and wellbeing). While modeling uncertainty remains large and impacts are complex, it is evident that exposure to heat extremes, drought, heavy precipitation events and floods can also impact the agricultural sector and food production, directly affecting SDG2 (zero hunger) and also potentially SDG3 (health). This is confirmed by our analysis for Malawi (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023) finding empirical evidence that drought exposure increases the risk of household food insecurity (SDG2 zero hunger) and leads to negative health impacts on children (SDG3 good health and wellbeing), with children living in smallholder farming households being especially vulnerable already at moderate drought intensities (SDG10 reduced inequality).

Our finding that children affected in their early childhood still exhibit negative impacts years after exposure highlights potential long-term implications for their development. Likewise, in Nigeria, exposure to flooding is more than doubling the risk of harvest failure (Berger, 2023), indicating implications for SDG2 (zero hunger). In both Nigeria and Malawi, already today the share of children being stunted, a measure from chronic undernutrition, as well as child mortality rates are among the highest in the world, thus climate change will further increase the challenge to make progress on SDG3 (health).

Our analysis also shows that the global food system is susceptible to systemic shocks from weather- induced production failures or conflicts (Falkendal *et al.*, 2021; Kuhla *et al.*, 2023), with implications for SDG2 (zero hunger) even for (importing) countries not directly affected by the extreme event, calling for the strengthening of international institutions (SDG16 on peace justice and strong institutions).

The identified direct and indirect effects such as the consequences of child health, poverty, inequality or reduced economic growth accumulate over many years and may therefore substantially exceed the directly measurable damages caused by extreme events e.g. in the form of asset destruction.

Our findings highlight the importance of developing effective coping strategies to mitigate undermining progress for the different SDGs. Our research identifies that making progress on SDG4 (quality education) can contribute to improving the resilience of households (Berger, 2023; Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023). On the other hand, taking children out of school is also a reported coping strategy in the household survey for Nigeria for dealing with shocks to the household, which would undermine progress for SDG4.

For Malawi, the most common reported coping strategy is relying on savings (Zimmer, A., Plinke, C., Lehmann-Uschner, K., Lange, S., 2023), which can lead to the risk of pushing households into poverty when savings are exploited (SDG1, end poverty). As an immediate solution to a loss in income due to tropical cyclones, households in the Philippines reallocate their budget in favor of housing repairs over health and educational expenditures (Schleypen, J., Plinke, C., Geiger, T., 2023), with implications for SDG3 and SDG4.

Within SLICE, we also assessed the role of national climate risk insurance schemes. We find that better national insurance schemes may allow for an effective mitigation of projected increases in losses due to an intensification of extreme weather events, at least in developed countries such as the US and when the warming can be kept within the Paris limits (Otto *et al.*, 2023).

However, strongly exposed developing countries will likely have to rely on efficient international climate finance instruments to cope with extreme weather events. Beyond the need to develop effective coping strategies, the findings also highlight the importance of developing effective adaptation strategies.

Importance of adaptation, limits to adaptation and implications for Loss and Damage (L&D)

Disaster reduction efforts, while streamlined with development policies and programs (e.g., Pantawid Pamilya Program in the Philippines), need to adapt to both the sources of vulnerabilities in strengthening adaptive capacity, as well as, the new challenges stemming from climate change (Schleypen, J., Plinke, C., Geiger, T., 2023). Moreover, adaptation and coping strategies need to be tailored to meet challenges posed by multiple events (Sauer *et al.*, 2023).

While the implementation of effective national insurance schemes can be one way of adapting to increasing climate risks, there are limits to what adaptation can achieve and prevent. For strongly exposed Small Island Developing States such as Haiti, it will be crucial that national and international mechanisms and institutions will be strengthened and that climate finance is provided (Otto *et al.*, 2023).

Richer countries typically have better capacity and financial resources to implement effective adaptation measures, either in terms of physical infrastructure (e.g. dikes) or in terms of institutions. Developing countries in contrast lack the financial resources and institutional capacities while at the same time they are projected to be particularly affected by climate impacts without having contributed much to global emissions.

Extreme events such as the recent major flood in Pakistan or the unusually persistent and destructive tropical cyclone “Freddy” affecting Mozambique and Malawi, costing lives and destroying many livelihoods, raise the question of who should bear the costs for the damages or the costs for implementing effective adaptation measures to prevent damages.

The work of the SLICE project made a contribution to quantifying the impacts from climate extremes, though further work is needed to estimate the damages. The science on climate change attribution may support proving a basis for evidence in how far specific climate events can be attributed to man-made climate change. However, many questions remain to be settled, especially around raising the required financial means for supporting affected countries to deal with the suffered losses and damages.

It remains to be seen to what extent the new Loss and Damage (L&D) fund, established at the international climate negotiations COP27 in Egypt at the end of 2022, will fill the current gap. While the fund and funding arrangements were officially established with the decision, its operational design remains to be worked out by a Transitional Committee.

The Transitional Committee has met 27-29 March 2023, three more meetings are scheduled for this year, and recommendations on the elements of the funding arrangements and design for the fund are expected by the end of 2023. However, as geopolitical tensions around the question of vulnerability and hence eligibility for receiving financial support, as well as sources of finance persist, outcomes are hard to predict and remain subject to political debate.

So far, conversations among Transitional Committee members indicate that attribution science may come to play a role in estimating the share of reconstructions costs that can be traced back to anthropogenic climate change.[1]

Highlighting the role of the "critical decade"

The projected increase in hazard intensities and frequencies as well as the insights on the high economic and non-economic costs resulting from climate change impacts clearly highlight the need for urgent action.

The IPCC's Sixth Assessment Report has reiterated the urgency of climate action, highlighting a closing time window for preventing the worst, with the current decade playing a critical role where major efforts to reduce emissions need to happen. Our findings in SLICE further underline this finding.

The Social Costs of Carbon (SCC) are typically strongly underestimated, as damages from extreme events such as tropical cyclones are typically not included, with SCC rising by up to 39.8% for Japan when accounting for tropical cyclone impacts (Krichene *et al.*, 2022).

More ambitious mitigation measures limiting global warming to 2°C by end of the century could spare 1.8 billion people, cumulatively until 2100, from being exposed to tropical cyclones

[1] Recordings of the meetings are publicly available (day 1, day 2, day 3).

globally compared to a less ambitious mitigation scenario reaching 2°C mean temperature increase already by mid-century (Geiger *et al.*, 2021).

Conclusions and outlook

Much research remains to be done to obtain a comprehensive understanding of the impacts of extreme weather events on the household level as well as on the macroeconomic level and indirect socio-economic impacts. Our empirical analyses have demonstrated the advantage of using indicators describing the impact of extreme events on natural and human systems indicators based on meteorological variables such as rainfall intensities or temperature variabilities only.

The reason is that the impact indicators allow for a better description of the processes which eventually lead to the impact, e.g., the area flooded by heavy precipitation is often a better indicator for the damages to houses and fields than the amount of rainfall. In this way, impact indicators allow building on the modeling expertise in the different impact modeling communities.

In recent years, harmonized multi-model impact simulations have become available through large-scale model intercomparison project such as the Inter-Sectoral Impact-Model Intercomparison Project (ISIMIP) and databases for the derived impact indicators such as the Climate Impact Explorer.[2] These efforts are key to broadening the use of impact indicators for empirical analysis in the future.

Further, our model-based analyses stress the advantage of event-based approaches. Resolving the response of the studied (socio-)economic system to individual events, with these models the effects of incomplete recoveries in between recurrent events can be understood which would remain hidden by more aggregated modeling approaches.

Further, agent-based modeling approaches as chosen for the assessment of the poverty effects of recurrent floods in the Philippines allow to account for the heterogeneity of households with regard to income, exposure, social networks etc. Capturing these heterogeneities is key to understanding differences in the households' recovery dynamics. Due to their granularity, these models allow for a detailed calibration with household survey data.

[2] https://climate-impact-explorer.climateanalytics.org

However, such detailed data are not always available and often not harmonized across countries or regions. Ideally (long-term) panel data would be needed to not only calibrate the household characteristics at a certain point in time but to also constrain their recovery dynamics by survey data.

In an ongoing effort such harmonized panel data are currently collected for many developing countries and will allow for more detailed empirical as well as model-based analyses on the recovery dynamics of households in the aftermath of climate shocks. These studies will allow to develop tailored and evidence-based coping and adaptation strategies providing critical information and decision support for the development of National Adaptation Plans.

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Technical Appendix

UNDERSTANDING THE SHORT AND LONG-TERM IMPACTS OF CLIMATE EXTREMES

Global simulations of fluvial floods based on the ISIMIP2 ensemble of global hydrological models

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1 General overview

The WP1 of the project Short- and Long-Term Impacts of Climate Extremes (SLICE) entails the provision of historical data and future projections of key hazard risk indicators for all project-relevant climate hazards in close collaboration with the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (Short- and Long-Term Impacts of Climate Extremes (SLICE), 2019). In particular, the flood hazard indicators are of special interest for scientists and stakeholders and were applied in several risk assessments. Here, we give an overview on the underlying method used to derive the flood risk indicators provided under ISIMIP2 DerivedOutput.

This document describes the methodology applied to generate the spatially explicit flood-depth and flooded areas provided by ISIMIP (simulation round 2). The data set includes:

I) historical simulations of annual river flood maxima (river discharge, flooded areas, flood depth), covering the time period 1971-2010, based on the input of climate reanalysis datasets (simulation round 2a).

II) future projections of annual river flood maxima (river discharge, flooded areas, flood depth), covering the time period 2006-2100 complemented by simulations driven by historical GCM runs covering the time period 1860-2006 and pre-industrial control runs (simulation round 2b)

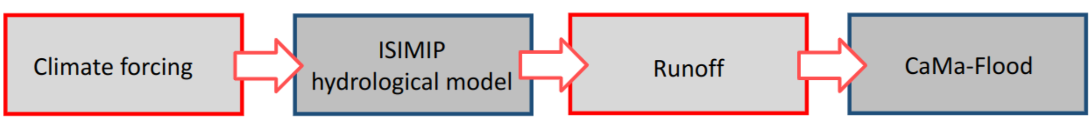

Fig. 1 Modeling chain for ISIMIP2 river flood simulations.

The dataset is based on the experiments from the global water sector included in the ISIMIP2 protocol (Table 1). For ISIMIP2a the modeling chain is based on climate input from climate reanalysis datasets. ISIMIP2b simulations use climate forcing data from global circulation models (GCMs). In both simulation rounds, the climate forcing is processed by a set of global hydrological models (GHMs) harmonized with regard to their underlying river routing scheme by means of the global hydrodynamic model CaMa-Flood (v. 3.6.2 Yamazaki *et al.*, 2011) (Fig. 1). To learn more on river flood modeling *ISIpedia: the open climate-impacts encyclopedia* provides additional background information (Volkholz, 2021).

Table 1: Overview of the experiments and indicators provided in the ISIMIP2 flood hazard dataset. The global hydrological models used in each experiment are provided in table 2 and 3.

	Scenario	Climate Forcing	Human Impacts	Time Period	Variables	Resolution
ISIMIP2a	hist[1]	GSWP3 PGMFD v2.1 (Princeton) WATCH-WFDEI WATCH (WFD)	nosoc[2]	1971-2010 1971-2001 for WATCH (WFD)	maximum annual river discharge (dis) *in m^3/s*	900arcsec
					maximum annual flooded fraction (fldfrc) *dimensionless [0,1]*	150arcsec 300arcsec
					maximum annual floodplain depth (flddph) *in m*	150arcsec 300arcsec
ISIMIP2b	historical[3]	GFDL-ESM2M HadGEM2-ES IPSL-CM5A-LR MIROC5	histsoc[4]	1861-2006	maximum annual flooded fraction (fldfrc) *dimensionless [0,1]* maximum annual floodplain depth (flddph) *in m*	150arcsec
	picontrol[5]		1860soc[6]	1661-1861		
	rcp26[7]		2005soc[8]	2006-2100		
	rcp60[9]		2005soc	2006-2100		
	rcp85[10]		2005soc	2006-2100		

[1] Historical climate information (observational climate data).
[2] No direct human influences on the water cycle. This is only for models that do not represent any water abstraction. Such model simulations should be labeled “nosoc” even if human land-use is represented.

[3] Historical climate and CO_2 concentration (simulated by GCMs).
[4] Varying historical land use and other human influences.
[5] Pre-industrial climate and 286ppm CO_2 concentration.
[6] Pre-industrial human influences.
[7] Future climate and CO_2 concentration from RCP2.6.
[8] Fixed year-2005 land use and other human influences.
[9] Future climate and CO_2 concentration from RCP6.0.
[10] Future climate and CO_2 concentration from RCP8.5.

2 ISIMIP2a Simulations

Hydrological modeling

To model fluvial flood hazards, we utilize runoff data from 12 Global GHMs involved in phase 2a of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2a). These GHMs are driven by four distinct observational weather datasets covering the period 1971–2010 (Table 2). The GHMs provide daily runoff at a resolution of 30' (~50 km × 50 km). The weather data products applied include (Table 1):

- the Global Soil Wetness Project version 3 (GSWP3; http://hydro.iis.u-tokyo.ac.jp/GSWP3) (Dirmeyer *et al.*, 2006)
- the Princeton Global Meteorological Forcing Dataset version 2.1 (PGMFD) (PGMFD; http://hydrology.princeton.edu/data.pgf.php) (Sheffield, Goteti and Wood, 2006)
- the ERA-Interim data (WATCH-WFDEI)(Weedon *et al.*, 2014)
- the Water and Global Change Forcing Data based on the ERA-40 reanalysis dataset (WATCH; https://doi.org/10.1029/2006gl026047, https://doi.org/10.1175/jhm-d-15-0002.1)(Weedon *et al.*, 2011)

Table 2: Overview of hydrological model runs included in ISIMIP2a flood modeling chain. Columns list observational weather data sets used to drive the global hydrological models (rows).

	GSWP3	PGMFD	WATCH	WATCH-WFDEI
CLM4.0	x	x	x	x
DBH	x	x	x	x
H08	x	x	x	x
JULES-W1	x	x	----	x
JULES-B1	x	x	x	----
LPJmL	x	x	x	x
MATSIRO	x	x	x	x
MPI-HM	x	x	x	x
ORCHIDEE	x	x	x	x
PCR-GLOBWB	x	x	x	x
VIC	x	x	x	x
WaterGAP2	x	x	x	x

We extract detailed information on river discharge, flooded areas, and flood depth from the harmonized multi-model simulations of 12 global gridded GHMs involved in ISIMIP2a. Specifically, we implement the "NOSOC" naturalized experiment outlined in the ISIMIP2a protocol. In this experiment, human influences such as dams and water extractions on river flow are not considered. This choice is justified for three main reasons: First, it ensures consistency with river routing simulations that do not account for human river management. Second, it aligns with prior research indicating minimal differences in hydrograph shapes, particularly for peak daily flow, between natural and human impact experiments (Pokhrel *et al.*, 2012).Third, this methodological approach is more appropriate to isolate climate-induced alterations in river discharge and flood impacts.

Harmonization of the river routing scheme

We first harmonize the output of the set of 46 combinations of climate data and Global Hydrological Models (GHMs) (Table 2) with regard to the river routing networks using the fluvial routing model CaMa-Flood (version 3.6.2), following the methodology employed in previous studies by Willner et al. (Willner *et al.*, 2018; Willner, Otto and Levermann, 2018). This process results in daily fluvial discharge data at a resolution of 15’ (~25 km × 25 km). Especially for peak discharges, CaMa-Flood demonstrates closer agreement with observed fluvial discharges compared to the direct output of the hydrological models (Zhao *et al.*, 2017). For the analysis of the flood data, we use the annual maximum daily discharge.

Model bias correction

For each of the 46 simulations of daily fluvial discharge and each grid cell on 15’ resolution, we fit a generalized extreme value distribution to the historical time series (1971-2010) of the annual maximum discharge using L-moment estimators of the distribution parameters. We then apply a model bias correction, following the approach by (Hirabayashi *et al.*, 2013) (Hirabayashi *et al.*, 2013). We map the return period of each event to the corresponding flood depth in a MATSIRO (Takata, Emori and Watanabe, 2003) model run driven by observed climate forcing (Kim *et al.*, 2009), in bins of 1-year (1 to 100) and 10-year (100 to 1000) return periods (linearly interpolated), providing flood depths at 15arcmin resolution. Results derived from the observation-driven MATSIRO output have shown to be consistent with observation-based data.

Protection standards

In addition, we provide data for three different protection assumptions. We assume ‘0’ protection, ‘100-year’ protection and FLOPROS protection. The ‘0’ protection implies that the flood takes place as if there were no protection at all. The ‘100’-year protection scenario assumes that only floods exceeding a 100 year return period take place. If the return period of the maximum annual discharge is below 100 years, no flood occurs in this grid-cell, while for return periods above 100-years, the flood takes place as if there were no protection at all. Additionally, we account for current flood protection standards at the subnational scale using the FLOPROS database (Scussolini *et al.*, 2016). This database currently presents the best global-scale knowledge of the maximum return period of floods that each country/region can prevent. In this modeling process, we use the "Merged layer" of the database. This layer combines empirical data concerning existing protection infrastructure ("Design layer"), information about protection standards and policy requirements ("Policy layer"), and model-generated outputs derived from an observed correlation between gross domestic product per capita and flood protection ("Model layer"). Here, we also apply a threshold procedure assuming that when the protection level is exceeded, the flood happens as if there was no protection in the first place (for example, dams break); below the threshold no flooding takes place.

Downscaling

In case that the return period of the discharge exceeds the protection level, the surplus water (water amount that exceeds the capacity of the river channel) is distributed across the floodplain taking into account the topography (Yamazaki *et al.*, 2011). This procedure allows a spatially-explicit representation of the floodplain, providing flooded area and floodplain depth at a 0.3’ resolution corresponding to the resolution of the model internal Digital Elevation Model. For the final assessment, we reaggregate the high-resolution flood depth data from 0.3’ to a 2.5’ resolution (~5 km × 5 km) by retaining the maximum flood depth as well as the flooded area fraction, defined as the fraction of all underlying high-resolution grid cells where the flood depth was larger than zero.

3 ISIMIP2b Simulations

Hydrological modeling

To model the flood hazard indicator, we use bias-adjusted climate input data at daily temporal and 0.5° horizontal resolution providing pre-industrial, historical, and future (RCP2.6, RCP6.0 and RCP8.5) conditions. The data are based on the CMIP5 output of the global circulation models (GCMs) GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, and MIROC5 (Table 1).

We model spatially explicit river discharge, flooded areas, and flood depth from the harmonized multi-model simulations of the global gridded GHMs participating in ISIMIP2b (Table 3). For future projections, we then assume constant socio-economic conditions from 2005 onwards regarding e.g., urbanisation patterns, river engineering and water withdrawal (2005soc) (Table 1). For the pre-industrial simulations, we assume also constant pre-industrial socio-economic conditions, while we use varying historical land use and other human influences for the historical simulations.

Table 3: Overview of hydrological model runs included in the ISIMIP2b flood modeling chain. Columns list the GCMs used to drive the global hydrological models (rows). The cells provide the scenarios for which the model combination is available.

	GFDL-ESM2M	HadGEM2-ES	IPSL-CM5A-LR	MIROC5
CLM4.5	picontrol, rcp26, rcp60, rcp85	picontrol, rcp26, rcp60, rcp85	picontrol, rcp26, rcp60, rcp85	picontrol, rcp26, rcp60, rcp85
CLM5.0	historical	historical	historical	historical
CWatM	picontrol, historical, rcp26, rcp60, rcp85	picontrol, historical, rcp26, rcp60,rcp85	picontrol, historical, rcp26, rcp60, rcp85	picontrol, historical, rcp26, rcp60, rcp85
H08	picontrol, historical, rcp26, rcp60, rcp85	picontrol, historical, rcp26, rcp60, rcp85	picontrol, historical, rcp26, rcp60, rcp85	picontrol, historical, rcp26, rcp60, rcp85
LPJmL	picontrol, historical, rcp26, rcp60, rcp85	picontrol, historical, rcp26, rcp60, rcp85	picontrol, historical, rcp26, rcp60, rcp85	picontrol, historical, rcp26, rcp60, rcp85
MATSIRO	picontrol, historical, rcp26, rcp60, rcp85	picontrol, historical, rcp26, rcp60, rcp85	picontrol, historical, rcp26, rcp60, rcp85	picontrol, historical, rcp26, rcp60, rcp85
WaterGAP2	picontrol, historical, rcp26, rcp60, rcp85	picontrol, historical, rcp26, rcp60, rcp85	picontrol, historical, rcp26, rcp60, rcp85	picontrol, historical, rcp26, rcp60, rcp85
MPI-HM	historical	historical	historical	historical
PCR-GLOBWB	historical	historical	historical	historical

Harmonization of the river routing scheme

As in ISIMIP2a, we follow the methodology applied previously in Willner et al. 2018. For the ensemble of climate forcing and GHM combinations we first harmonize the output of the different GHMs with respect to their fluvial network using the fluvial routing model CaMa-Flood (version 3.6.2). This yields, again, daily fluvial discharge at a 15arcmin (~25 km × 25 km) resolution. For the global annual flood maps, we select the annual maximum daily discharge for each grid cell.

Model bias correction

For each of the GCM/GHM model combinations and each grid cell on 15' resolution, we fit a generalized extreme value distribution. In contrast to ISIMIP2a, we here use pre-industrial time series of the annual maximum discharge to derive L-moment estimators of the distribution parameters. As in ISIMIP2a, we then apply the model bias correction approach by Hirabayashi et al. (2013) (Hirabayashi *et al.*, 2013).

Protection standards

We follow the method described for ISIMIP2a simulations.

Downscaling

We follow the method described for ISIMIP2a simulations.

4 Limitations

Deficits in the flood hazard indicators could be introduced along the entire modeling chain ranging from i) inaccuracies in observational climate forcing data and the representativeness of the GCM runs ii) translation of daily climate data into discharge iii) translation of discharge into flooded areas:

i) Climate reanalysis data constrain the performance of GHMs and may cause a spatial variation in the overall performance of the modeling chain (Ruane, Goldberg and Chryssanthacopoulos, 2015; Beck *et al.*, 2017), e.g., due to spatially and temporarily heterogenous global data coverage. The ISIMIP2b simulations only include one ensemble member from each GCM provided by the CMIP5 simulations. This may limit the representativeness of the climate input and the output of the overall modeling chain.

ii) There are several sources of uncertainty associated with the translation of the climate forcing into discharge, which could arise due to inadequate process-understanding or inadequate representation of human influences. They may refer to the exact timing and scaling of peak-runoff (Beck *et al.*, 2017; Zaherpour *et al.*, 2018). Validation studies of the GHMs included in ISIMIP2a indicate a variation in performance across hydrobelts (Beck *et al.*, 2017; Zaherpour *et al.*, 2018) with a better performance in the wetter equatorial and Northern hydrobelts than in drier Southern hydrobelts (Zaherpour *et al.*, 2018).

iii) Regarding the exact modeling of flood extents and flooded areas, the river routing model CaMa-flood has been validated in many studies (Ikeuchi *et al.*, 2015; Mateo *et al.*, 2017; Bernhofen *et al.*, 2018) outside the ISIMIP2a context. Previous studies on selected river basins in Nigeria and Mozambique revealed performance differences ranging from poor to good across river basins and a strong dependence on the return period of input flows (Ikeuchi *et al.*, 2015). A validation study for flood extents simulated with CaMa-Flood and ISIMIP2a hydrological models for selected events shows that the selection of GHM and climate forcing have mutually dependent effects on flood model performance. Additionally, there are differences in the regional performance of climate forcings and GHMs (Mester *et al.,* 2021).
The translation of discharge into spatially explicit flood-depth on the basis of Digital Elevation Models causes inaccuracies in the estimation of the floodplain depth as they are known to be fraught with high levels of uncertainty (Yamazaki *et al.*, 2011). The representation of flooded areas may particularly depend on the adequate representation of flood protection levels only roughly known and implemented based on FLOPROS in this study. Accounting for flood protection according to the FLOPROS database rather degrades the average agreement between simulations and observations, by reducing or eliminating simulated flood extent in many cases. The 100-year protection most likely overestimates protection levels especially in areas with less developed infrastructure, while assuming no protection at all most likely leads to an underestimation of protection levels in highly developed areas.

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