FREDERICK S. PARDEE CENTER
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JOSEF KORBEL SCHOOL OF INTERNATIONAL STUDIES
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UNDP

The Impact of Climate Change on Human Development in Yemen

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DISCLAIMER

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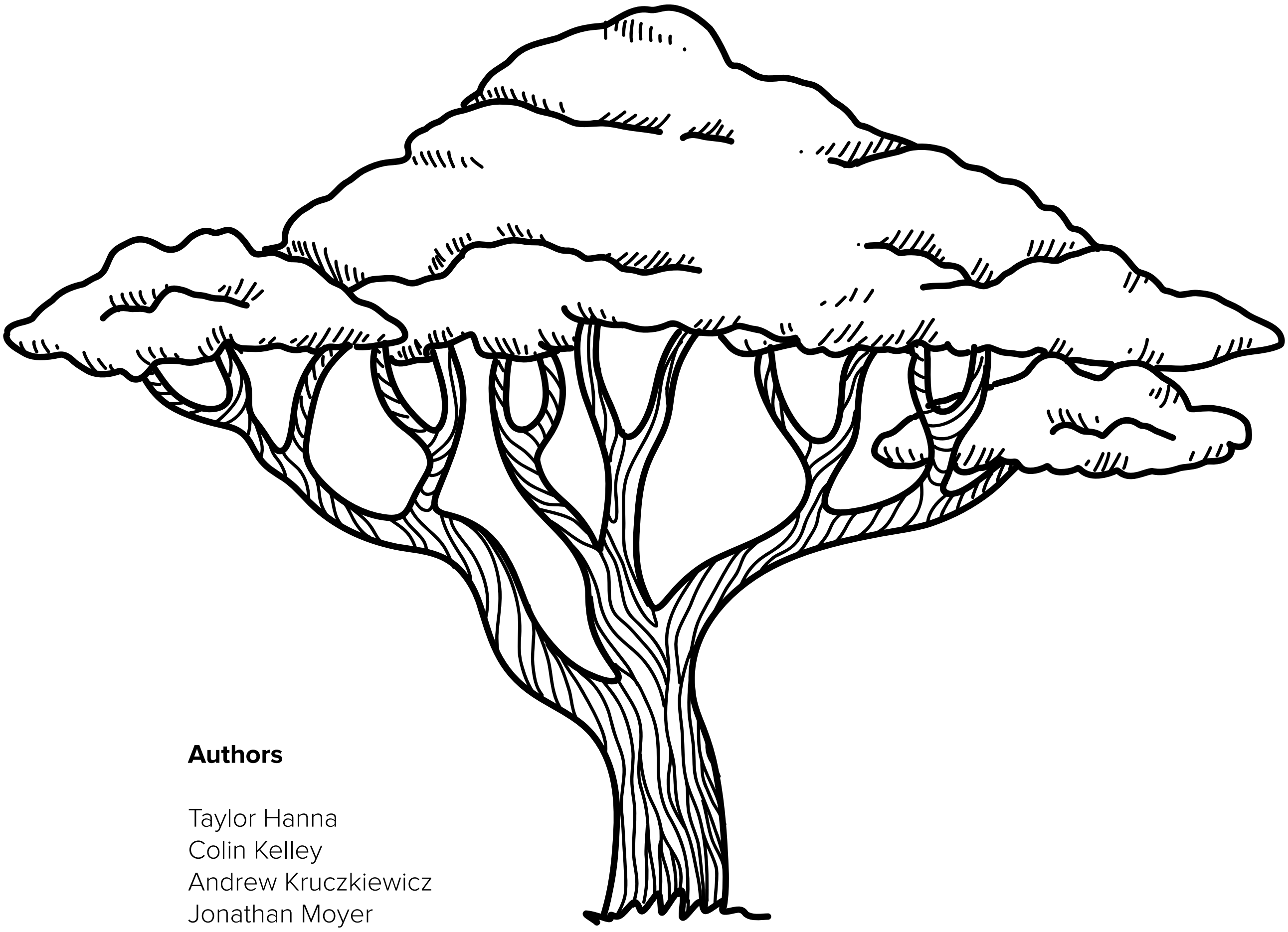
United Nations Development Programme (UNDP)
60th Meter Road
P.O. Box: 551 Sana’a, Republic of Yemen

Website: http://ye.undp.org



Authors

Taylor Hanna
Colin Kelley
Andrew Kruczkiewicz
Jonathan Moyer

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List of abbreviations

CHIRPS	Climate Hazards Group InfraRed Precipitation with Station
CMIP6	Coupled Model Intercomparison Project Phase 6
CRU	Climatic Research Unit
GDP	Gross domestic product
IFs	International Futures
IPCC	Intergovernmental Panel on Climate Change
RCP	Representative concentration pathway
RICCAR	Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region
UNDP	United Nations Development Programme

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Preface

This study, “The Impact of Climate Change on Human Development in Yemen,” was commissioned by UNDP in the beginning of 2023 as part of a collaboration with the Frederick S. Pardee Center for International Futures, Josef Korbel School of International Studies, University of Denver and Appalachian State University. Yemen is frequently said to be experiencing one of the worst development and humanitarian crises in the world after more than eight years of ongoing conflict. At the same time, it is among the countries most vulnerable to climate change and for decades has faced a worsening water crisis. This report seeks to better understand Yemen’s likely climate future and how climate change could affect economic and human development in the long run.

The report analyses historical data on temperature and precipitation across regions and seasons, identifying recent trends, and uses statistical techniques to forecast likely climate futures through 2050. It draws on the International Futures (IFs) model—an open-source, integrated modelling system designed to help explore how development changes across time and issues. IFs has previously been applied to assess the effect of ongoing conflict in Yemen on human development and to examine possible recovery pathways in the *Impact of War* trilogy of reports produced by UNDP and the Frederick S. Pardee Center for International Futures. This current report applies the same modelling techniques to the future of climate change by comparing a likely climate change scenario to a counterfactual in which climate change does not occur. Key adaptation and development interventions are combined into a third scenario focused on building resilience to the threats posed by climate change and accelerating progress towards better human development.

Climate change threatens to further set back progress in a country that has already been devastated by crisis. Yemen’s climate future is uncertain but is expected to be hotter and more variable, with adverse effects on the economy and human development. But it is not too late to make transformative changes and build resilience to future crises, saving the lives of hundreds of thousands and building a brighter future for Yemenis.

Executive summary

Yemen is experiencing one of the world's worst humanitarian and development crises as a result of eight years of devastating conflict. Globally, it is among the countries most vulnerable to climate change, a point underscored by the damage and disruption caused by recent natural disasters, including excessive flooding. At the same time, it is among the most water-scarce countries in the world. With Yemen's development challenges already complex and multifaceted, climate change acts as an uncertainty multiplier with the potential to seriously constrain the future of the country. On the other hand, if Yemen can achieve transformative changes, there is potential to build resilience to the effects of climate change while also advancing towards a more sustainable, secure and prosperous future.

The first objective of this report is to better understand how climate change is likely to manifest in Yemen. For this, we analysed observed historical data on temperature and precipitation, specifically examining temporal variability and trends at subnational and subseasonal scales. We used the findings to project future trends in climate change out to 2050, employing a range of statistical techniques. Finally, we compared these trends with climate model projections and examined the uncertainties.

Temperatures are expected to continue to rise across Yemen. The observed near-surface temperature has risen significantly in all subregions, or agroecological zones, over the past several decades. Because the trends have been quite linear over the last 60 years, there is high confidence that this trajectory will continue in similar fashion through 2030 to 2050.

Trends and projections of rainfall, based on the representative concentration pathway (RCP) 4.5 and 7.0 scenarios, are more uncertain and regionally varied, but Yemen is likely to experience more frequent and intense flooding. The observed rainfall during the summer over the highlands and Red Sea coast is increasing significantly. This trend is expected to continue in the future, with high confidence. Not only is the mean rainfall increasing but the variability is also escalating in a significant way, resulting in larger extremes. These have manifested as major and often persistent flood events and changing rainfall patterns. Spring rains have been declining modestly, resulting in a change in the seasonality of rainfall in both regions that will likely affect agricultural production. To better understand these dynamics, we used integrated modelling and scenario analysis through the International Futures (IFs) modelling tool to assess the effects of climate change on human development. We created two scenarios. The *Climate Change* scenario reflects likely climate change effects on human development in Yemen as identified in the literature. The *No Climate* scenario provides a counterfactual for comparison to help identify the climate-attributable effects on human development. The findings from a scenario analysis is below.

The effects of climate change are likely to slow economic growth gradually, with a disproportionate effect on the poor. We find that a cumulative $93 billion in gross domestic product (GDP) would be lost as a result of a likely *Climate Change* scenario through 2060, by which point GDP would be 10 percent lower than in a *No Climate* Change scenario. The rate of extreme poverty would be more than 25 percent higher, as 8.1 million people would be pushed into poverty as a result of the *Climate Change* scenario by 2060.

Climate change in Yemen will likely adversely affect population health and nutrition in the long run. In the *Climate Change* scenario, 3.8 million more people would suffer from malnutrition than in the *No Climate* scenario. Moreover, climate change would be responsible for over 121,000 deaths by 2060.

A third scenario, *Building Resilience*, is meant to simulate a world in which transformative and collective efforts by policymakers, practitioners and donors contribute to a system of support and progress in Yemen. This scenario assumes the effects of the *Climate Change* scenario as a baseline but then includes additional interventions addressing environmental and broader development challenges, including improvements in agriculture and infrastructure, education, peace and security, and women's empowerment.

***Building Resilience* would boost economic growth well beyond both the *Climate Change* and *No Climate* scenarios.** This would result in cumulative gains of nearly $360 billion relative to the *Climate Change* scenario by 2060 and a GDP per capita that would be 27 percent greater.

Even under the conditions of climate change, the lives of the poorest can improve. The *Building Resilience* scenario would result in 9.5 million fewer Yemenis in extreme poverty and 13 million fewer suffering from malnutrition by 2060. It would result in over 400,000 deaths averted from climate change-related and other causes.

Through the *Building Resilience* scenario, Yemen can more than make up for the damage caused by climate change. But this will require a significant effort to make gains in all aspects of development. Through identifying the most powerful components of the *Building Resilience* scenario, we pinpointed key areas to address vulnerabilities and transform development. This led to the following conclusions and recommendations.

It will be critical to address the nexus of agriculture, food security and water security to mitigate the damage of climate change in Yemen. With existing agricultural limitations and a growing population, Yemen will still need imports to meet food demand, but targeted interventions to improve both agriculture and food accessibility can prevent families from going hungry as a result of climate change.

Improvements to security would have a significant effect in building resilience to climate change. A fully resilient Yemen will be peaceful and secure. Ongoing conflict and insecurity will otherwise continue to damage development and prevent resources from being spent on human development.

A special focus on the economic and social empowerment of women and girls, among other marginalized communities, will be critical to building resilience to future challenges. Initiatives must pay special attention to the wellbeing of women, who are more vulnerable to the impacts of climate change and will play an important role in preparing society for the challenges to come. Improvements in gender equality lead to development gains for all.

These results reflect our best understanding based on the current state of the science, but it is important to recognize the constraints of this work. Challenges range from data and sample size limitations to the uncertainty inherent to climate models, and the results presented here, as in all climate analyses, should be considered imperfect. Even so, the overarching trends are significant and provide valuable insight into future climate and development pathways.

Like many low-income countries, Yemen has contributed little to the climate crisis. Accounting for less than 0.1 percent of global carbon emissions, it has no capacity to stop climate change alone. Instead, it faces great uncertainty as one of the most climate-vulnerable places in the world, while also dealing with extreme water scarcity and a high dependence on imports for food. Strong and transformative action today can help build resilience and protect the population of Yemen from the worst consequences of these challenges. The Government of Yemen has limited capacities and resources to assume this sizable ambition alone; it will require the full commitment and support of policymakers and practitioners as well as the private sector, donors and the international community.

Photo: UNDP Yemen. Yemeni grapes.

Introduction

Climate change is a global challenge that will be felt disproportionately by the most vulnerable countries. Yemen is one of these as well as one of the countries that is least prepared to adapt (Chen et al. 2023). With much of the population dependent on agriculture for work, the agricultural effects of climate change impact the lives and livelihoods of most Yemenis. At the same time, agricultural productivity is low and largely reliant on rainwater or inefficient irrigation, a challenge exacerbated by the increased production of a water-intensive crop, qat (Abu-Lohom et al. 2022). Yemen relies on imports for the vast majority of its food, leaving poor households highly vulnerable to global price fluctuations. Heavy rain and flooding in recent years have taken lives and destroyed property and infrastructure, even as Yemen remains one of the most water scarce countries in the world.

After eight years of continuous and high-intensity conflict, Yemen's economy is in continued crisis. Estimated economic output in 2022 was still more than 40 percent lower than it was in 2014, and GDP per capita has fallen by nearly 60 percent over the same period. Roughly 6 out of 10 Yemenis live in extreme poverty, meaning households have very little ability to cope with economic shocks or increases in food prices. The country is split between two competing economies, the public sector is fragmented and governance is weak. This crisis has left Yemenis in a precarious and uncertain situation, which is only exacerbated by the uncertainty of climate change. Moreover, climate change could exacerbate resource scarcities that exist already and fuel additional conflict and insecurity.

Without building and growing adaptive capacity, communities in Yemen will continue to face severe water scarcity, the fragility of coastal and mountain ecosystems, continued land degradation, and the declining productivity of fisheries and agriculture. With millions of displaced people suffering from extreme food insecurity, sustainable rural livelihoods are at risk due to climate change.

Purpose of this report and limitations

This report explores the future of climate change in Yemen and identifies prospects for building resilience to the challenges that the future may bring. Given a great deal of uncertainty about the trajectory of both climate change and development in Yemen, this report is not intended to make definitive predictions. Instead, it helps to provide greater understanding about the risks from climate change and the strategies to build adaptive capacity.

This work features two main analytical methodologies, each with their own limitations. Data availability remains a considerable challenge for climate forecasting. Daily data of sufficient quality do not exist in Yemen for observed sea-level rise, heat waves (consecutive days above a critical threshold) and flash flood incidence. The statistical fitting techniques applied to 10-day rainfall and monthly near-surface temperature are limited by sample size and potential recency bias, as record extreme events in recent years suggest a non-linear increase. Climate models have shown difficulty in sufficiently resolving rainfall variability over complex topography, although efforts have been made to utilize downscaled versions of climate models to potentially address these challenges in the Arab region.[1] These and other factors combine to create large uncertainty with respect to projecting future pathways of changes related to mean climate change and changes in extreme variability, particularly with respect to how greenhouse gas emission trajectories will evolve over the next 10 to 25 years.

This uncertainty is also an important limitation in modelling the economic and human development effects of climate change. The scenarios in this report are meant to map a potential climate change future for Yemen but effects could easily

1 See, for example, the Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR) at www.riccar.org.

be more extreme or more muted. The purpose of this exercise is not to predict the specific future of climate change and human development but to explore the different pathways through which climate change could be affected as well as strategies for building resilience.

The report begins with an exploration of the futures of climate change in Yemen through analysis and projection of observed temperature and precipitation patterns for each of five agroecological zones. It then reviews literature on pathways through which climate change is likely to affect human development. Building on this work, the paper uses integrated modelling techniques to analyse the effect of climate change on human development before turning to a focus on building resilience.

Photo: UNDP Yemen. Socotra Island.

Photo: UNDP Yemen. Rehabilitating small-scale agricultural infrastructure, Taiz, Yemen.

Climate futures in Yemen

Yemen's topography is highly complex and diverse, and strongly related to rainfall and temperature patterns. These factors explain historical and modern population distribution, agricultural productivity, and economic opportunity and success. The majority of the population resides in the mountain highlands located in the west and in the coastal port cities. There is a coastal plain along the Red Sea to the west, extending to the Gulf of Aden in the south and bordering a large mountain range in the west. The inland areas to the east include a broad plateau, the Hadhramut Mountains and part of the Rub al Khali Desert, or 'empty quarter'. An archipelago includes the island of Socotra with its extremely sensitive and unique biodiversity.

Knowledge gaps and challenges in forecasting climate change in Yemen

There are numerous challenging aspects to evaluating climate in Yemen. A paucity of data is common in countries with fragile sociopolitical contexts but Yemen is uniquely challenging given the duration and magnitude of the conflict (Mason et al. 2015). The few ground-based observations that existed prior to the recent conflict are no longer available.

Extreme climatic events have had devastating consequences, especially in recent years. Floods occur on different timescales, ranging from severe but short duration flash floods to more persistent rainfall events that can last for weeks to months. The character and locations of floods can be quite distinct among different subregions and governorates. While periods of intense precipitation have been increasingly documented, below-average precipitation is also occurring more frequently, causing increasing concern about droughts.

As climate variability increases with climate change, swings between flooding and drought will become greater, resulting in combined hardships such as food shortages and famine and the destruction of infrastructure. The persistence of extremes is equally concerning, as recovery will be delayed and resilience further reduced. Sea-level rise is another prominent worry, causing shoreline erosion, saltwater intrusion and land loss, with some areas of the Yemen coastline at relatively higher and lower levels of risk from these impacts.

Although the general features of Yemen's climate are known, certain elements are unclear, primarily due to the lack of data availability and the temporal extent of available data. These historical gaps cannot be filled by the installation of new weather stations, yet if appropriately collected, cleaned and calibrated, new data will help to provide an increased understanding of historical climate over future decades.

A lack of ground observations presents difficulties, particularly with respect to examinations of high-resolution characteristics. For example, analysis of heat spells or flash flood events requires daily or even subdaily data. Further, data on the impacts of these events require similar spatial and temporal scale details, which are also difficult to access, if they are at all available. Although daily observed data sets do exist, for rainfall and temperature, coverage of Yemen must rely heavily on remotely sensed satellite data. Analysis of specific urban areas requires a high spatial resolution.

Global climate models have frequently been used to predict future changes, globally and regionally, using different scenarios or pathways forward into the future forced by increased greenhouse gas emissions. Global and regional climate models have gradually increased their spatial resolution (providing more information at more local scales) and modelling complexity (providing more detail across more frequent time intervals) over the last several generations of the Intergovernmental Panel on Climate Change (IPCC) reports. The typical spatial resolution of the current generation is on the order of 1 to 2 degrees of latitude by 1 to 2 degrees of longitude. Although higher-resolution models are available, for regions similar in size to Yemen, which is roughly 10 degrees of longitude by 6 degrees of latitude in size, these have encountered difficulties in resolving rainfall over particularly complex topography, specifically more extreme values of rainfall, which are the most important to consider in understanding the intense rainfall that drives sudden onset floods. Models also exhibit regional biases with respect to climatologies and temporal and spatial variability. To attempt to reduce these, the Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR) project employed bias-correction techniques. These uncertainties will be discussed within the context of what has been observed.

Climate data

Trends in annual rainfall and annual temperatures have been observed in Yemen. Evidence indicates that it is likely that annual rainfall totals and annual average temperatures have increased in recent decades. This report seeks to present a more detailed analysis of Yemen's climate variability, trends and extremes at the subnational scale and at seasonal to subseasonal timescales. These analyses can be used to evaluate the climate model simulations and provide baselines for climate projections.

For these reasons, it is appropriate to utilize rainfall data from the Climate Hazards Center of the University of California Santa Barbara (CHIRPS v2) and temperature data from the University of East Anglia's Climatic Research Unit (CRU v4.07). Both data sets are strong candidates for inclusion in analyses in a variety of contexts on a global scale. The CHIRPS data have been evaluated specifically over the Yemen highlands and found to be the most reliable of the observed historical data sets (AL-Falahi et al. 2020). Near-surface temperature data were also examined over Yemen using the ERA5 re-analysis.

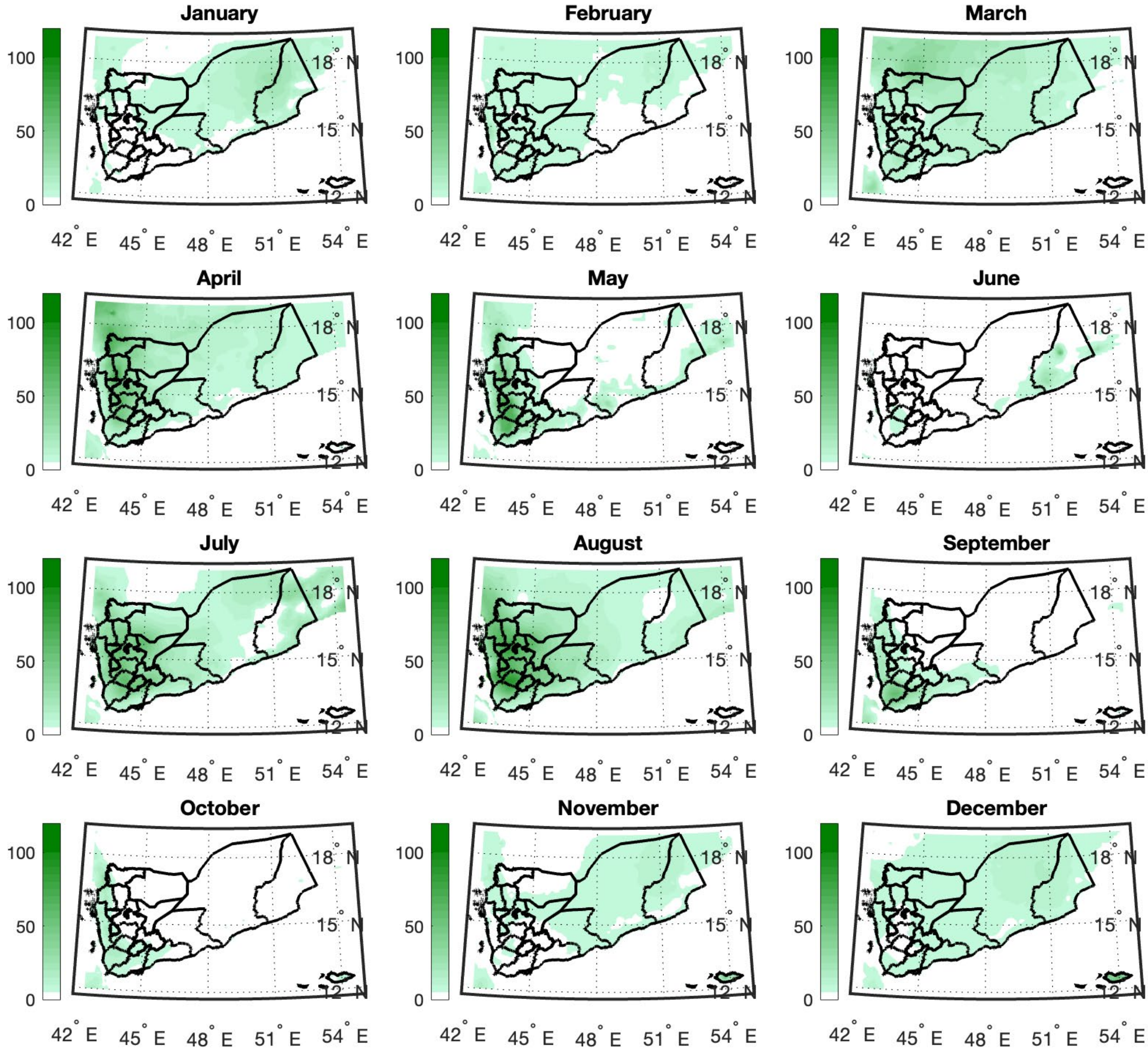
After consideration, CHIRPS v2 and CRU v4.07 were deemed the most appropriate of the accessible data sets. The CHIRPS v2 data allow examination of 10-day rainfall from 1981 through the present day at a very high spatial resolution. The CRU v4.07 data have a spatial resolution of 0.5 degrees of latitude by 0.5 degrees of longitude.

Recent research that examined future heavy rainfall events with the most recent IPCC Coupled Model Intercomparison Project (CMIP6) climate models made a valuable contribution towards addressing questions related to future shifts in precipitation (Gadain and Libanda 2023). Additional work is warranted, however, particularly for tackling specific questions related to future states of seasonal variability, magnitude and peaks of precipitation. This report draws from recent examinations and further analyses the best-performing models to assess uncertainty in future projections within Yemen. Employing statistical techniques, it produces a range of possible future trajectories of these metrics and discusses a variety of uncertainties.

Results

As a first step in understanding precipitation, seasonal cycles should be defined. The climatological seasonal progression of rainfall for each month is shown in Figure 1. Although there is modest rainfall during the boreal winter months in the east, there are essentially two primary rainy seasons: March through May and July through August. June is typically the driest month, separating the spring and summer rainy seasons. The preponderance of total annual rainfall occurs in the western highlands and along the Red Sea coastal plain. March, April and August are the months when non-zero quantities are probable in nearly all locations of Yemen. These are the months with the widest distribution of precipitation. There are no months where all locations are likely to see zero precipitation, although June and October are when the fewest locations are likely to see any precipitation. Snowfall occurs at higher elevations, particularly in the Majz district and Saada province in northern Yemen.

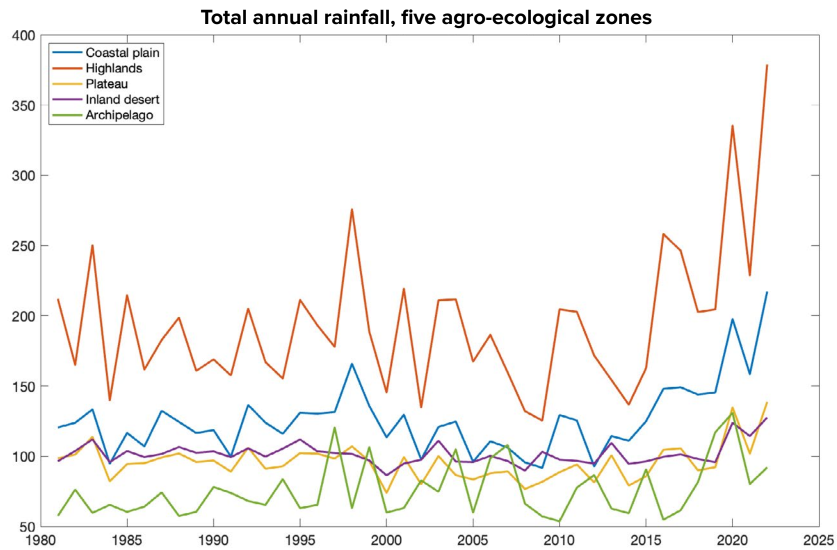
Figure 1: Climatological rainfall (millimetres) by month, 1981–2022 mean
Source: CHIRPSv2 data product.



To explore regional climate futures in Yemen, the county is divided into five previously defined agroecological zones: the western and southern coastal plain, the western highlands, the eastern plateau, the north-eastern desert and the archipelago. Figure 2 shows the timeline and spatial trends of total annual rainfall. The coastal plain and highlands zones have seen a marked increase in rainfall since 2015. Some decadal variability (on 10- to 20-year cycles) is visible in increased precipitation both from 1990 to 1997 and 2015 to the present. By comparison, the RICCAR Mashreq domain climate outputs show generally increasing rainfall with more intense events and more extended droughts in between these events. These outputs indicate increasing rainfall across Yemen but most strongly along the west coast.

Figure 2: Timelines of total annual rainfall for each of the five agroecological zones (top panel); observed annual rainfall trend based on a linear best fit (bottom panel)

Source: CHIRPS v2 data product.



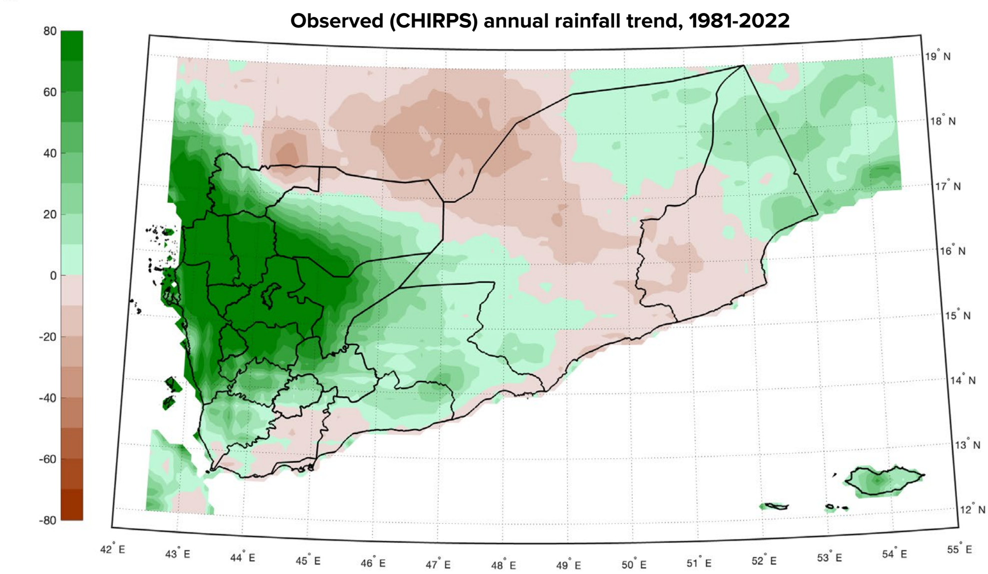


Figure 3 shows the timelines and linear trends of the annual near-surface temperature for each zone. The linear trends are quite similar in magnitude, indicating broad national warming. Figure 4 shows the spatial trend. The strongest warming has occurred in the west, over the mountains and Red Sea coast, and over the north-east. The southern coast and the highlands have experienced much less change, even a slight cooling since 1960 (Figure 2). Although 2022 was a much cooler year compared to the last decade (in the archipelago, desert and highlands), this is not unexpected and reinforces the point that sharp swings in year-to-year temperatures often occur. This does not subvert the highly significant warming trend that is occurring.

Figure 3: Timelines of annual near-surface temperatures for each of the five agroecological zones, with a linear best-fit trendline
Source: CRU TS v4.07 data product.

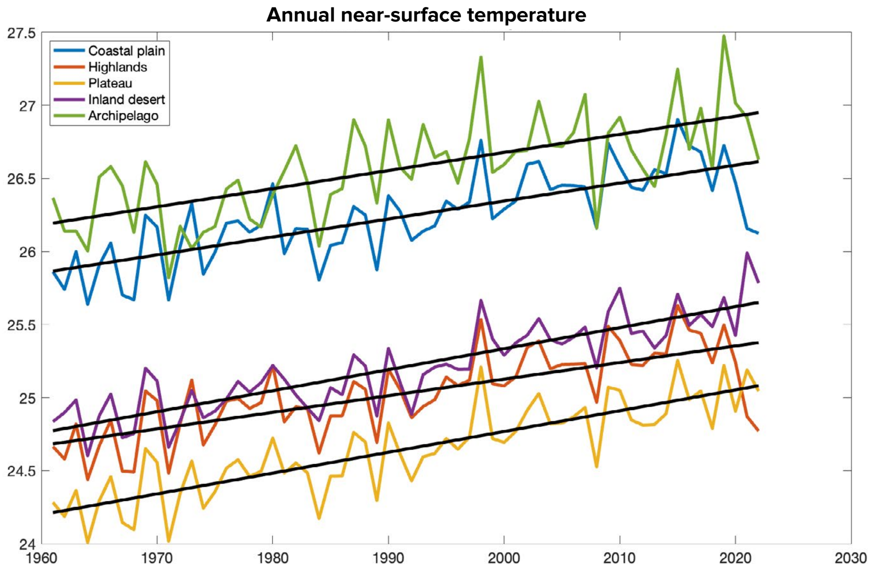
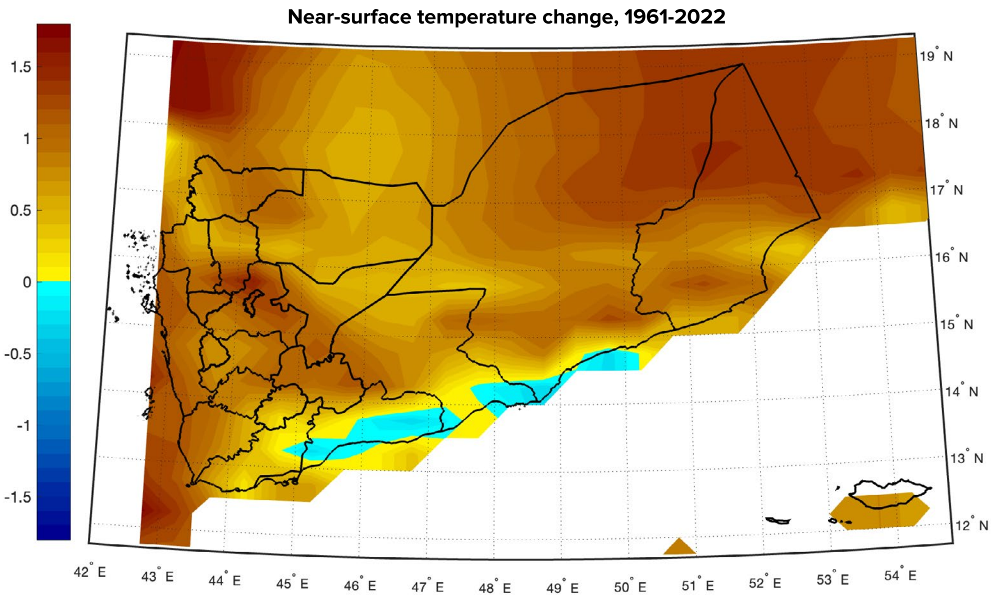


Figure 4: Annual near-surface temperature change based on a linear best-fit trendline
Source: CRU TS v4.07 data product.

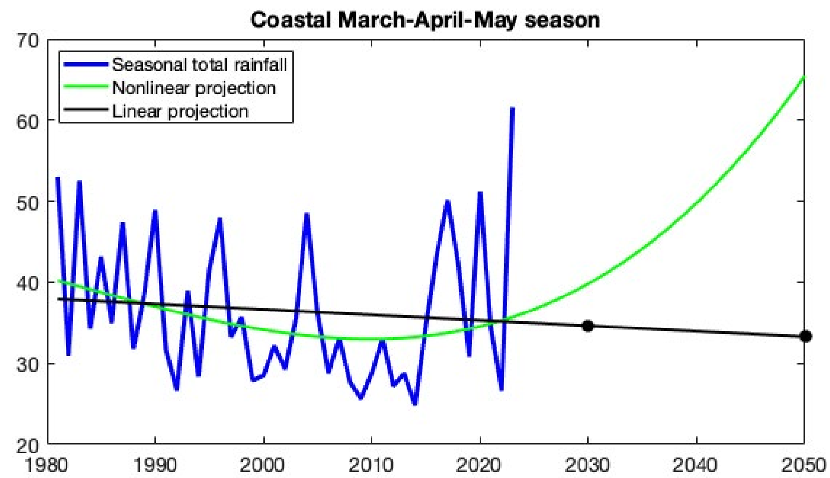


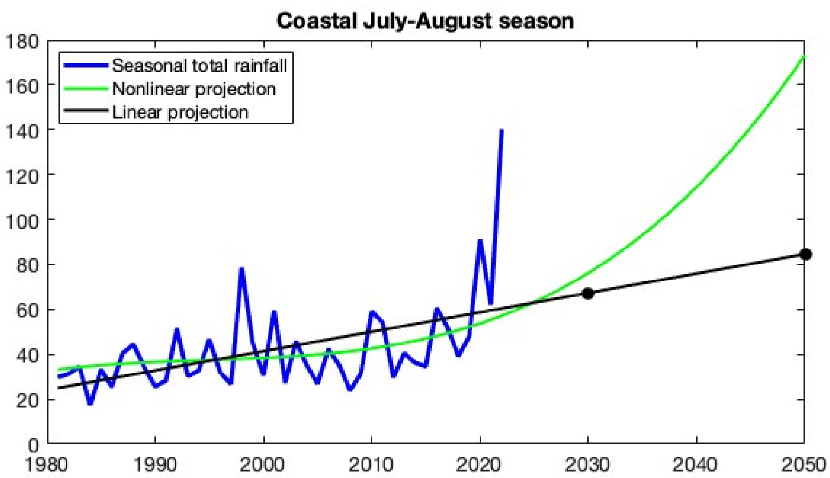
The following sections explore these trends in greater detail for each of the five agroecological zones. The linear trend of the observed changes over the last 42 years (1981 to 2022) was determined and then used as a baseline to project into the future. For rainfall, which is much more heterogeneous in space and non-linear in time than surface temperature, single spectrum analysis was employed to determine the non-linear trends and produce a range of projections based on two time horizons of interest, 2030 and 2050. The likelihood of more robust, non-linear future changes was also examined. Although there is considerable uncertainty, the linear trend represents a more conservative projection. Other methods consider potentially larger future changes. Essentially, the linear trend represents the lower bounds of the projection range and the non-linear trend represents the upper bounds. By comparing 10-day rainfall events from the 1981-2001 period to the 2002-2023 period, we can more closely evaluate the observed shift in extremes and project the change into the future.

Coastal zone

Figure 5 shows the timeline of seasonal rainfall for the coastal zone. Several recent years, particularly 2020 and 2022, have been much wetter than normal. Rainfall in July and August 2022 (140 mm) was far above any other summer observed in the last 42 years. The 2020 summer rainfall was the previous record year at 91 mm. Based on a linear trend, the total summer (July and August) rainfall from 1981 to 2022 increased dramatically, from 25 to 60 mm.

Figure 5: Timeline of total seasonal rainfall for the coastal zone, with linear and non-linear best-fit trendlines
Source: CHIRPS v2 data product.





Were this linear increase to continue, total summer rainfall accumulation would reach 67 mm by 2030 and 85 mm by 2050. If the recent record years portend a non-linear increase into the future, these rainfall accumulations could be considerably higher. It is also possible that they could be outliers and that the coming years will return to a range of values more resembling the linear trend in the decades before 2020. The highly significant wetting trend over the last 42 years has been accompanied by a strong increase in year-to-year variability. Very wet years are more often followed by very dry years, and vice versa. A continuation of this trend would make extreme rainfall years more prevalent in the future. Depending on the type of precipitation, and the political will to address flood risks, this could potentially lead to both more severe flooding events in areas used to experiencing them and to other areas experiencing flooding for the first time. Recent flood events have been devastating, with some people noting that this has been the first time in memory that a particular community had experienced flood impacts. Floods have destroyed critical infrastructure and inhibited the ability to restore it, thus presenting significant future challenges and increasing the risk of cancelling human development gains achieved in recent years.

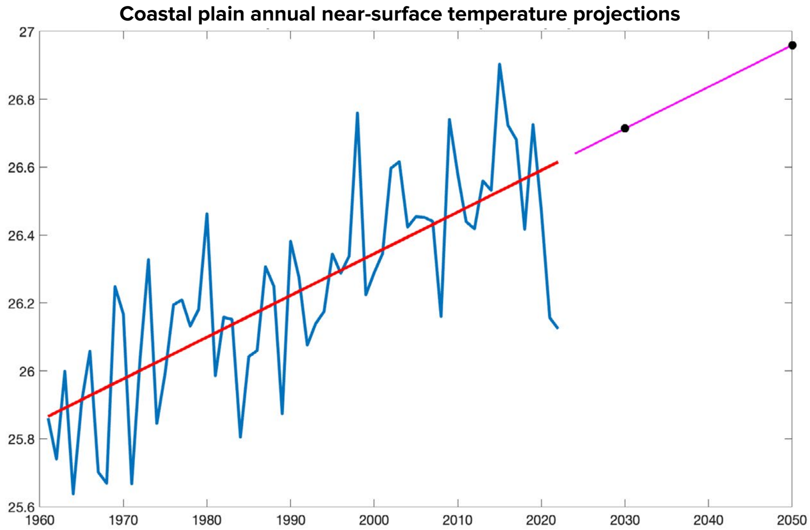
During the spring rains, from March through May, the rainfall trend has been quite different than in summer, with a slight decrease. This does not mean that every or any particular year will lead to lower-than-average rainfall. For example, the spring rains in 2023 reached a record at nearly 61 mm, far above the mean of the last 42 years (36.5 mm). The year-to-year variability during spring has increased over the last 42 years, though less so than for the summer season. The 2023 spring floods followed a drought in the 2022 spring season (26.6 mm) and record rainfall in the summer of 2022. These large fluctuations and the persistence of such large extremes from season to season and year to year significantly hamper resilience and development—and they are expected to increase in frequency and severity in the future.

A recent study comparing 11 different climate models for two regions in Yemen (the western highlands and the Red Sea coast/Tihama Plain) illustrated the complexity of forecasting future precipitation within Yemen (Gadain and Libanda 2023). Using three metrics to examine heavy rainfall, the study found an expectation of increased precipitation intensity and frequency in the highlands and to a lesser degree in the Red Sea coast and Tihama Plain region. Moreover, even the best-performing models correlated weakly with reference data and were not always in agreement on trends in rainfall (past or future). Model ensembles tended to overestimate climatological rainfall over this coastal region. Large variations were also apparent regarding spatial trends. Further analysis in this study showed that none of these models exhibit the recent (2015-2022) observed sharp increase in rainfall. These findings confirm that there is substantial uncertainty in future climate projections, even with the best-performing models.

As with other zones (Figure 3), the observed near-surface temperature in the coastal zone has risen steadily and significantly since 1960, by .75°C, or at a rate of .125°C per decade (Figure 6). This projects as an increase to 26.7°C by 2030 and 27°C by 2050. RICCAR Mashreq data project generally non-linear changes into the future, with increases from the 1995-2014 baseline of .65°C by 2040 and 1.43°C by 2060, based on the RCP-8.5 scenario.

Figure 6: Timeline of annual near-surface temperature for the coastal zone, with linear trend and projection

Source: CRU TS v4.07 data product.



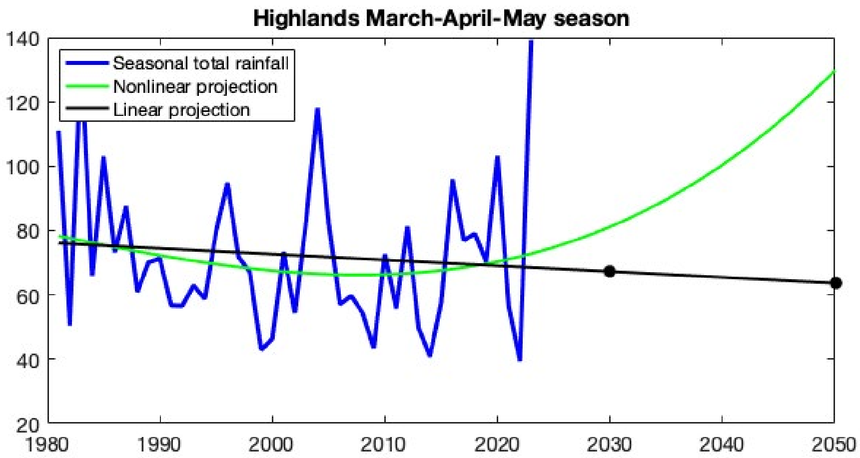
Although the last two years were much cooler than the previous 10, the upward trend is expected to continue, with high confidence. Rising temperatures are closely associated with more frequent and intense summer heat waves, which have been of notable concern to public health, particularly in urban coastal cities such as Hudaydah, Aden and Mukalla. Each of these are prominent ports for Yemen's trade. Most humanitarian aid passes through Hudaydah. During the conflict, Aden has served as the temporary capital.

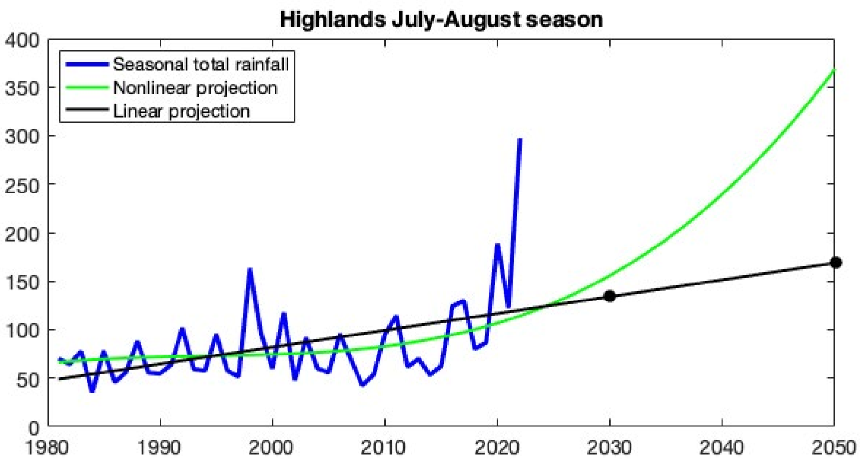
Highlands zone

The highlands zone, which includes six of the nine most populous cities in Yemen, typically receives about twice as much rainfall as the coastal zone. As with the coastal zone, the trend in spring (March, April, May) rainfall has been a modest linear decline (Figure 7), but with a record wet 2023 spring. During the summer (July and August), however, there has been a clear and significant positive rainfall trend since 1981. If recent record rains in 2020 and 2022 are an indicator, a non-linear signal may be emerging.

Figure 7: Timeline of total seasonal rainfall for the highlands zone, with linear and non-linear best-fit trendlines

Source: CHIRPS v2 data product.



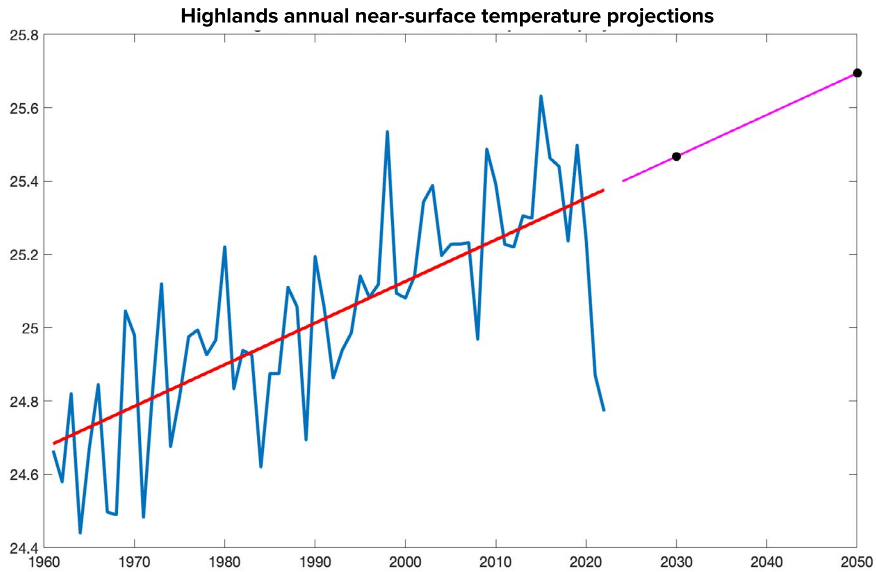


The 2022 summer rains, which reached nearly 300 mm, inundated the region with persistent flood events, particularly those driven by intense sudden onset periods of rainfall in localized areas. Even if recent years are statistical outliers, a linear trend shows that summer rainfall has increased considerably from 49 mm to 120 mm over the last 42 years. This trend should be considered robust, representing a significant shift in the seasonality of rainfall in a crucial agricultural zone. In the 1980s, total rainfall during the spring was of comparable magnitude to rainfall during the summer. In recent years, rains have been much more abundant during the summer. The linear trend projects an increase to 134 mm by 2030 and 168 mm by 2050. If recent years do indicate the emergence of a non-linear trend, increasingly frequent and severe flood events may become the new normal in this mountain zone, adversely affecting a sizable portion of Yemen's population, particularly the most vulnerable people.

Gadain and Libanda (2023) found that the western highlands is expected to experience further increases in both rainfall frequency and intensity, more so than other regions. Using the model scenarios, the study showed corroborating evidence for the changing shape of the distribution of rainfall towards heavier events that has already been observed. As with the coastal region, however, there is considerable disagreement among even these best-performing models, indicating significant uncertainty. RICCAR Mashreq future projections corroborate the observed increases in extreme summer rainfall in the Sanaa Basin.

The observed annual near-surface temperature trend in the highlands (Figure 8) has been similar to that of the coastal zone. The increase from 1961 to 2022 was roughly .7°C or a rate of .11°C per decade. Extrapolating this linear trend into the future, further temperature increases to 25.5°C by 2030 and 25.7°C by 2050 are expected. Average summer (June to August) temperatures are predicted to exceed 30.1°C by 2050, with high confidence.

Figure 8: Timeline of annual near-surface temperature for the highlands zone, with linear trend and projection
Source: CRU TS v4.07 data product.

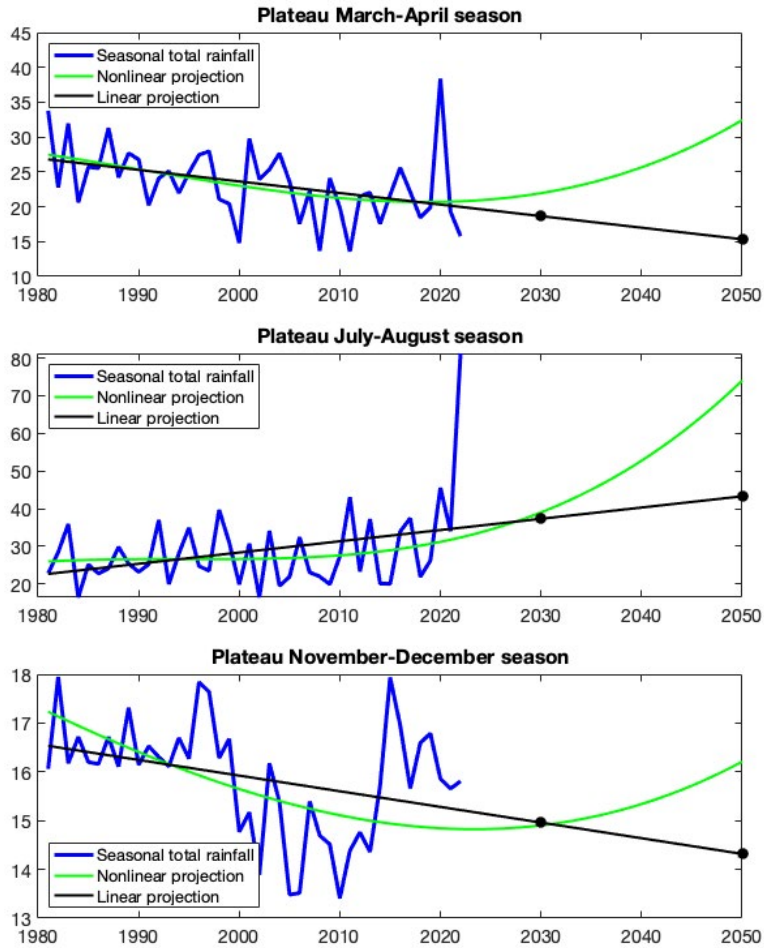


Plateau zone

During the three rainfall seasons in the central plateau zone (March to April, July to August and November to December, Figure 9), summer is the only season demonstrating a significant positive trend since 1981. The spring and winter seasons reflect a decline in seasonal rainfall. The 2020 and 2022 summers were unusually wet. The spring season has seen a modest linear decline in rainfall over the last 42 years. It is not expected that seasonal rainfall totals will likely change significantly in the coming decades based on observations over the last four decades.

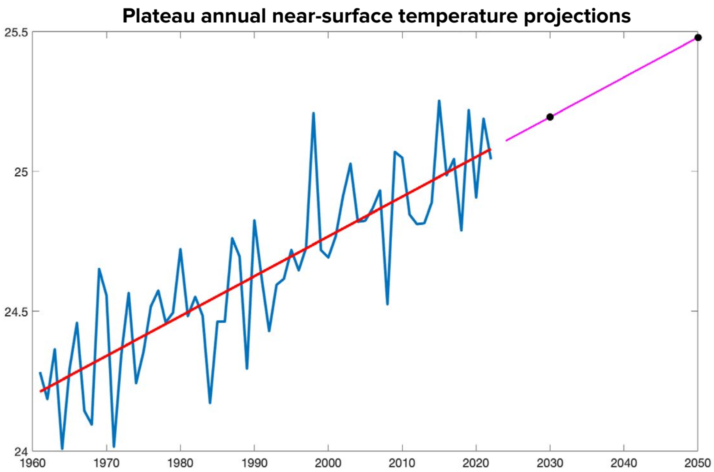
Figure 9: Timelines of total seasonal rainfall for the plateau zone, with linear and non-linear best-fit trendlines

Source: CHIRPS v2 data product.



The plateau, along with the north-eastern desert, has seen the largest rise in annual near-surface temperatures (Figure 10) among the five agroecological zones, roughly .87°C since 1961. The increase has been linear, as with the other zones, and is projected to reach 25.2°C by 2030 and 25.5°C by 2050.

Figure 10: Timeline of annual near-surface temperature for the plateau zone, with linear trend and projection
Source: CRU TS v4.07 data product.



North-eastern desert zone

The north-eastern desert also has three seasons with rainfall at very modest levels: March to April, July to August and November to December (Figure 11). The 2022 summer was exceptionally wet. The spring and winter seasons have seen a very modest but steady decline in rainfall since 1981. The north-eastern desert is projected to warm to 25.8°C by 2030 and 26.1°C by 2050 (Figure 12).

Figure 11: Timelines of total seasonal rainfall for the desert zone, with linear and non-linear best-fit trendlines
Source: CHIRPS v2 data product.

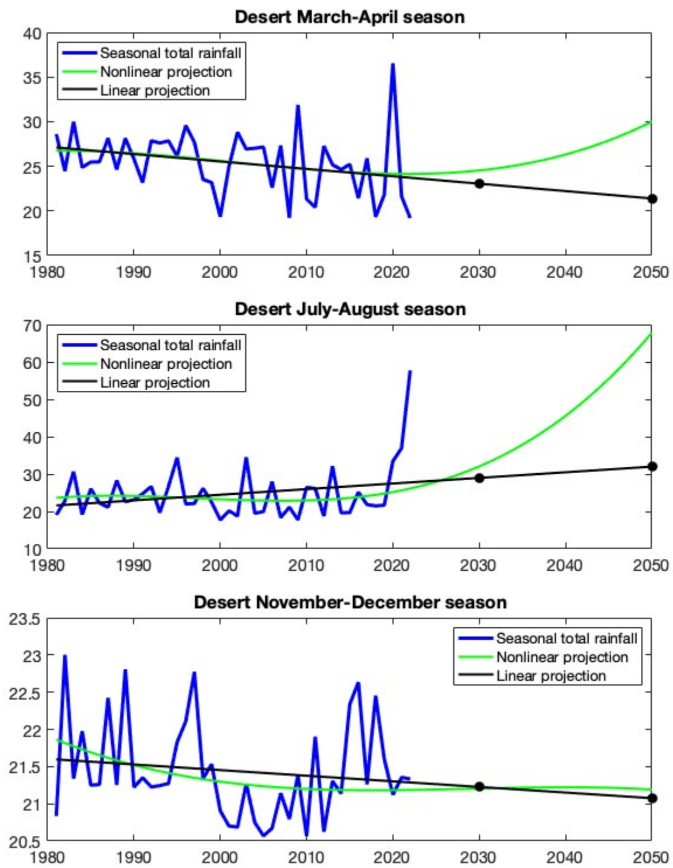
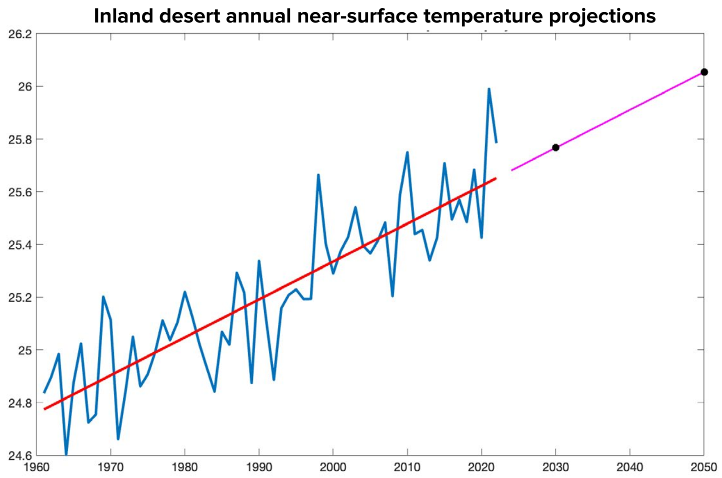


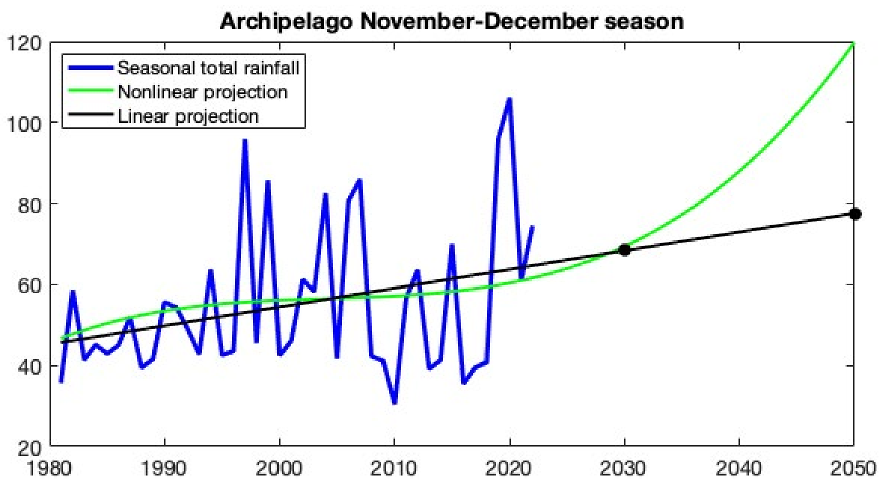
Figure 12: Timeline of annual near-surface temperature for the desert zone, with linear trend and projection
Source: CRU TS v4.07 data product.



Archipelago zone

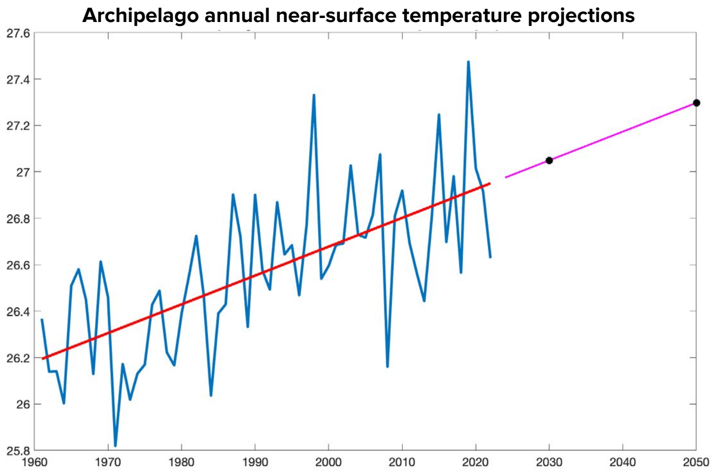
The Socotra archipelago has one rainy season, November to December (Figure 13). There has been a significant positive linear trend in rainfall since 1981. Year-to-year variability has increased over recent decades, and the island experienced record rainfall in consecutive years in 2019 and 2020. The archipelago was quite dry from 2008 to 2018, before turning extremely wet. A continued increase in seasonal rainfall is expected to reach nearly 80 mm by 2050.

Figure 13: Timelines of total seasonal rainfall for the archipelago zone, with linear and non-linear best-fit trendlines
Source: CHIRPS v2 data product.



The annual near-surface temperature in the archipelago (Figure 14) has increased significantly, in a linear fashion as in the other zones. Mean temperatures are expected to reach 27.3°C by 2050.

Figure 14: Timeline of annual near-surface temperature for the archipelago zone, with linear trend and projection
Source: CRU TS v4.07 data product.



Summary

Despite the tremendous uncertainties associated with climate in Yemen, a number of important features can be gleaned from these analyses. The following points should be understood as presented against a backdrop of various layers of uncertainty; substantive discussions with climate scientists should take place before integrating the results into policy and decision-making to ensure appropriate use.

First, a key outcome of these analyses is that the observed near-surface temperature has risen significantly in all subregions or agroecological zones. As trends have been quite linear over the last 60 years, there is high confidence that this trajectory will continue in a similar fashion through 2050. Although subregions such as the southern coastal plain have seen much less change (Figure 4), this does not reflect what is occurring in the rest of the country. In summary, gradients of warming exist, with the lowest levels at the southern coastline and near equal levels elsewhere.

Second, the data show that rainfall patterns are changing across Yemen. For example, observed rainfall during the summer in the highlands and Red Sea coast is increasing significantly. This trend is expected to continue in the future, with high confidence. Not only is mean rainfall increasing but variability is also rising in a significant way, resulting in larger extremes of both high and low levels of precipitation over various timescales. These extremes have manifested as large and often persistent flood events. The spring rains have been declining modestly, resulting in a change of the seasonality of rainfall in both regions that will likely affect agricultural production.

Gadain and Libanda (2023) provide a valuable critical examination of the performance of current state-of-the-art climate models from the IPCC CMIP6. While it is unsurprising that climate models are unable to fully resolve the complex topography of Yemen with respect to rainfall simulations and projections, it is quite valuable to confirm that these uncertainties exist. Despite these uncertainties, the authors also reveal model evidence that corroborates observed increases in rainfall variability, in terms of both the increasing severity and frequency in the future projections. These predictions of heavier future rainfall in the model outputs are realistic based on the observations, particularly if recent years are a strong indicator.

With respect to the range of uncertainty in future projections, this work establishes a baseline for what can reasonably be expected from future trends at a subnational and subseasonal scale. It allows for the distinct possibility that rainfall in the west of Yemen has begun to increase in a non-linear fashion. More research is needed to assess if and the extent to which changes in temperature and precipitation will occur, as well as key aspects of timing, magnitude and extremes. The analyses here are a robust basis, however, for the various statements above to inform policy.

UNDP Yemen. Improving farmers' resilience and agricultural practices for food and livestock production, Taiz, Yemen

Climate change and human development

Climate change is likely to have far-reaching effects across all aspects of human development through its impacts on food and water scarcity, economic disruptions, and migration and displacement. While climate change will affect all populations, it will cause the most damage to the most vulnerable groups, including the poor, women, children and marginalized populations. The following sections discuss the literature around some of climate change's direct and indirect effects on human development.

Literature on climate change and economic and human development

Climate change is expected to affect countries, economies and their populations in myriad ways. One approach to quantify the effects of climate change on economies is by using damage functions, which estimate the relationship between changing climate factors and economic output. This approach is useful for putting a figure on the damage caused by climate change. It has numerous limitations, however, including an inability to represent some impacts, a tendency to smooth over potential effects from extreme events or increasing variability, and a calibration based on underlying studies that are often individually focused on sectors or regions (many from Europe and North America) and are outdated (Diaz and Moore 2017). While this approach is useful for estimating damage at a broad level, it cannot say much about how different countries or regions are expected to incur that damage and, thus, how they might build resilience to climate change's effects.

Based on data and the literature, this report identifies a number of pathways through which climate change may significantly alter human development trajectories in Yemen.

Agriculture and food systems

Rising temperatures will affect crop yields around the world. While higher temperatures along with carbon fertilization may lead to initial increases in yields in more temperate regions, yields are expected to decrease in more tropical and water-constrained regions (Vermeulen et al. 2012). Rising marine temperatures are likely to affect marine productivity differently by region, increasing production in some and reducing it in others (Vermeulen et al. 2012, Watts et al. 2021), while also causing fish stocks to shift across zones (Palacios-Abrantes et al. 2022).

Extreme events, such as flooding, wildfires and storms, may destroy and damage crops, lowering yields and reducing the food supply (Pacetti et al. 2017, Rahman and Di 2020). Continued cycles of drought and floods can exacerbate runoff and erode the soil, hampering yields beyond the immediate term. Moreover, these events may have effects across the food supply chain, including through post-harvest loss and damage to infrastructure for food storage and distribution (Vermeulen et al. 2012).

Floods in Yemen have affected agricultural production through losses of cropland and livestock as well as the destruction of irrigation and other key infrastructure (de Coning et al. 2023). This has led to agricultural income losses as well as increased hunger among farming households for years after a flood (Breisinger et al. 2012, Breisinger and Verner 2013).

The effects of climate change on crop yields vary. While some crops are more heat and drought tolerant, others, such as millet, could see yield reductions due to rising temperatures (Lewis et al. 2018). Much of Yemen's agriculture is rain-fed, making it especially vulnerable to changes and variability in precipitation. The World Bank (2010) found uncertainty around how temperature rise is likely to affect crop production in Yemen, with effects ranging from a 27 percent reduction in production by the end of the century to an increase of 6 percent. The depletion of groundwater reserves, however, is likely to have an even greater effect on agriculture, regardless of the climate change scenario, diminishing production by up to 40 percent (The World Bank 2010).

Livestock farming, especially raising small ruminants, is an important income source for many rural households in Yemen. A recent survey of vulnerable households across the country (FAO 2021) found that nearly 70 percent of respondents participated in livestock farming, and the sale of livestock products was the first or second main source of income for roughly 25 percent. Climate change and continued environmental degradation could affect grazing land and threaten livestock farming, while rising temperatures could amplify the burden of disease (The World Bank 2010). Flooding and other natural disasters can lead to the direct loss of livestock.

Yemeni households will not only be affected by local agricultural effects but also by global changes to agriculture from climate change. Climate change will likely raise food prices (Nelson et al. 2010), which could lead to some benefits in the short term for farming households (Breisinger and Verner 2013). Yemen is highly dependent on imports for food, however. Imports make up 70 percent of food by volume and over 80 percent of calories consumed by Yemenis (IOM et al. 2023). As a result, poor households are especially vulnerable to rising global food prices and shocks to the global market, which could lead to growing poverty and hunger (Breisinger and Verner 2013, Hertel et al. 2010).

Human health

Temperature rise is likely to have direct effects on health through increased mortality and morbidity from heat stress, heatstroke, and cardiovascular and respiratory disease (Green et al. 2019, Watts et al. 2021), including in regions that both are and are not accustomed to high temperatures (Hajat and Kosatky 2010). Older populations (over age 65 years), persons with disabilities and pre-existing conditions, and people who work outdoors are especially vulnerable (Hajat and Kosatky 2010, Watts et al. 2021). With temperatures expected to rise in the Arab region as a result of climate change (ESCWA 2017), Yemen is at risk of seeing more hot days and extreme heat conditions (The World Bank 2021). In a context of limited access to electricity and high dependence on agricultural work, the population is especially vulnerable to health effects from rising temperatures.

Warming is also associated with increased risks and expanded areas with vector-borne diseases (Rocklöv and Dubrow 2020, Watts et al. 2021), while the effect of changing precipitation patterns depends on local context. An increase in precipitation could expand mosquito breeding sites as could the use of water collection during a drought (Rocklöv and Dubrow 2020). Sea-level rise is associated with water quality and supply concerns, disease vectors, flooding and saltwater intrusion and can lead to myriad health effects (Watts et al. 2021), including an increase in waterborne diseases such as cholera and diarrhoeal illnesses (Rabbani et al. 2010). Yemen has already seen severe cholera outbreaks in recent years, spurred by conflict and associated infrastructure collapse (Federspiel and Ali 2018), and associated with periods of heavy rainfall (Camacho et al. 2018).

Extreme events such as storms and flooding can lead to death and injury and may be exacerbated by storm surges in coastal areas (Lloyd et al. 2016). They may also worsen existing health challenges. For example, wildfires may intensify respiratory symptoms, and extreme events may disrupt the delivery of health services across the system (Watts et al. 2021). Dust storms in Yemen, which are associated with climate change-linked environmental factors, can lead to adverse health outcomes, including respiratory effects (Ghalib et al. 2021).

Of all natural disasters, flooding has led to the greatest loss of life and impact on human health in Yemen historically (Dammag 2014, Nasser 2009). In recent years, flooding has killed hundreds of Yemenis and affected hundreds of thousands, including many already displaced or made vulnerable by the conflict (IFRC 2021, OCHA 2020). Flooding has also disrupted humanitarian activities and access to food and services by destroying and blocking road access (IFRC 2021). Losses in agricultural production and incomes have resulted in increased hunger (Breisinger et al. 2012, Breisinger and Verner 2013). Other disasters affecting human lives, causing injuries and health complications, and threatening the economy and human well-being include droughts, earthquakes, tsunamis, landslides and volcanic eruptions (Dammag 2014, Nasser 2009).

Infrastructure and energy

Rising temperatures are likely to strain critical infrastructure such as electrical grids. Hot weather and heat waves place greater pressure on electricity infrastructure and also affect their operation (Panteli and Mancarella 2015). This can lead to power outages, increased prices and higher costs for food storage due to the need for air conditioning and refrigeration (Vermeulen et al. 2012). Extreme weather events, such as flooding and storms, are a major cause of electrical disturbances, including power outages, while coastal power assets are especially threatened due to sea-level rise (Panteli and Mancarella 2015). Rising temperatures are also expected to increase energy demand. The effect of climate change on the energy sector may be especially severe in Yemen, as rising temperatures will increase electricity demand due to rising needs for cooling (RCCC 2021). Recent fuel shortages due to the conflict have caused immense damage. Climate change further exposes fuel production and transportation infrastructure to risk.

The vast majority of economic losses from natural disasters in Yemen have been due to flooding and flash floods (ESCWA 2017), which damage roads and critical water and power infrastructure. Access to electricity is already low, and power shortages and load-shedding are highly disruptive to the economy and to human life (Al-Wesabi et al. 2022). Moreover, roughly half of those with electricity are not connected to the public grid and rely instead on power sources such as diesel generators or solar panels (Al-Wesabi et al. 2022). There is high potential for renewable energy in the country, especially from solar, wind and geothermal sources (Alkipsy et al. 2020, Al-Wesabi et al. 2022, Pacudan 2008). But while in recent years the use of solar energy has grown dramatically in order to cope with the destruction of the electricity grid, these projects are generally small and limited in capacity (Aklan and Lackner 2021).

Energy insecurity is closely linked with housing insecurity, as poor households may not be able to afford the increased costs of heating and cooling in extreme temperatures (Bezgrebelna et al. 2021, Jessel et al. 2019). Extreme events could push people out of their homes and into informal settlements, where they will continue to be more vulnerable and exposed to climate change effects (Bezgrebelna et al. 2021, Sverdlik 2011). Conflict has already left an estimated 4.5 million people displaced internally, many living outside official displacement camps and without access to basic services (IDMC 2023). Severe flooding caused 170,000 displacements in 2022; many were secondary displacements of people already forced to move by conflict (IDMC 2023).

Water stress

Climate change is expected to exacerbate existing water scarcity and stress. This could result in a severe decline in water resources for an additional 15 percent of the global population and a 40 percent increase in the population experiencing absolute water scarcity (Schewe et al. 2014). Many developing countries are already witnessing considerable pressures on water resources due to population and economic growth alone, which in many places will only be worsened by the effects of climate change (Schlosser et al. 2014).

Yemen is one of the most water-stressed countries in the world, and groundwater resources are declining rapidly (Firebrace 2015, Weiss 2015). Renewable freshwater resources are estimated to be 86 cubic metres per capita, less than one fifth of the 500-cubic-metre threshold for absolute water scarcity (Gadain 2023). Future water scarcity will be largely driven by increasing demand due to population growth, growing per capita water demand, technology allowing extraction for irrigation that goes well beyond recharge levels, and rising temperatures and greater variability in rainfall patterns driven by climate change (Aklan and Lackner 2021). The vast majority of available water in Yemen is consumed by the agriculture sector, and about half of that is estimated to be wasted as a result of inefficient irrigation systems (Baig et al. 2019). Disputes over scarce water resources have resulted in violence in the past, a risk which could intensify as the problem worsens (Small Arms Survey 2010). Yemen's water scarcity is not caused by climate change but could be made much worse by rising temperatures, greater variability in precipitation, and more frequent and severe droughts.

Inequality and poverty

Climate change has been linked to increasing inequality globally (King and Harrington 2018), across countries (Ahmed et al. 2009, Diffenbaugh and Burke 2019, Mendelsohn et al. 2006) as well as within countries (Hallegatte and Rozenberg 2017, Paglialunga et al. 2022). Rising global food prices will strain the budgets of poor households, pushing more people into poverty and trapping those already in it (Hallegatte and Rozenberg 2017, Hertel et al. 2010). Through effects on agricultural productivity and markets, climate change may reduce the incomes of many vulnerable farming and rural households (Hertel et al. 2010). Temperature rise could dampen labour productivity for workers in high-intensity sectors such as agriculture (Orlov et al. 2020), while health impacts such as stunting, malaria and diarrhoeal diseases further squeeze budgets and result in lost working days and income (Hallegatte and Rozenberg 2017). Natural disasters cause greater damage in countries with high levels of inequality (Cappelli et al. 2021) and result in disproportionate impacts on poor and vulnerable populations. Moreover, the loss of assets and income from a shock can push individuals into a vicious cycle of loss and vulnerability (Heltberg et al. 2015).

Food accounts for a large share of consumption for most Yemeni households, and historically high food prices have slowed economic growth and contributed to rising poverty levels (Breisinger et al. 2010). Over the past eight years, conflict has thrust even more households into poverty (Arezki et al. 2018; Moyer, Bohl et al. 2019). The vast majority of Yemeni households are net purchasers of food (Breisinger et al. 2010), and most of the poor live in rural areas. Climate change is likely to result in even greater strains on the poorest households and rising rates of poverty and income inequality.

Gender equality

Climate change is likely to further entrench existing gender inequalities. Extreme weather events have led to poorer health and mortality outcomes for women and girls (Fruttero et al. 2023, Ha et al. 2017, Kuehn and McCormick 2017, Neumayer and Plümper 2007). To cope with the need for agricultural labour and due to economic pressure, girls are more likely to drop out of school and women to withdraw from the workforce (Fruttero et al. 2023). With lower wages and limited access to assets and economic opportunities, women are less able to build resilience to withstand and recover from shocks.

Natural disasters may disrupt access to basic services and require households to spend more time on unpaid domestic work, a burden that falls disproportionately on women and girls (Ferrant et al. 2014, Fruttero et al. 2023). Those in poor or rural households may also be affected by growing water scarcity (Regassa et al. 2010, WHO 2014) as they are often dependent on the natural world for food, water and fuel.

Women in Yemen have more limited access to resources and often limited decision-making power in households, especially women without incomes (ACAPS 2023). The rate of female labour force participation is among the lowest in the world at 6 percent. Women's care burden is high (Gressmann 2016). Many women, along with their children, must travel long distances to collect water, which exposes them to physical risk and interferes with their ability to attend school or earn an income (Zabara 2018).

Climate change is likely to exacerbate the challenges faced by women and girls. Increased water scarcity could lead to even further travel to collect water (Luqman and Al-Sakkaf 2022). Women and children are more vulnerable to extreme weather and natural hazards, such as drowning in floods (Luqman and Al-Sakkaf 2022) and have fewer resources to overcome challenges.

Migration and displacement

Climate change could lead to population movements as people move away from areas affected by land degradation, drought, flooding and fires (Burrows and Kinney 2016). By one estimate, climate change could lead to the internal migration of over 200 million people in six regions across the world (Clement et al. 2021). Migration and displacement from climate change can occur due to both slow-onset events, such as changing rainfall patterns and sea-level rise, and sudden events, such as storms and flooding.

Conflict has already generated considerable displacement in Yemen, affecting more than 4.5 million people. Natural disasters have led to nearly 700,000 internal displacements since 2008, with roughly 85 percent of those due to flooding (IDMC 2023). Even while conflict-related displacements have slowed recently, climate-related displacements increased 93 percent in 2022 compared with the previous year (OCHA 2022). Climate change in Yemen could spur further internal migration and displacement both from slow-onset effects as well as from natural disasters, and could even lead to the secondary displacement of already displaced populations.

Photo: UNDP Yemen. Agricultural interventions strengthen farmers' resilience to climate change and improve food production, Hajjah, Yemen.

Effects of climate change on human development in Yemen

This report uses a combination of climate analysis, described above, and integrated modelling and scenario analysis using the IFs model to estimate and project the effects of different climate change impact pathways on human development indicators in Yemen.

International Futures

The IFs model is a global integrated assessment modelling tool that forecasts dynamically linked human and economic development systems as far as 2100. The model simulates interactions within and across 188 countries and 12 core systems: agriculture, demographics, economics, education, energy, environment, finance, governance, health, infrastructure, international politics and technology. IFs has been used to explore the effects of climate change on poverty globally using a damage function approach alongside additional scenario analysis. It has helped to better understand the effects of ongoing conflict on development and potential recovery pathways (Hanna et al. 2021; Moyer, Bohl et al., 2019; Moyer, Hanna et al., 2019). More information about the IFs model can be found in Hughes (2019).

Scenarios

Several scenarios were modelled for this report to explore different methods for measuring the effects of climate change along with different pathways through which climate change is likely to affect human development. The scenarios are summarized in Table 1. Scenarios built for this project were intended to model the most relevant pathways through which climate change is expected to influence human development in Yemen.

Table 1: Summary of human development scenarios used in this report

Scenario name	Description
No Climate	The *No Climate* scenario simulates a world in which climate change does not occur – turning off the linkages in the model.
Climate Change	This scenario models expected global and local effects of climate change using the pathways available in the IFs model, including from rising ambient temperature, an increase in heatwaves, and increased water scarcity, through modeling the effects on health outcomes, labor productivity, water stress, and agricultural productivity, including effects on fisheries. It also models some expected effects from flooding, including reduced food accessibility and damage to infrastructure.
Building Resilience	This scenario models the effect of an integrated package of development improvements intended to build resilience and mitigate the effect of climate change on the most vulnerable. This scenario includes the effect of the *Climate Change* scenario.

The *No Climate* scenario serves as a counterfactual scenario to help measure the effects of climate change on the future of development in Yemen.

The *Climate Change* scenario includes a number of interventions intended to model various pathways through which climate change is expected to affect human development in Yemen. These include:

- Global changes in crop yields in line with climate change expectations
- Reductions in agricultural production through reduced yields and fishery production
- Higher mortality rates due to heat stress
- Reduced labour productivity resulting from rising temperatures
- Destruction and slowed growth of road, water and sanitation infrastructure due to increased flooding
- Growing inequality in the distribution of income and calories in line with the literature

The *Climate Change* scenario is not meant to represent a 'worst case' scenario or to generate a prediction of what Yemen will look like in the future. It is designed to help stakeholders understand the various interacting pathways through which climate change is likely to affect human development.

Finally, the *Building Resilience* scenario simulates the intervention of an integrated package of policies intended to mitigate the effects of climate change on human development and create a more resilient Yemen. Interventions were identified through the literature and assessment of the country's current context. They are ambitious (beyond the otherwise expected development trajectory) but achievable even given severe economic and governmental constraints. These interventions include:

- Improvements in crop yields and an expansion of arable land used for agriculture
- Improvements in the distribution of income and calories
- A more rapid recovery of the educational system from the damage already suffered by conflict
- Expanded access to safely managed water and sanitation, with a targeted effort to improve access for those who are worst off
- Accelerated production of renewable energy
- Expanded access to electricity
- An expansion of the road network
- An increase in welfare transfers (cash transfers) to poor households
- Improved security through a reduction in the probability and magnitude of conflict
- Increased government effectiveness, as measured by The World Bank's World Governance Indicators
- An increase in the female labour force participation rate

Just as the *Climate Change* scenario is not meant to represent a worst or best case of climate change, the *Building Resilience* scenario is not meant to simulate the upper limit of improvement in the country. Instead, it should help policymakers, practitioners and donors better understand how combining policy strategies can help to mitigate the damage from climate change and improve lives and livelihoods in Yemen over the long run.

More details about the specific scenario interventions, their magnitude and supporting evidence are in Appendix 1. The following section explores results from the three scenarios and is followed by a broader discussion.

Results

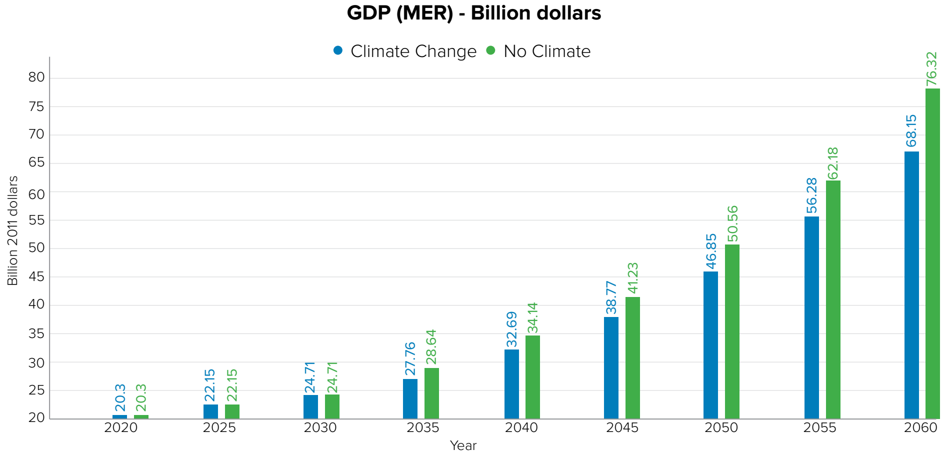
The effects of climate change

Comparing the *Climate Change* scenario with the *No Climate* scenario allows a better understanding of the expected effects of climate change in Yemen in the long run.

Climate Change would lower economic growth relative to *No Climate* gradually over time. By 2060, GDP in a world with climate change would be 10 percent lower than in a world without it. In per capita terms, *Climate Change* would reduce GDP per capita by over $200 or nearly 8 percent. While these overall growth reductions are not catastrophic, over time they would add up to significant lost production and opportunity. By 2060, over $98 billion in cumulative GDP would be lost due to climate change (Figure 15).

Figure 15: GDP at market exchange rates in Yemen

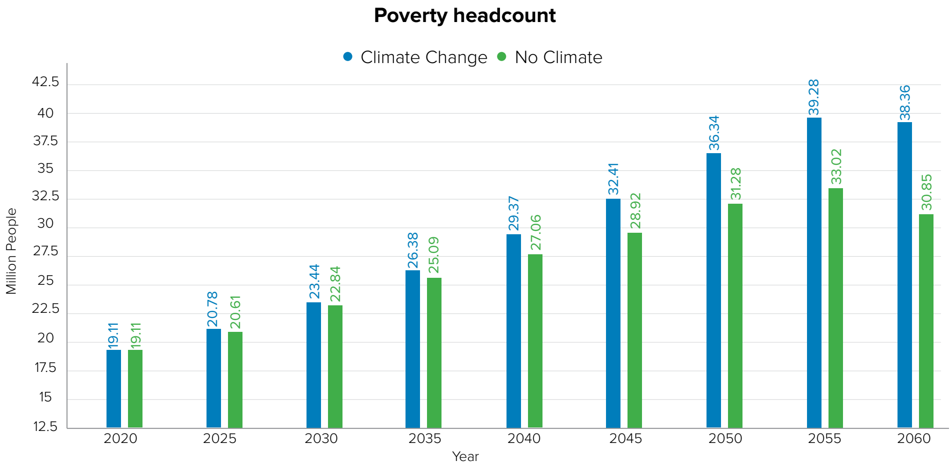
Source: IFs 8.02.



Damage from climate change would be felt most strongly by already poor and vulnerable populations who lack the adaptive capacity to cope with rising prices, natural disasters and additional health complications. Conflict has already thrust millions of Yemenis into poverty and, even in a *No Climate* scenario, poverty rates are projected to fall only gradually, leaving nearly half (49 percent) of the population living on less than $2.15 per day by 2060. *Climate Change* would place additional burdens on vulnerable households and result in a nearly stagnant poverty rate, reaching 60 percent by 2060. The poverty headcount is expected to grow in both scenarios due to population growth. *Climate Change*, however, would result in 7.5 million more Yemenis living in poverty by 2060 (Figure 16).

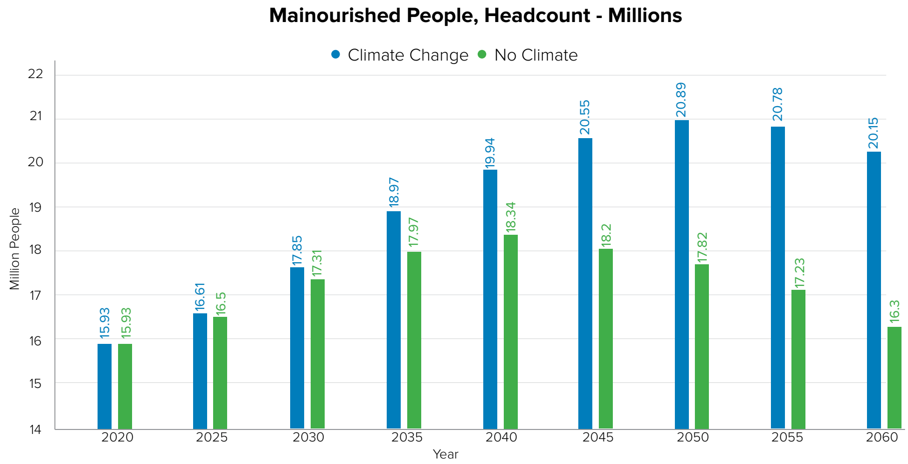
Figure 16: People living in extreme poverty in Yemen, $1.90 per day threshold, in millions

Source: IFs 8.02.



Through water stress, effects on infrastructure and a reduction in food accessibility, the *Climate Change* scenario would have impacts on hunger across the population. As food access becomes more unequal while incomes are constrained and the population grows rapidly, malnutrition is expected to increase in coming decades, even beyond the *No Climate* projection. By 2060, climate change would result in over 3.8 million additional malnourished people (Figure 17).

Figure 17: Malnourished population in Yemen, millions
Source: IFs 8.02.



Through the direct health effects of heat stress as well as the indirect effects of water stress, poverty and malnutrition, *Climate Change* would lead to higher rates of mortality. By 2060, it would be responsible for 131,000 excess deaths, or deaths that would not occur in a *No Climate* scenario. *Climate Change* would also slow the reduction in infant mortality, resulting in an infant mortality rate two times higher than under the *No Climate* scenario. The under-5 child mortality rate would be 2.2 times higher.

Building resilience

Climate change will affect development and lives in Yemen in many ways. Some are well known; many more are uncertain. Yemen produces very few carbon emissions and makes a minimal contribution to the global problem of climate change, so there is little space to slow the process on a country level. It is possible, however, to adapt and build resilience to the likely and potential challenges that climate change will pose. The *Building Resilience* scenario includes a number of interventions identified in the literature and through analysis that can enable Yemen to adapt and develop even with *Climate Change*. This is not a scenario meant to simulate Yemen's greatest potential for development, but it does encapsulate a reasonable set of interventions providing moderate protection against the effects of climate change.

Table 2: Results across key indicators for all scenarios in 2022, 2030, 2045 and 2060
Source: IFs 8.02.

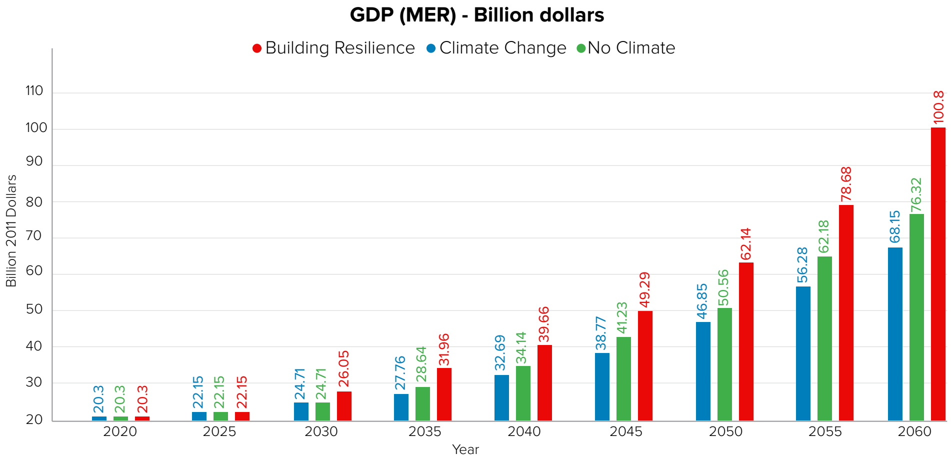
	Scenario	2022	2030	2045	2060
GDP, market exchange rates (billions of dollars)	*No Climate*	20.4	24.7	41.2	76.3
	Climate Change	20.4	24.2	38.8	68.2
	Building Resilience	20.4	26.1	49.3	100.8
GDP per capita at purchasing power parity (thousands of dollars)	*No Climate*	1.67	1.77	2.16	3.0
	Climate Change	1.67	1.74	2.04	2.78
	Building Resilience	1.67	1.83	2.4	3.69
Extreme poverty rate (percentage, at $1.90 per day threshold)	*No Climate*	61	58	55	49
	Climate Change	61	59	62	61
	Building Resilience	61	57	50	38
Extreme poverty headcount (millions, at $1.90 per day threshold)	*No Climate*	20.2	22.8	28.9	30.9
	Climate Change	20.2	23.4	32.4	38.4
	Building Resilience	20.2	22.7	25.6	23.3

	Scenario	2022	2030	2045	2060
Malnourished population (percentage)	*No Climate*	48.5	43.9	34.9	25.9
	Climate Change	48.5	45.3	39.3	31.8
	Building Resilience	48.5	35	19.1	10.8
Malnourished population (millions)	*No Climate*	16.2	17.3	18.0	16.3
	Climate Change	16.2	17.9	20.6	20.2
	Building Resilience	16.2	13.8	9.9	6.6
Under-5 child mortality rate (deaths per 1,000 live births)	*No Climate*	47.9	41.6	29.9	19.8
	Climate Change	47.9	42.8	31.8	22.1
	Building Resilience	47.9	39.1	24.1	14.8

In *Building Resilience*, GDP growth would accelerate well beyond both other scenarios, resulting in cumulative gains of $400 billion relative to the *Climate Change* scenario by 2060. GDP per capita would be one third greater (Figure 18).

Figure 18: GDP at market exchange rates in Yemen

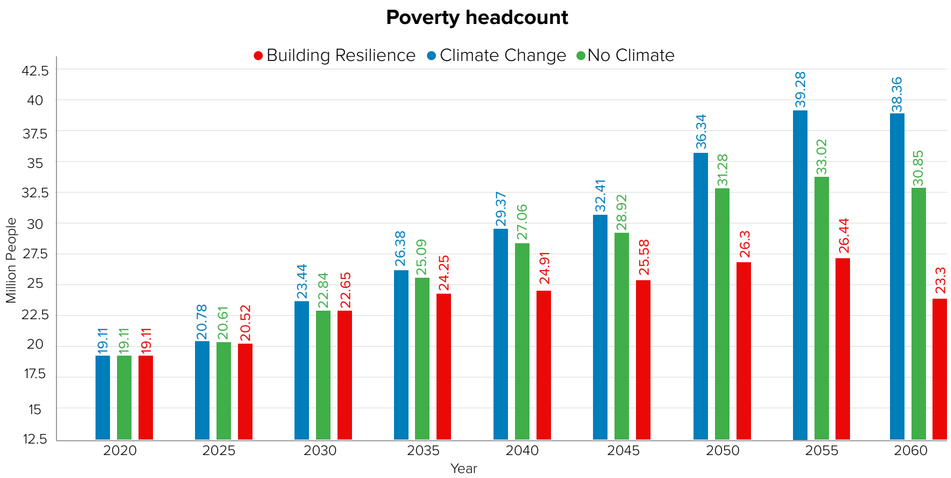
Source: IFs 8.02.



Extreme poverty would fall through a concerted effort to support poor and vulnerable populations and mitigate the inequality effects of climate change. The rate of people living in extreme poverty would drop by more than 20 percentage points from a high in recent years of over 60 percent. The total poverty headcount would continue to grow along with the population, but much more slowly, with 15 million people leaving extreme poverty by 2060 compared with the *Climate Change* scenario (Figure 19).

Figure 19: People living in extreme poverty in millions, Yemen

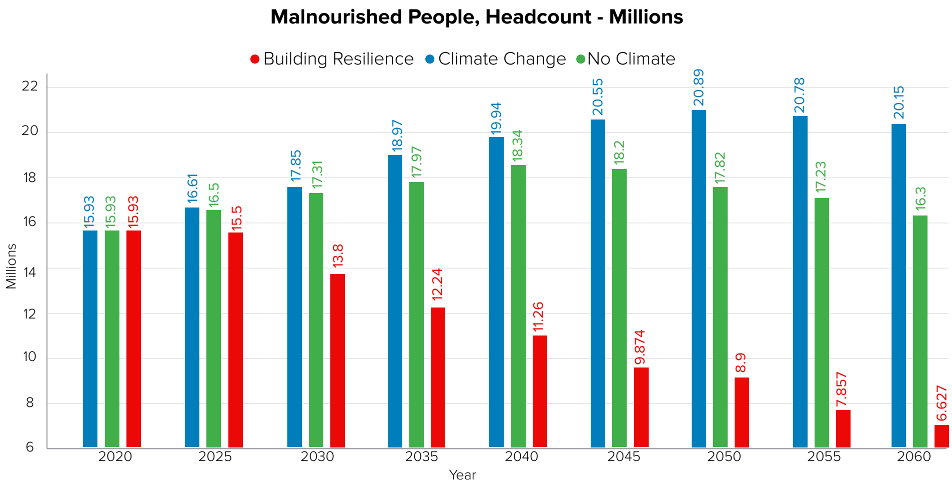
Source: IFs 8.02.



Through an effort to improve equality in access to calories, the *Building Resilience* scenario would result in a significant reduction in the number of malnourished people, which is expected to rise in both the *Climate Change* and *No Climate* scenarios as a result of population growth. Through the *Building Resilience* scenario, more than 13 million people would be pulled out of hunger relative to the expectation under *Climate Change* (Figure 20).

Figure 20: Malnourished population in Yemen, millions

Source: IFs 8.02.



The *Building Resilience* scenario would result in improved health outcomes across the population. Overall, it would see 437,000 fewer deaths than under the *Climate Change* scenario through 2060, more than making up for the expected effect of *Climate Change* described above. Improvements in health and infrastructure would have an especially significant impact on the mortality of younger age groups, reducing the infant mortality rate by 38 percent below the expected rate by 2060. Under-5 child mortality would decline by nearly one third (Figure 21).

Figure 21: Under-5 child mortality rate in deaths per 1,000 live births, Yemen

Source: IFs 8.02.

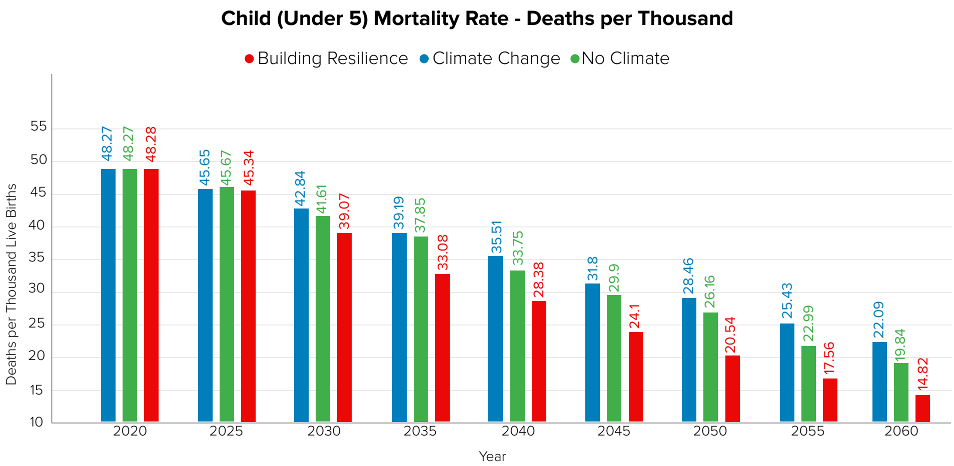


Photo: UNDP Yemen. Cash-for-work programme to safeguard farms against future disasters, Socotra, Yemen.

Conclusions and recommendations

While much about climate change and its implications for Yemen remain highly uncertain, this work establishes a baseline of what can be reasonably expected from future trends at a subnational and subseasonal scale, and allows for the distinct possibility that rainfall in the west of Yemen has begun to increase in a non-linear fashion. Yemen is expected to experience rising temperatures and will likely see an increase or at least a continuation in the frequency and magnitude of severe events like flooding.

Climate forecasts have different implications for each zone, though some events and outcomes will occur in most if not all zones. More frequent, severe and persistent flood events are projected in the highlands zone, producing a number of significant outcomes. Already, the loss of human life has occurred due to flash flooding, as dams have burst. Streets have been submerged and homes and property damaged. Floods inundate fields, damaging crops and irrigation and other infrastructure, and preventing efforts to repair them. Damage to shelters at internally displaced people's camps is causing further human displacement. Livelihoods have been deeply disrupted, leaving many without access to shelter, clean water, and sanitation and hygiene facilities. Bacterial diseases outbreaks such as cholera will continue to accompany extremely wet conditions. Humanitarian food distribution and other interventions are more difficult with the flooding and loss of critical infrastructure. The modest development gains that have occurred are often wiped away.

In eastern Yemen, rising temperatures and drought conditions cause dust events, which have health consequences, such as irritation to the eyes, nose and throats of both humans and livestock. Along the Red Sea and Gulf of Aden coasts, desert locusts have been sighted, their presence aided by continued and increased rainy conditions. Coastal residents' livelihoods rely strongly on fishing and other marine resources, and continued sea-level rise will create further challenges, including increased risks of coastal flooding and salt-water intrusion. Rising temperatures along the coast have led to a higher incidence of heat waves, affecting health.

At a national level, these effects will likely slow economic growth and result in lost opportunities. Climate change will also worsen inequality, pushing more people into poverty and malnutrition than would be the case otherwise, and leading to 131,000 excess deaths. While there is little that Yemen can do to walk back climate change on its own, there remains plenty of opportunity to build resilience and prevent the worst of the potential damage.

The *Building Resilience* scenario offers a view into a world in which Yemen can recover from its current crises and better prepare for the risks posed by climate change. This is a recovery led by Yemenis that leverages the country's rich renewable resources along with its population, including and especially women. Critically, it also is a recovery that must be supported by a working and effective government as well as international support. The total gains in economic output from this scenario exceed $400 billion, with 15 million fewer Yemenis in poverty, 13 million fewer suffering from hunger, and 437,000 lives saved.

Based on this report, we recommend the following priorities for building resilience to climate change in Yemen.

1. **Prioritize food security and accessibility to the poor.** Food security is and will continue to be one of the greatest risks from climate change. Yemen relies heavily on imports for food and, even in an optimistic scenario, will continue to do so for the foreseeable future. This makes it vulnerable to rising global food prices, a vulnerability exacerbated by limited access to foreign exchange. Climate change is likely to have adverse effects on agricultural production, including fishery production, on which many poor and coastal households rely to survive. In addition, existing production practices, including a heavy focus on qat, are highly water-intensive and linked with land degradation, jeopardizing the future of agriculture and water security. Policy interventions should include measures to improve agricultural productivity in a sustainable manner, such as through more efficient irrigation

systems; increase food production with a focus on climate-resilient crops; address high food prices and ensure that poor households have access to food.

2. **Emphasize and invest in water security.** Yemen would be critically water stressed even without climate change, which threatens to exacerbate and complicate the problem. The *Climate Change* scenario includes the effects of increased water stress on yields and of limited water access, but it may even underestimate the potential effects of running dry. Building resilience to this challenge requires all policy measures to be water sensitive, especially considerations for agriculture and development. Expanding access to clean water is also critical in improving child health and preventing disease outbreaks.

3. **Continue efforts to reach a peaceful end to the conflict and improve security.** The effects of climate change pale in comparison to the effects of years of devastating conflict (Hanna et al. 2021; Moyer, Bohl et al. 2019). The *Climate Change* scenario assumes a low level of continued conflict. Further escalation would be devastating for human development, while an end to the conflict and improvements in security and government effectiveness, including strengthening governance systems across levels, could result in vast improvements to human well-being. If Yemen is to weather the uncertain future of climate change, security and governance are critical to building prosperity and resilience.

4. **Invest in women's empowerment to reach the most vulnerable and to accelerate growth across the population.** A better future in Yemen depends on gender-sensitive development and the role of women in building it. Women are already especially vulnerable and stand to suffer disproportionately from the likely effects of climate change on health, hunger and poverty. Protecting and directing policies to help women and girls specifically will be vital to mitigating climate change's societal damage. At the same time, the economic and social empowerment of women represents a significant opportunity to build peace, resilience and prosperity.

5. **Call on the international community to support Yemen.** Significant financial resources will be required to build resilience to climate change in Yemen. It is already experiencing one of the world's worst humanitarian and development crises, while being one of the countries most vulnerable to climate change, a global problem caused by the richest countries. At the United Nations Climate Change Conference in 2022, countries agreed to provide funding for loss and damage suffered by vulnerable countries. This and other commitments will be critical to saving lives and alleviating suffering resulting from climate change in Yemen. At the same time, it will be essential to improve capacities to access and mobilize climate financing within the country.

Yemen faces numerous complex challenges to development, including ongoing conflict, split and competing systems of governance, severe water stress and low agricultural productivity. Climate change will further complicate the road to recovery, although considerable uncertainty remains about exactly how. While climate change will cause additional challenges, transformative actions and an integrated push for development can more than make up for the damages and set Yemen on the path to a more positive future.

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Appendix 1: Detailed assumptions for IFs scenarios

This appendix provides detailed information about the interventions used in the IFs model for each of the three scenarios assessed for this report: *No Climate*, *Climate Change* and *Building Resilience*.

No Climate

The *No Climate* scenario includes several interventions meant to shut off forward linkages between climate change-related variables and economic and human development variables. It also comprises several interventions meant to adjust the baseline in the model to reflect data and known information about Yemen's context (Table A.1.1).

Table A.1.1: Detailed interventions for the No Climate scenario

Note: The IFs operationalization column lists the specific parameter used in the IFs model and how that parameter was modified for each intervention.

Intervention	General description	Literature backing	IFs operationalization
BASELINE ADJUSTMENTS: The following interventions were made to fine-tune the IFs model to better reflect the current development situation in Yemen based on existing data and literature. They are included as the baseline for all scenarios.			
Income inequality increase	The Gini coefficient is increased by 20 percent and maintained through 2100.	In the current version of IFs, this intervention yields a level of poverty similar to that modelled in previous work looking at the effect of conflict on Yemen (Moyer, Bohl et al. 2019), which was supported by two microsimulation studies (Arezki, Mottaghi, Barone, Fan, Harb et al. 2018; Arezki, Mottaghi, Barone, Fan, Kiendrebeogo et al. 2018).	*ginidomm* initialized at 1.2 and held over the horizon.
Caloric coefficient of variation	The caloric coefficient of variation is increased by 20 percent and maintained through 2100.	The coefficient of variation parameter mirrors that of the Gini, reflecting inequality in access to food.	*clpccvm* initialized at 1.2 and held over the horizon.
Reductions across the education system	Educational variables, including intake, graduation and transmission rates across primary and secondary levels, are reduced.	Conflict in Yemen resulted in reduced access to education (Moyer, Bohl et al. 2019; UNICEF 2018). This intervention adjusts the current path to reflect this challenge early in the time horizon.	The following parameters are changed to 0.75 through the current conflict years before being slowly returned to 1 by the end of the horizon: *edpriintnm, edprisurm, edseclowrgram, edseclowrtranm, edsecupprgram, edsecupprtranm.*
Reduction in electricity access	Electricity access is reduced to 43 percent of the population.	According to the latest data from the International Energy Agency (IEA 2020), in 2019, just 43 percent of Yemenis had access to electricity.	*infraelecaccm* for the total is set at 0.55 and maintained throughout the horizon.

Intervention	General description	Literature backing	IFs operationalization
NO CLIMATE ADJUSTMENTS: The following scenarios are made exclusively in the No Climate scenario in order to simulate a counterfactual world without climate change.			
Climate change forward effects turned off	A number of parameters are used to mute the effect of climate change on agriculture and the economy in the IFs model.	NA	*envco2fert* and *envylchgm* are set to 0 through the horizon, turning off effects on crop yields. *climeconimpsw* and *climeconimpperctrysw* are set to 1 through the horizon while *climeconimpsq* is set to 0.

Climate Change

The *Climate Change* scenario includes interventions meant to simulate the pathways through which climate change is likely to impact human development in Yemen according to data and literature (Table A.1.2). These interventions are made on top of the baseline interventions listed in Table A.1.1.

Table A.1.2: Detailed interventions for the Climate Change scenario

Note: The IFs operationalization column lists the specific parameter used in the IFs model and how that parameter was modified for each intervention.

Intervention	General description	Literature backing	IFs operationalization
Temperature and precipitation series	Country-level projections for temperature and precipitation in an RCP 6.0 scenario are imposed exogenously.	Series on projected temperature and precipitation change are taken from CMIP5 projections.	*Ifsexomodeltype* is set to 1 through the horizon, indicating that the exogenous series should be taken in as absolute values. *ifsexomodelid* is set to 163, identifying the appropriate exogenous series.
Increased mortality from heat stress	Mortality and morbidity rates grow for cardiovascular and respiratory diseases due to the effects of heat stress, such that overall mortality rates increase by 4 percent by 2100.	Bressler et al. (2021) estimate net increases in mortality rates from temperature-related mortality in an RCP 4.5 and RCP 8.5 world for a number of countries (excluding Yemen). According to their figures, neighbours (Ethiopia, Oman and Saudi Arabia) had mortality rates rise from 2 to 7 percent by the end of the century across the two scenarios.	*hlmortm* for cardiovascular, respiratory and other non-communicable diseases all interpolated to 1.2 by 2100.

Intervention	General description	Literature backing	IFs operationalization
Reduced productivity	Labour productivity is reduced by 7 percent by 2100 to reflect an expectation that it will fall due to rising temperatures, especially for outdoor and high-intensity sectors, like agriculture.	Orlov et al. (2020) predicts reductions in worker productivity regionally and by intensity of work. Productivity loss estimates from Western Asia in an RCP 8.5 scenario are used and reduced by 30 percent for a more reasonable climate change scenario. The following intensity levels are assumed: high (agriculture), moderate (energy, materials, manufacturing, services) and low (information and communications technology) to create a weighted average expected productivity loss estimate for Yemen of 6.7 percent. If services is categorized instead as low intensity, expected productivity loss is 5.85 percent. It is categorized as moderate due to low rates of access to electricity and cooling in Yemen.	Beginning in 2023, *mfpadd* is interpolated to -0.002 by 2100 so that the loss in labour productivity by 2100 is just below 7 percent, compared to the No Climate scenario.
Increased water stress	Exploitable, renewable water is reduced by 30 percent, which has further effects on agricultural yields.	Climate change is expected to reduce fresh groundwater availability. The impact of climate change could speed up the observed rate of groundwater abstraction by up to 15 percent (van der Gun 2009).	Beginning in 2023, *watresexploitrenewm* is interpolated to 0.7 over 10 years. *watertoyieldswitch* is set to 1.
Income distribution	Income inequality grows, as measured by the Gini, which increases by roughly 25 percent above the No Climate baseline.	The literature suggests that climate change is likely to lead to an increase in income inequality. Paglialunga (2022) identifies a relationship in which a 1 percent increase in temperature is associated with a 0.5 percentage point increase in the Gini coefficient on a 100-point scale.	*ginidomm* increases from a baseline of 1.2 to 1.5 over 30 years. This results in a change to Gini reflecting the elasticity identified in Paglialunga 2022.
Caloric distribution	Food access becomes less equal.	Climate change is likely to result in increasing inequality in access to food as a result of changes to local agricultural production and global food prices (Havlík et al. 2015).	*clpccvm* increases from a baseline of 1.2 to 1.4 over 25 years.
Infrastructure, roads	The expansion of the road network slows due to regular flooding events and other disasters.	Climate change is likely to result in more frequent and intense weather events, like flooding. Flooding in Yemen in recent years has resulted in considerable damage to road infrastructure (IFRC 2023).	*infraroadm* falls to 0.8 over 50 years.
Infrastructure, sanitation	The expansion of safely managed access to sanitation slows due regular flooding events and other disasters.	Climate change is likely to result in more frequent and intense weather events, such as flooding, which both damage existing infrastructure and prevent the expansion of new connections, while also displacing populations.	*sanithhm* for the 'safely managed' category falls to 0.9 over 25 years.

Intervention	General description	Literature backing	IFs operationalization
Infrastructure, water	The expansion of safely managed access to water slows due to regular flooding events and other disasters.	Climate change is likely to result in more frequent and intense weather events, such as flooding, which both damage existing infrastructure and prevent the expansion of new connections, while also displacing populations.	*waterhhm* for the 'safely managed' category falls to 0.9 over 25 years.
Reduced agricultural production	Reduced crop yields and cropland.	Climate change in Yemen is likely to result in reduced agricultural production due both to warming temperatures in some regions and increased extreme weather (Lewis et al. 2018, The World Bank 2010).	*ylm* and *ldcropm* decline to 0.8 over 25 years.
Reduced fishery production	Reduced agricultural productivity from fish catch and fisheries.	Ocean warming and acidification leads to reduced fish catch and shifting fish stocks (IPCC 2023). Yemen is one of the most vulnerable economies to potential climate change effects on fisheries (Allison et al. 2009).	*fishcatchm* reduced to 0.7 over 30 years.

Building Resilience

The *Building Resilience* scenario assumes the same level of climate change as the Climate Change scenario, so includes all those interventions as a base. Table A.1.3 lists the additional interventions.

Table A.1.3: Detailed interventions for the Building Resilience scenario, which are layered onto the Climate Change scenario

Note: The IFs operationalization column lists the specific parameter used in the IFs model and how that parameter was modified for each intervention.

Intervention	General description	IFs operationalization
Agricultural improvements	Improvements in crop yields and an expansion of arable land used for agriculture, alongside improvements in fish production.	*ylm* is increased to 1.3 over 10 years while ldcropm is increased to 3. *fishcatchm* is increased to 3 over the same period.
Caloric coefficient of variation	The caloric coefficient of variation, a measure of the inequality of calorie distribution, is reduced.	*clpccvm*, initialized at 1.2 to reflect climate change, is returned to 1 over 20 years.
Improvements across the education system	The education system improves more rapidly from the damage experienced due to conflict.	The following parameters are initialized at 0.75 and returned to 1 over 10 years: *edpriintnm, edprisurm, edseclowrgram, edseclowrtranm, edsecupprgram, edsecupprtranm*.
Improved access to safe water	Access to safely managed water resources is expanded, while the portion of the population living off surface water is reduced.	*waterhhm* for safely managed water is increased to 1.2 over 10 years, while *waterhhm* for surface water is reduced to 0.8 over the same period.
Improved access to sanitation	Access to safely managed sanitation is expanded, while the portion of the population using open defecation is reduced.	*sanithhm* for safely managed water is increased to 1.2 over 10 years, while *sanithhm* for surface water is reduced to 0.8 over the same period.

Intervention	General description	IFs operationalization
Road network expansion	The road network is expanded.	*infraroadm* is increased to 1.2 over 10 years.
Increased renewable energy production	The generation of renewable energy from wind, solar and geothermal sources is boosted.	*enpm* for the OthRenew category, which encompasses wind, solar, and geothermal energy, is interpolated to 2 over 10 years.
Expansion of electricity access	Electricity access expands across the populations.	*Infraelecaccm* is increased from its original position of 0.55 to 1 over 10 years.
Improved security	The security situation improves and conflict declines as measured by the likelihood and magnitude of conflict.	*sfintlwaradd*, a measure of the likelihood of internal war in a forecast year, is reduced to -.2, while *sfintlwarmagm*, measuring the magnitude, is reduced to 0.8, both over 10 years.
Cash transfers to poor households	Cash transfers increase and are directed towards poorer households.	*govhhtrnwelm* is increased to 1.4 over 20 years, directed toward unskilled households.
Improved government effectiveness	Government effectiveness, as measured by The World Bank's World Governance Indicators, improves.	*goveffectm* is increased to 1.5 over 10 years.
Female labour force participation	Women's participation in the labour force grows.	*labparm* for females is increased to 1.5 over 10 years.

Appendix 2: Climate modelling comparisons

Global climate models have frequently been used to predict future changes, globally and regionally, using different scenarios or pathways forward into the future forced by increases in greenhouse gas emissions. Global and regional climate models have gradually increased their spatial resolution and modelling complexity over the last several generations of the IPCC reports. The typical spatial resolution of the current generation is on the order of 1 to 2 degrees of latitude by 1 to 2 degrees of longitude. Although higher-resolution models are available for regions similar in size to Yemen, which is roughly 10 degrees of longitude by 6 degrees of latitude in size, models have had difficulty in resolving rainfall over particularly complex topography. Models may also exhibit regional biases with respect to climatologies, and temporal and spatial variability. These uncertainties are discussed here within the context of what has been observed for Yemen's climate variability, trends and extremes at the subnational scale and on seasonal to subseasonal timescales. These analyses are used to evaluate the climate model simulations and provide baselines for climate projections.

This report utilizes highly regarded rainfall data from the Climate Hazards Center of the University of California Santa Barbara (CHIRPS v2) and temperature data from the University of East Anglia's Climatic Research Unit (CRU v4.07). The CHIRPS data allow an examination of 10-day rainfall from 1981 through the present day at a very high spatial resolution. The CRU data have a spatial resolution of 0.5 degrees of latitude by 0.5 degrees of longitude.

Recent research (Gadain and Libanda 2023), hereafter referred to as GL2023, examines future heavy rainfall events in Yemen according to the most recent IPCC Coupled Model Intercomparison Project (CMIP6) climate models. This report draws from those examinations and further analyses the best-performing models to assess uncertainty in future projections within Yemen. Employing statistical techniques, a range of possible future trajectories of these metrics is produced, followed by a discussion of the range of uncertainties.

Results

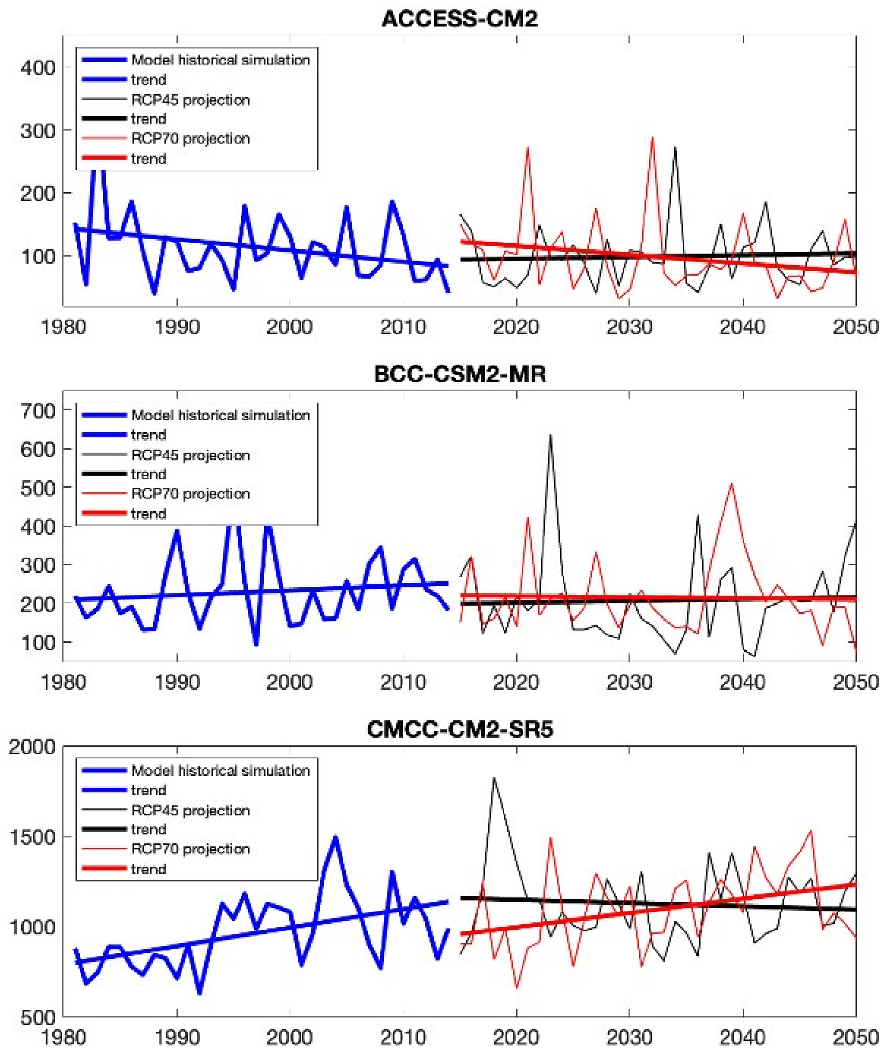
Of the 11 climate models tested in the GL2023 study, three models (ACCESS, BCC and CMCC) were the best performing. Because climate models perform differently, it is sound practice to create a multimodel ensemble, typically using a minimum of three models over a minimum of a 20-year period, when evaluating respective climate parameters. The study used a Taylor diagram to compare the reference observed data (CHIRPSv2) to the 11 climate models, examining the correlation coefficient, root mean square difference and standard deviation in a single mathematical diagram. The two best-performing of the 11 models were combined into an ensemble, with the other models discarded. Two Yemen regions were evaluated, the western highlands and the Red Sea coast/Tihama Plain. The study used three metrics to evaluate heavy rainfall intensity and frequency. Overall, particularly over the highlands, the authors found "weak and often contrasting correlations between individual CMIP6 models and the reference dataset" (Gadain and Libanda 2023, p. 5).

For the Red Sea coast (Figure A.2.1), the two best-performing models according to GL2023 were the CMCC and BCC-CSM2 (with correlation coefficients of up to 0.3). For the highlands (Figure A.2.2), the two best-performing models were the ACCESS and BCC-CSM2 (with a correlation coefficient of $R^{\sim}.2$ to .3). In both regions, GL2023 found the use of ensembles showed modest improvement over individual models alone, particularly over the coast (to $R^{\sim}.6$ and $R^{\sim}.5$, respectively).

The model simulations over the ensemble historical reference period (1981 to 2005) were able to correctly reproduce some large-scale features of the observations, such as simulating the heaviest rainfall over the highlands and demonstrating an east-west gradient in rainfall. The models in the ensembles, however, demonstrated a number of shortcomings with respect to the CHIRPS reference data.

Ensembles tended to overestimate climatological rainfall, especially over the coastal (Figure 1) region. Large differences were also apparent in spatial trends. The three models employed disagreed on the trend in annual rainfall from 1981 to 2014. The model historical simulations ended in 2014 with the projections beginning in 2015. None of the models exhibited the recent (2015 to 2022) apparent increase in rainfall that has been observed. The ACCESS model most closely resembled the observed drying over the reference period. The CMCC model simulated a robust wetting trend over the same period. With respect to the model projections, a surprising feature was the difference in the sign of the predicted trends between the RCP 4.5 and RCP 7.0 scenarios, for each model. These findings confirm that there is substantial uncertainty in future climate projections, even for these best-performing models.

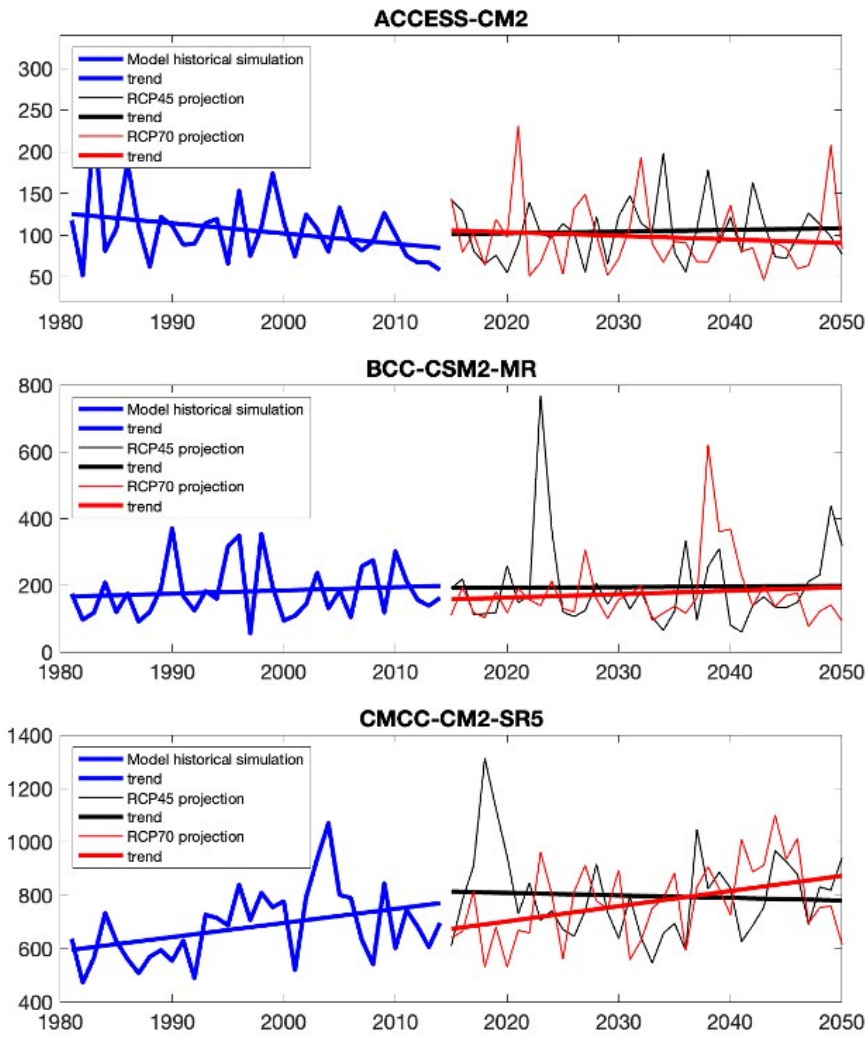
Figure A.2.1: Timelines of total annual rainfall for the coastal zone, for three IPCC CMIP6 climate models



The third of the three CMIP6 models (CMCC) simulated year-to-year highlands rainfall variability that was much larger than in the observations over the reference period of 1981 to 2005 (Figure A.2.2). The three models employed disagreed with each other with respect to the trend in annual rainfall from 1981 to 2014. As in the coastal case, projected future trends also disagreed with each other, particularly with respect to the opposite sign of the trends under the RCP 4.5 and RCP 7.0 scenarios. The GL2023 study, using empirical probability density functions from the model scenarios, does show valuable corroborating evidence for the changing shape of the distribution of rainfall towards heavier rainfall events as the radiative concentration increases.

The study reports: “The number of heavy rainfall days (R10 mm) is (also) expected to increase substantially and with larger variability under SSP5-8.5 compared to the SSP2-4.5 scenario.” It goes on to state that “...with anomalies of up to 110 mm per year, heavy rainfall events (R95p) are again expected to be more intense over the highlands than over the Red Sea coast and Tihama Plain. In both cases, however, the heaviest rainfall events are expected over southern parts of Dhamar, Raymah, Ibb, Al Dhale’e, and parts of eastern Taizz. By the mid-century, we observe a downward gradient of heavy rainfall from the north to the south of the Red Sea coast and Tihama Plain region with southern Al Hudaydah being expected to experience heavier downpours ranging between 75 and 80 mm under SSP2-4.5 relative to the 1981–2005 baseline period” (Gadain and Libanda 2023, p. 8).

Figure A.2.2: Timelines of total annual rainfall for the highlands zone in three IPCC CMIP6 climate models



Summary and conclusions

The recent modelling study performed by GL2023 provides a valuable critical examination of the performance of current state-of-the-art climate models from the IPCC CMIP6. While it is unsurprising that climate models are unable to fully resolve the complex topography of Yemen with respect to rainfall simulations and projections, it is quite valuable to confirm that these uncertainties exist. Despite these uncertainties, the authors of GL2023 also reveal model evidence that corroborates observed increases in rainfall variability, in terms of both mounting severity and frequency in future projections. These predictions of heavier future rainfall in the model outputs are realistic based on the observations, particularly if recent years are a strong indicator.

United Nations Development Programme (UNDP)
60th Meter Road
P.O. Box: 551 Sana’a, Republic of Yemen

Website: http://ye.undp.org