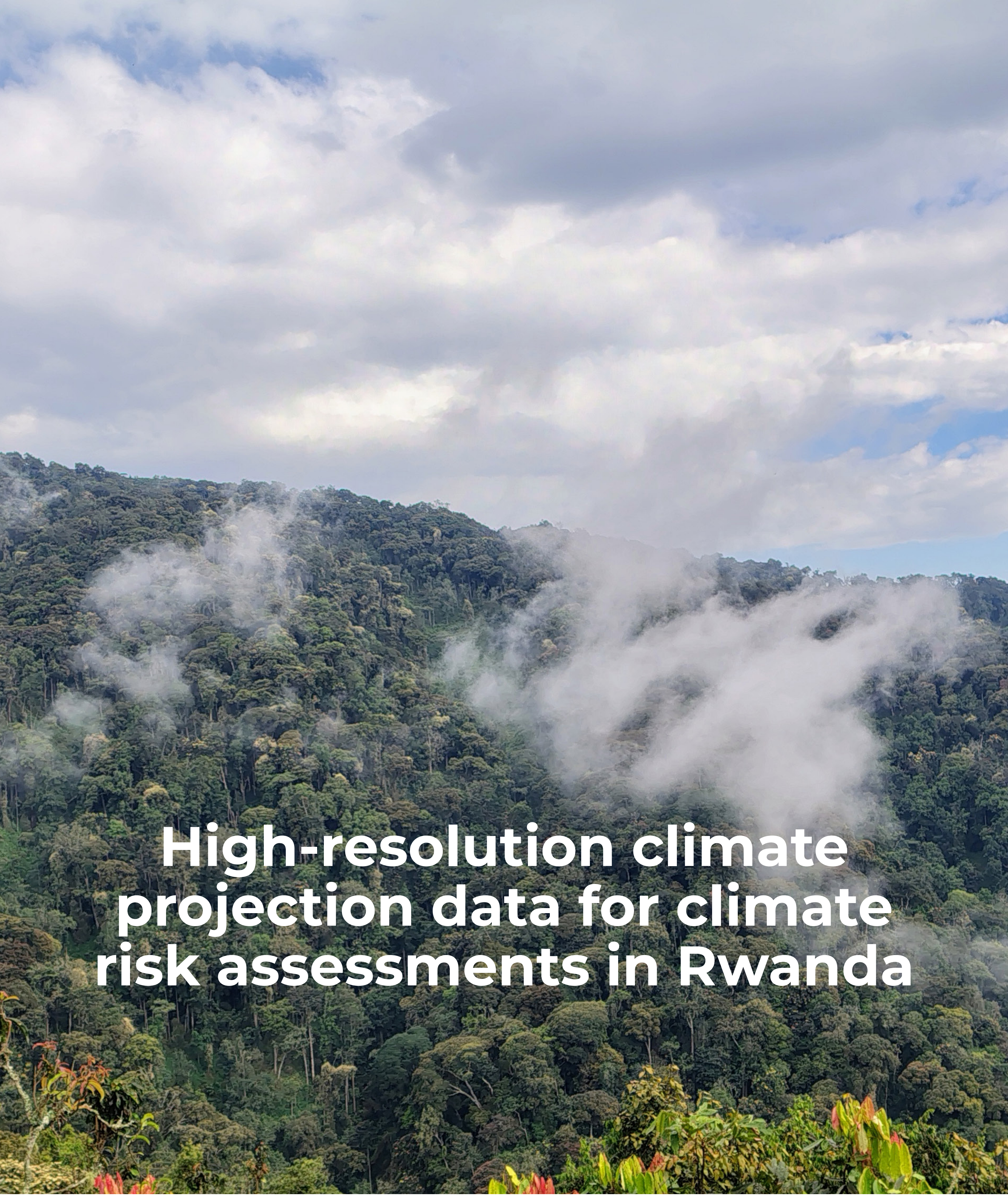

High-resolution climate projection data for climate risk assessments in Rwanda

Rwanda Meteorology Agency

german cooperation
DEUTSCHE ZUSAMMENARBEIT

Implemented by giz

PIK

Description

This report has been produced in collaboration between the Rwanda-German bilateral project Capacity Development for the Implementation of Rwanda's Nationally Determined Contribution (NDC), implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ), the Rwanda Meteorology Agency (Meteo Rwanda), and the Potsdam Institute for Climate Impact Research (PIK) through the Providing High-Resolution Climate Projections for Agricultural Impact Assessment (HiClAP) initiative.

Citing this report

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Abbreviations

CHELSA	Climatologies at high resolution for the earth's land surface area
CMIP	Coupled Model Intercomparison Project
CORDEX	Coordinated Regional Climate Downscaling Experiment
GCM	Global Climate Model
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
ISIMIP	InterSectoral Impact Model Intercomparison Project
LDC	Least developed country
NDC	Nationally Determined Contribution
RCP	Representative Concentration Pathway
SRES	Special Report on Emissions Scenarios (IPCC)
SSP	Shared Socioeconomic Pathway
UNFCCC	United Nations Framework Convention on Climate Change
WCRP	World Climate Research Programme

1. Introduction

1.1 Country context

Rwanda is a landlocked country in East Africa, bordered by Tanzania, Burundi, the Democratic Republic of Congo, and Uganda, with a total area of 26,338 km^2 (Republic of Rwanda, 2018, 2020, 2026). The total population is about 13.2 million people, out of which 72.1% are living in rural areas (National Institute of Statistics of Rwanda (NISR), 2023). The capital, Kigali, is the most urbanized City (National Institute of Statistics of Rwanda (NISR), 2023). With 503 people per km^2, Rwanda is densely populated compared to other African countries, and the population is projected to further increase in the future (National Institute of Statistics of Rwanda (NISR), 2023). Rwanda has a constant GDP per capita of 994.2 US$ and is considered a least developed country (LDC) according to the United Nations Committee for Development Policy (United Nations Committee for Development Policy, 2024). Rwanda's economy is mainly dominated by services (44.34% of GDP), followed by agriculture, fishing, and forestry, as well as industry and manufacturing (World Bank, 2024).

Rwanda's hilly orography, with altitudes ranging from 900m to 4507m, moderates the tropical climate, which contributes to the diversity of Rwanda's six different climatic regions: i) the Lake Kivu climate zone; ii) the mountain forest climate zone; iii) the mountain climate zone; iv) the temperate climate zone of the central highlands; v) the central plateau climate zone and vi) the eastern low land climate zone in the eastern part of the country. The country's overall climate is characterized by the long (MarchMay) and short (SeptemberDecember) rainy seasons and the long (JuneAugust) and short (JanuaryFebruary) dry seasons (World Bank, 2025). Rwanda's diverse array of ecosystems encompasses humid montane and planted forests to savannahs, water resources and wetlands. The country holds the largest mountain rainforest in Africa, which is home to closedcanopy forests, bamboo thickets and open flowerfilled marshes. In total, Rwanda's forests cover 30.4% of the land (Rwanda Environment Management Authority (REMA), 2024).

Rwanda is situated within the catchment areas of two major river basins: the Nile Basin, which covers 67% of the territory, and the Congo Basin, which covers 33% (The Republic of Rwanda Ministry of Natural Resources, 2011). Nyabarongo and Akanyaru are the principal rivers of the Nile Basin in Rwanda. Together with their tributaries, they form the Akagera River, which ultimately discharges into Lake Victoria (The Republic of Rwanda Ministry of Natural Resources, 2011). A network of wetlands consisting of shallow lakes and marshes along these rivers forms a key water reservoir (The Republic of Rwanda Ministry of Natural Resources, 2011). The Congo Basin is made up of several short rivers that feed into Lake Kivu and the Rusizi River, which flows from Lake Kivu into Lake Tanganyika. The Ruhwa River, its main tributary, marks the southern border between Rwanda and Burundi (TheRepublic of Rwanda Ministry of Natural Resources, 2011). To the northwest, the Sebeya River flows into Lake Kivu (The Republic of Rwanda Ministry of Natural Resources, 2011).

1.2. Climate change adaptation in Rwanda

Rwanda's dependence on natural resources (The World Bank Group, 2021) and rainfed agriculture for export earnings and the population's food and nutrition security makes the country vulnerable to climate change (Mwongera et al., 2019). Rwanda follows a development pathway towards a lowcarbon, climateresilient economy by integrating climate change considerations into all sectors, as set out in its Green Growth and Climate Resilience Strategy (GGCRS). It specifically highlights the need for robust observed climate data and climate projections for adaptation planning (Republic of Rwanda, 2022). Rwanda ratified the Paris Agreement (*Rwanda | UNFCCC*, 2025) and committed to climate change mitigation and adaptation commitment as laid out in its updated Nationally Determined Contribution (NDC) (Republic of Rwanda, 2020). As part of its United Nations Framework Convention on Climate Change (UNFCCC) commitments, Rwanda aims to reduce its greenhouse gas (GHG) emissions by 38% by 2030 with a focus on the energy sector, industrial processes and product use, agriculture, and waste. In terms of adaptation, Rwanda has established a comprehensive legal, policy, and strategic framework to address risks and economic losses caused by climate change and climate variability. The NDC includes quantified targets for adaptation and resilience (Republic of Rwanda, 2020), with a strong focus on natural resources sectors like water, agriculture, land, and forestry.

1.3 Existing literature

Several grey literature studies have assessed the impacts of climate change in Rwanda. Existing studies differ in the observational climate data used, the climate hazards and sectors assessed, and the climate models, time horizons, and scenarios used to analyze projected future changes. Most studies assess the historical or current climate (GIZ Rwanda & AIMS RIC, 2025; Ingeri et al., 2024; Muhire et al., 2015; Niyigena et al., 2025; Rusanganwa et al., 2024; Rwanda Meteorological Agency et al., 2022; Safari Kagabo et al., 2024; Umutoni et al., 2021; Uwimbabazi et al., 2022; Zhou et al., 2021) as well as projected climate change for periods ranging from the nearterm (Hunter et al., 2020; MINAGRI & UNDP, 2023; USAID, 2019; Wamicwe et al., 2024) to longterm (The World Bank Group, 2021; CSC, 2013; Rwanda Environment Management Authority & Rwanda Meteorology Agency, 2022; World Bank Group, 2022; Federal Ministry for the Environment, Nature Conservation, Nuclear Safety et al., 2025d, 2025c, 2025b, 2025a)[1] .

With few exceptions (Wamicwe et al., 2024), the future climate change scenarios used in existing studies are either based on the IPCC Special Report on EmissionsScenarios (SRES) (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety et al., 2025a, 2025d, 2025c) or the Representative Concentration Pathways

1 Roughly following the IPCC terminology, defining in 2022 near term as 2021–2040, mid term as 2041–2060, and long term as 2081–2100 (IPCC, 2021).

(RCP) (Hunter et al., 2020; Rwanda Environment Management Authority & Rwanda Meteorology Agency, 2022; The World Bank Group, 2021; World Bank Group, 2022), or both (CSC, 2013; Federal Ministry for the Environment, Nature Conservation, Nuclear Safety et al., 2025b), by using different generations of data from Global Climate Models or Earth System Models (GCMs) from the Coupled Model Intercomparison Project Phase (CMIP), such as CMIP5 (The World Bank Group, 2021) or CMIP6 (Kazora et al., 2023; Rwanda Environment Management Authority & Rwanda Meteorology Agency, 2022). The climate or potentially climaterelated hazards covered by the analyses are precipitation, drought, heatwaves, dry spells, floods, hail, landslides, wind, pests and diseases, soil erosion, thunderstorms, and lightning. To analyse the changing risk of these hazards, the studies generally use climate indices such as annually, seasonally, or monthly averaged precipitation and temperature; the number of cold and hot days and nights; the frequency and intensity of heavy rain events during these time scales; the number of dry spells in the rainy season or the rainy season duration. Some of these hazard analyses were motivated by agroclimatic risks specifically (Kubwimana et al., 2025). Where the literature examined the impacts of these climate indices and their changes, most studies focused on the agricultural sector. (CSC, 2013; Federal Ministry for the Environment, Nature Conservation, Nuclear Safety et al., 2025a; Hunter et al., 2020; Rwanda Environment Management Authority & Rwanda Meteorology Agency, 2022; The World Bank Group, 2021; USAID, 2019; Wamicwe et al., 2024; World Bank Group, 2022), but also the water (CSC, 2013; Federal Ministry for the Environment, Nature Conservation, Nuclear Safety et al., 2025d; Rwanda Environment Management Authority & Rwanda Meteorology Agency, 2022; The World Bank Group, 2021; USAID, 2019; World Bank Group, 2022), energy (CSC, 2013; Federal Ministry for the Environment, Nature Conservation, Nuclear Safety et al., 2025d; The World Bank Group, 2021; USAID, 2019), and forestry (CSC, 2013; Federal Ministry for the Environment, Nature Conservation, Nuclear Safety et al., 2025c; The World Bank Group, 2021) sectors have been considered.

The spatial resolution of climate projections used in the vast majority of studies so far is suboptimal for a small and hilly country like Rwanda, where topography is important (Ntwali et al., 2016). Coarse resolution limits impact modelling possibilities and does not capture complex orography. Spatial resolutions used in the literature range from the coarse GCM resolution (up to about 2°x2° or more, corresponding to approximately 222kmx222km for Rwanda) over 0.5°x0.5° (approximately 56kmx56km) (CSC, 2013; World Bank Group, 2022) to 0.22° (approximately 24kmx24km) (Rwanda Environment Management Authority & Rwanda Meteorology Agency, 2022). One report did apply topographic downscaling to create highresolution climate projections used for crop suitability modelling, highlighting the benefit of this approach (Wamicwe et al., 2024). Also, more recent peerreviewed literature on climate and climate change in Rwanda may use observational or reanalysis data of higher resolution (Jonah et al., 2021; Sebaziga et al., 2023; Siebert et al., 2019a) but future projection data at coarser resolution, including those provided by the Coordinated Regional Climate Downscaling Experiment (CORDEX) that has complementary advantages through a dynamical downscaling approach (Safari et al., 2023; Sebaziga et al., 2025b, 2025a; Umuhoza et al., 2021).

Having climate change scenarios at the regional and local levels is essential for evaluating the impacts and vulnerabilities across different socioeconomic sectors and for designing effective adaptation strategies (Rwanda Environment Management Authority & Rwanda Meteorology Agency, 2022). This study therefore uses a topographic downscaling method (described below) that adjusts climate data to topography and produces climate projections at 1 km resolution, which can support more localized and regionspecific climate change adaptation planning and investments.

1.4 Analysis approach

The changing climate risks relevant for Rwanda are assessed here, showing new spatially highresolution data. These are produced by processing the global climate projections used in the latest report by the Intergovernmental Panel on Climate Change (IPCC). Specifically, a biascorrected and spatially downscaled subset of model data provided by the InterSectoral Impact Model Intercomparison Project (ISIMIP) is here further downscaled to veryhigh resolution by a published algorithm that accounts for the influence of topography on local climate, described in more detail below. The thusderived highresolution climate projections are compared with equally downscaled observationally derived reanalysis data and with a Rwandan observational climate dataset based on weather station data and satellite records.

The choice of relevant climate risk indicators has been made based on the climate risk literature summarized above with the agricultural sector in mind. Agriculture is an important sector in Rwanda, contributing significantly to employment, food security, and export earnings. Agriculture contributes about 25% to the GDP, and 68.9% of all households are engaged in agriculture (National Institute of Statistics of Rwanda (NISR), 2023). Agriculture accounts for a significant share of foreign exchange earnings from exports, with tea and coffee having the highest export value (FAOSTAT, 2024a). Most agricultural goods are produced by smallholder farmers in rainfed farming systems (Hunter et al., 2020; Rwanda Development Board, 2024). With regard to agricultural output, the most predominant crops are bananas, cassava, sweet potatoes, potatoes, maize, dry beans, pumpkins, squash and gourds, taro, sorghum, Tea leaves and Rice (FAOSTAT, 2024b). Growing seasons relevant for these range from SeptemberJanuary/February and FebruaryJune/July (beans and maize, sorghum, respectively) (Food and Agriculture Organization of the United Nations (FAO), 2025a) to September/OctoberMarch/July (coffee) (Rwanda Development Board, 2025). Based on these, we assessed historical and projected future climate risks on the annual scale for SeptemberJanuary (SONDJ) and FebruaryJuly (FMAMJ) separately.

The definitions of agroclimatic indices were again based on the literature review above and insights from earlier work on climate risk characterization elsewhere (Cronauer, Carla et al., 2025; Murken et al., 2024). The indicators and their definitions are listed in Table 1. Specifically, we used annual and growing season mean daily temperatures as a general indicator for temperature conditions. We further used a magnitudebased heat index that captures the average daily maximum temperature of the hottest fiveday period, as generally relevant for climate impacts. We similarly used annual and growingseason total precipitation as a general indicator for climate impacts, specifically in the agricultural sector. To address heavy precipitation that might lead to flooding, we used the number of days per year, and growing seasons of extremely high precipitation compared to the historical period. To capture drought conditions, we used the number of dry spells, adjusted to the threshold of 1 mm typically used by Meteo Rwanda.

Table 1. *Agroclimatic indices analysed in this assessment as an example for usage for a sectoral impact assessment. Listed are (left) a simplified name of the index as referred to in the text; a (middle) technical abbreviation of this index; and (right) a technical description stating the necessary detail to reproduce the calculation based on the data provided and the information given in the text.*

Index	Technical abbreviation	Description
Temperature	Tmean	Annual and growingseason average of dailymean nearsurface temperature
Heat	TX5x	Maximum daily maximum nearsurface temperature during any consecutive 5day period centered within the year/ growing season
Precipitation	prsum	Precipitation amount summed over all days in the year/growing season
Extreme precipitation	nprgtp95	Number of days per year/growing season with precipitation > its 95% percentile for that day of the year across the reference period
Meteorological drought	n5daydry1mm	Number of events (dry spells) with 5 or more consecutive dry days (dry day = day with precipitation amount <1mm) per year/growing season (7day dry spell counts only once, not three times)

2. Data and methods

2.1 Observational climate data

Observational gridded data for rainfall (here from now on referred to as precipitation), maximum temperature, and minimum temperature were sourced from the Rwanda Meteorology Agency. These datasets combine groundbased weather station observations with precipitation estimates from the Tropical Applications of Meteorology using SATellite and groundbased observations (TAMSAT) data(Maidment et al., 2017) and air temperature data from the Japanese 55year Reanalysis (JRA55) reanalysis (Harada et al., 2016; Kobayashi et al., 2015). The satellite and reanalysis data were first downscaled and biascorrected before being merged with the ground station observations (Siebert et al., 2019b). This process produced gridded datasets with a 4 km resolution for precipitation and a 5 km resolution for temperatures. The temperature datasets cover the period from 1983 to 2021, while the precipitation datasets span from 1981 to 2021. The dataset is also referred to as "ENACTS" (Siebert et al., 2019c).

2.2 Climate model data

Data from nine models forming part of the latest Coupled Model Intercomparison Project (CMIP6) by the World Climate Research Programme (WCRP) (Eyring et al., 2016) were used. The models are global and in resolution vary between close to 1° and 2°. Primary and secondary climate input data from the InterSectoral Impact Model Intercomparison Project (ISIMIP) (ISIMIP, 2018) phase 3b were used (Lange & Büchner, 2022). This means the data had been biascorrected and downscaled to 0.5°x0.5° resolution by Lange et al. (Lange, 2019) using a trendpreserving quantile mapping, which has been found to perform well in preserving spatial variability and extremes (ibid.). The reference data used for the bias correction is version 2.0 of WFDE5 over land merged with ERA5 over the ocean (W5E5) (Cucchi et al., 2020).

The model data consists of the first ensemble member from each of these models: Institut PierreSimon Laplace's IPSLCM6ALR model (Boucher et al., 2020); Max Planck Institute's MPIESM12HR model (Gutjahr et al., 2019); the Meteorological Research Institute Earth System Model Version 2.0, MRIESM20 (Yukimoto et al., 2019); UK Earth System Model UKESM10LL (Sellar et al., 2019); the Canadian Earth System Model version 5, CanESM5 (Swart et al., 2019); Centre National de Recherches Météorologiques and Cerfacs's fully coupled atmosphereocean general circulation model of sixth generation, CNRMCM61 (52), and their Earth system model of second generation, CNRMESM21 (Séférian et al., 2019); the Earth system model ECEarth3 (Döscher et al., 2022); the sixth version of the Model for Interdisciplinary Research on Climate, MIROC6 (Tatebe et al., 2019). The other models/simulations available as part of ISIMIP3b did not provide all variables necessary for further downscaling (GFDLESM4) and/or were not available at the time of data processing (CESM2WACCM, IITMESM, KACE10G, TaiESM1).

The projections are based on the Shared Socioeconomic Pathways (SSPs) underlying the IPCC assessments (Riahi et al., 2017) that are more comprehensive in scope than the earlier RCPs, being the result of a detailed scenario generation process. SSP1.26 stays below two degrees of warming relative to an early industrial baseline (18501900; median) and implies net zero carbon dioxide emissions in the second half of the century compared to the previous scenarios; it is closest to RCP2.6 (Fuglestvedt et al., 2021). SSP3.70 is an intermediatetohigh scenario resulting from no additional climate policy, where carbon dioxide emissions roughly double from current levels by 2100 and emissions of other pollutants are particularlyhigh; compared to the previous scenarios, it lies between RCP6.0 and RCP8.5. SSP5.85 is a high scenario with no additional climate policy, where carbon dioxide emissions roughly double from current levels by 2050; compared to the previous scenario, it is closest to RCP8.5. This project was restricted to the data provided after biascorrection and downscaling by ISIMIP, which is only a subset of the larger number of SSP projections provided as raw model output from CMIP.

Here, the data over the Rwandan domain were further downscaled to approximately 1 km x 1 km (30 arcsec) latitude/longitude resolution using a version 2 of the Climatologies at high resolution for the earth's land surface areas (CHELSA) method (Karger et al., 2017, 2023). The algorithm is a topographically informed, mechanistic downscaling method that downscales nearsurface air temperatures (tas, tasmax, tasmin) based on air temperature lapse rates in the lower atmosphere and downscales precipitation rates (pr) using orographic terrain effects. The method had already been applied to the global climate reanalysis data also used here, resulting in the CHELSAW5E5 dataset (Karger et al., 2023). In that study, the topographically downscaled climate data were found to compare well with the results of dynamical downscaling with the Weather Research and Forecasting (WRF) regional climate model, while associated with substantially lower computational cost in the production.

The downscaling method accounts for the influence of highresolution topography on local climate. However, the downscaling cannot correct for biases in the models that result from not resolving clouds and convection. These biases are introduced by the coarse spatial resolution of the climate model simulations (the climate models' 'native resolution') provided by the modelling groups when producing the data for CMIP, so no postprocessing procedure can account for them. Currently, there are also no longterm climate projections available in cloud- and/or conventionpermitted spatial resolution due to the high computational demands of these simulations.

2.3 Data analysis

A selection of climate hazard indices was computed based on Table 1 and data availability. The analysis thus includes annually and seasonally aggregated mean and extreme temperature and precipitation indices covering daily mean temperature and precipitation aggregated over the year and growing seasons, as well as indices capturing heat, extreme precipitation, and meteorological drought.

To evaluate the climate model simulations and show the increased spatial resolution (Figures 12), we computed averages of observations, of the downscaled W5E5 reanalysis data, of the climate model data in ISIMIP resolution, and of the further downscaled HiClAP model data during a recent historical baseline. The baseline chosen is 1/1/1985 to 31/12/2014, noting the historical climate model simulations end in 2014.

To show how the hazard indices are projected to change over time (Figures 37), we aggregated the data from all model grid boxes that lie within a latitude/longitude boxcapturing Rwanda (2.9625°S1.05°S; 28.5375°E30.975°E; Figure 1). Lines show the multimodel mean values of the 21year running means for the historical period (yellow), SSP1.26 (orange), SSP3.70 (red), and SSP5.85 (purple), and the shading shows the full spread of the thussmoothed data in the 5member model ensemble. The multimodel mean is considered the best estimate of how climate change will manifest here. Note that the values observed in any specific year will vary around this estimate (line) and even go beyond the multimodel range (shading), regardless of model uncertainties due to interannual climate variability that is smoothed out here.

To show the projected changes in three future time horizons at fine spatial resolution (Figures 812 and S1S2), future periods comparable to those in the existing literature were used. These define '2030' as 1/1/201531/12/2044, '2055' as 1/1/204031/12/2069, and '2080' as 1/1/206531/12/2094. The multimodel mean and standard deviation of each model's difference between the temporal averages across the respective future and the historical period of the spatial average of each index across the project regions were further quantified (Tables 25 and S1). These numbers represent the best estimate for how the respective climate indices will be different in the future compared to now, and an uncertainty estimate thereof.

3. Current climate and climate model evaluation

For the historical baseline, the downscaled climate model data represent the finer spatial differences within the region due to differences in elevation, with higher areas being climatologically cooler consistently for climate model output and reanalysis data by methodological design (Figure 1). Regarding annual total precipitation, the climate model output reproduces the higher observed precipitation in the southwestern part of Rwanda and less rain in the eastern part (Figure 2). Both reanalysis data and model output underestimate the precipitation amounts in the very southeastern part of the country, and both datasets are spatially smoother than the observational data, showing limits of what such downscaling can achieve.

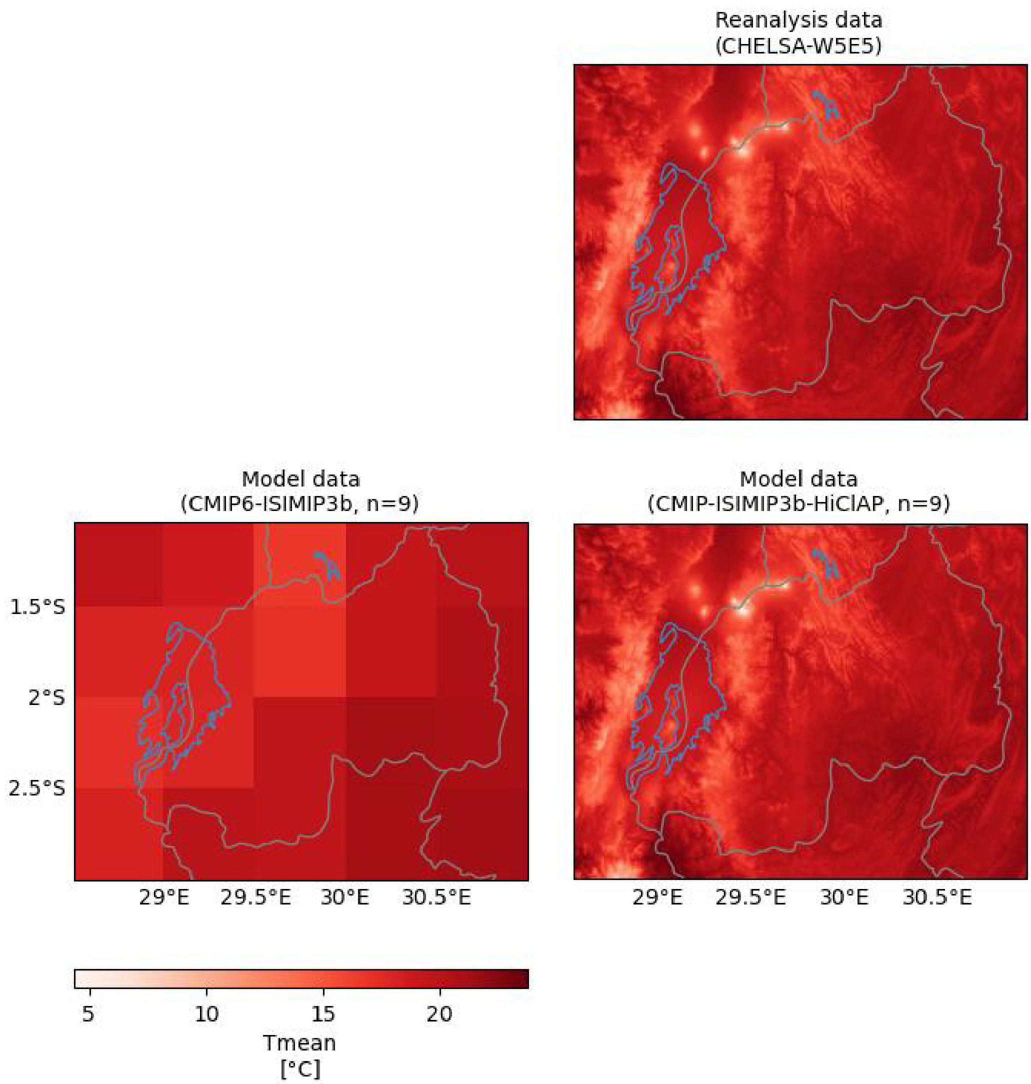

Figure 1: *Recent historical climate in Rwanda. Spatial map of annualmean dailymean temperatures (Tmean) in Rwanda averaged over the historical baseline period (19852014) as (top right) the further downscaled observationallyderived dataset used for the model bias correction and ISIMIP downscaling, (bottom left) the model output (ISIMIP resolution), and (bottom right) model output (further downscaled – these are the HiClAP data). For the model data, the multimodel mean across all simulations is shown.*

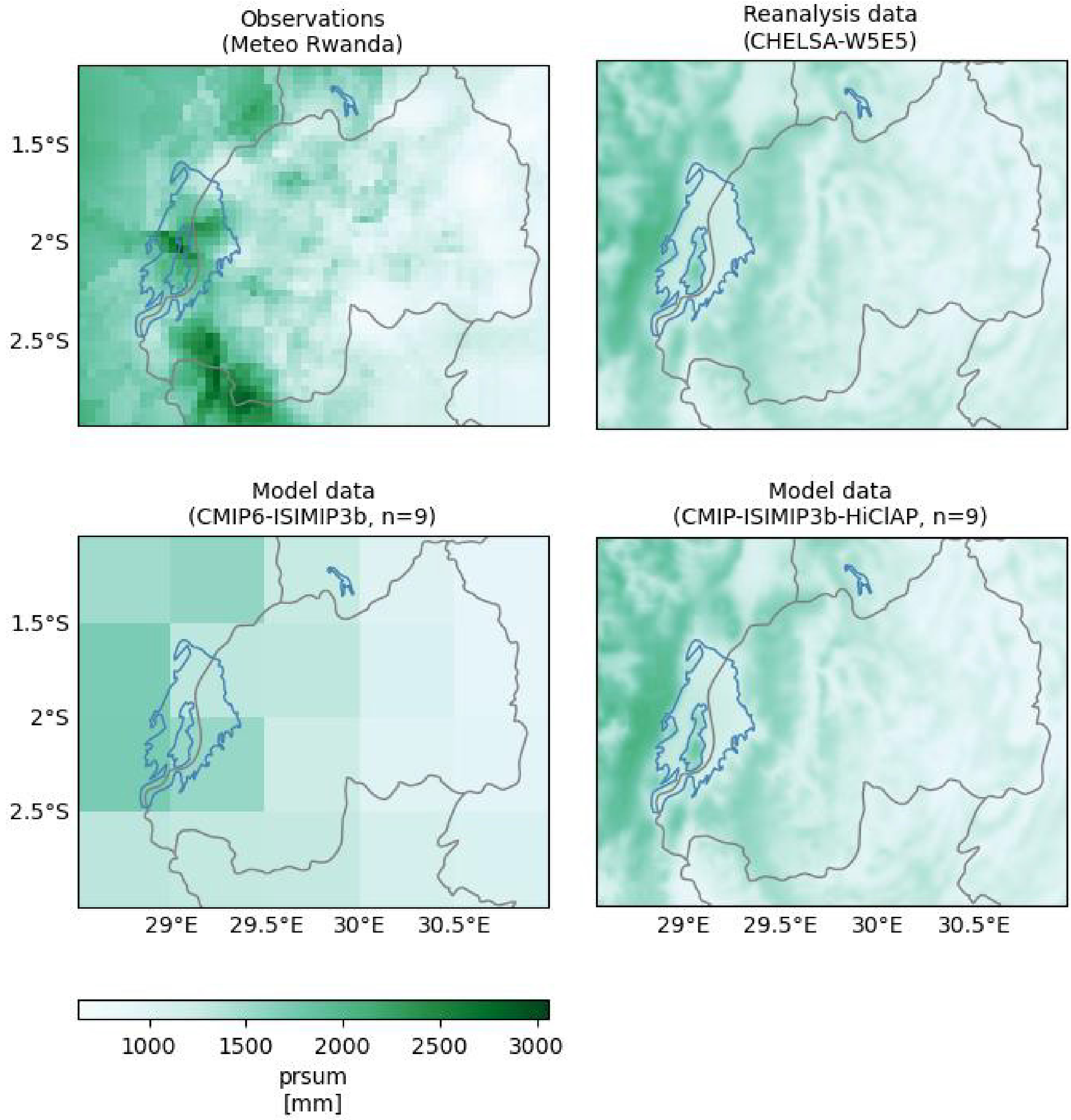

Figure 2: *Recent historical climate in Rwanda. Spatial map of total annual precipitation (prsum) in Rwanda averaged over the historical baseline period (19852014) as (top left) observed according to Meteo Rwanda, (top right) the further downscaled observationallyderived dataset used for the model bias correction and ISIMIP downscaling, (bottom left) the model output (ISIMIP resolution), and c) model output (further downscaled – these are the HiClAP data). For the model data, the multimodel mean across all simulations is shown.*

Looking at temporal change and variability rather than spatial differences, the climate model simulations capture the reanalysis data for most indices analysed: The reanalysis time series lies within the model ensemble's envelope (shading in Figures 37). Heat is underestimated in the model compared to both reanalysis data and the national observational dataset (as introduced in section 2.1, based on weather stations and satellite records) (Figure 4).

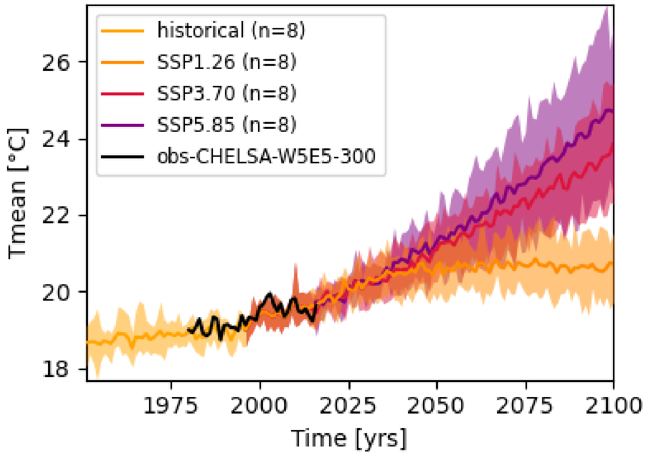

Figure 3: *Time evolution of Rwandamean temperature. Shown are historical and projected annualmean temperature (Tmean) showing annual values for (black line) the observationallyderived reanalysis data used as reference for bias correction and downscaling, and (colourful line) the multimodel mean value and the (colourful shading) full range of the model ensemble for data from 9 global climate model simulations for the different climate change scenarios in order of mitigation ambition from (orange) SSP1.26 over (red) SSP3.70 to (purple) SSP5.85. In the legend entry for CHELSAW5E5300, "obs" is short for "observationally derived", not for "observations".*

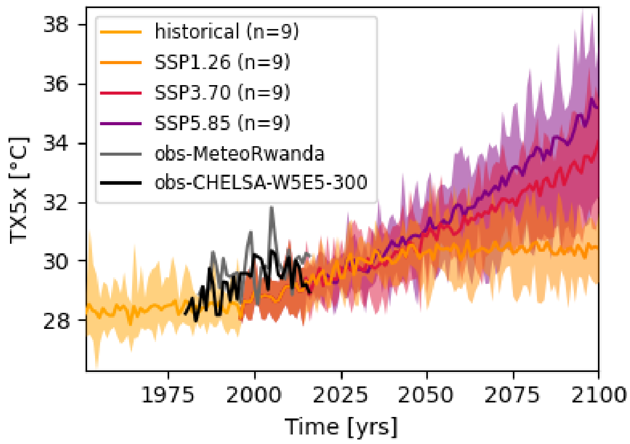

Figure 4: *Time evolution of Rwandamean heat indices. Shown are historical and projected values for the temperature of the hottest 5day period per year (TX5x) showing annual values for (black line) the observationallyderived reanalysis data used as reference for bias correction and downscaling, (grey line) national observations from Meteo Rwanda, and (colourful line) the multimodel mean value and the (colourful shading) full range of the model ensemble for data from 9 global climate model simulations for the different climate change scenarios in order of mitigation ambition from (orange) SSP1.26 over (red) SSP3.70 to (purple) SSP5.85. In the legend entry for CHELSAW5E5300, "obs" is short for "observationally derived" and in the legend entry for Meteo Rwanda, it is short for "observations".*

As is generally the case, precipitation is more variable and precipitation changes are more uncertain than for temperature (Figure 5). The reanalysis and model data also agree with the observational dataset in terms of extreme precipitation (Figure 6). The index representing meteorological drought is compatible between model and reanalysis data but shows fewer drought days than the national observational dataset (as introduced in section 2.1., based on station data and satellite observations) (Figure 7).

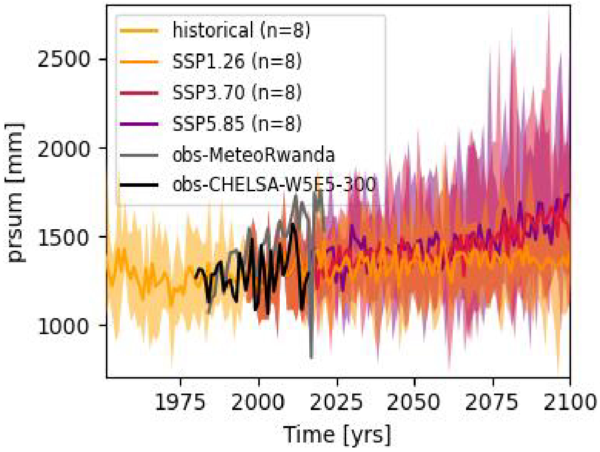

Figure 5: *Time evolution of Rwandamean precipitation. Shown are historical and projected total annual precipitation (prsum) averaged over the Rwandan region, showing annual values for (grey line) observations from Meteo Rwanda, (black line) the observationallyderived reanalysis data used as reference for bias correction and downscaling, and (colourful line) the multimodel mean value and the (colourful shading) full range of the model ensemble for data from 9 global climate model simulations for the different climate change scenarios in order of mitigation ambition from (orange) SSP1.26 over (red) SSP3.70 to (purple) SSP5.85. In the legend entry for CHELSAW5E5300, "obs" is short for "observationally derived" and in the legend entry for Meteo Rwanda, it is short for "observations".*

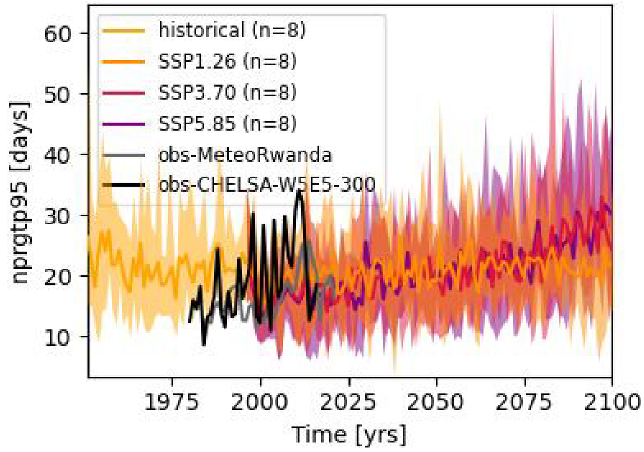

Figure 6: *Time evolution of Rwandamean extreme precipitation. As Figure 5, but for the number of heavyprecipitation days (nprgtp95). In the legend entry for CHELSAW5E5300, "obs" is short for "observationally derived" and in the legend entry for Meteo Rwanda, it is short for "observations".*

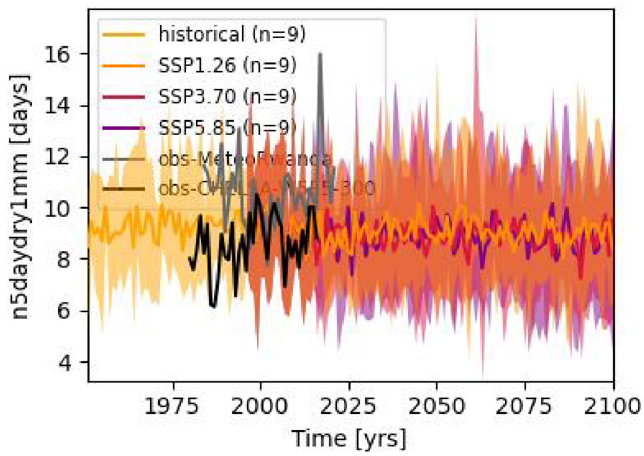

Figure 7: *Time evolution of Rwandamean meteorological drought. As Fig. 5, but for the number of dry spells (n5daydry1mm). In the legend entry for CHELSAW5E5300, "obs" is short for "observationally derived" and in the legend entry for Meteo Rwanda, it is short for "observations".*

4. Projected future climate

Regarding annual mean temperatures, all climate change scenarios lead to substantial warming (Figure 8, Table 2). Even in the most ambitious mitigation scenario (SSP1.26), the projected temperature increase adds a similar amount of areamean warming than that observed during the last decades. The projected changes for SSP1.26 are clearly distinguishable from those for SSP3.70 and SSP5.85, showing the scope for global climate change mitigation. The temperature increase is very homogeneous across the country (Figure 8), meaning that absolute temperatures will remain lower in the climatologically colder higherelevation parts of the country (Figures 1, 8). The best estimate for the areamean temperature increase in the highest climate change scenario gives values between 3°C and more than 5°C compared to the recent historical baseline.

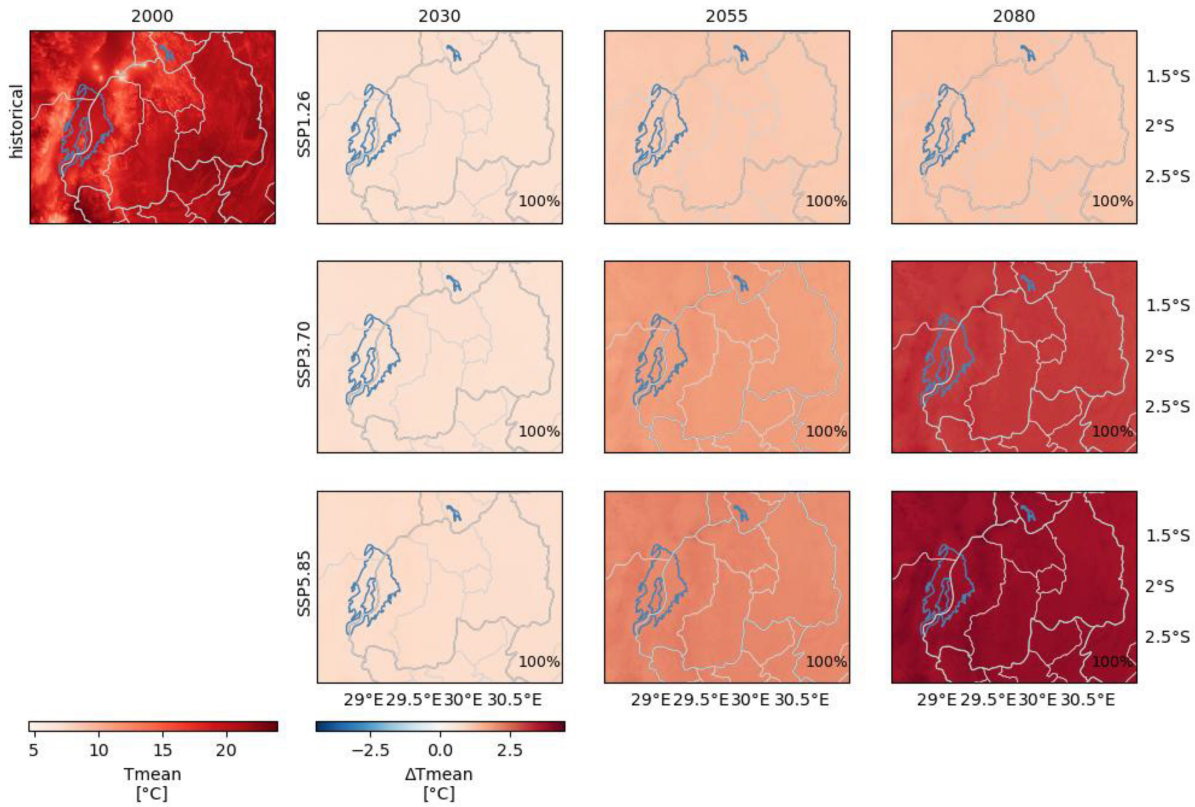

Figure 8: *Historical and projected future changes in air temperature. Change of annualmean dailymean temperature (Tmean) between the baseline period (19852014) and those centred around 2030 (20152044), 2055 (20402069), and 2080 (2065, 2094), showing the multimodel mean for the different climate change scenarios (from top to bottom) SSP1.26, SSP3.70, and SSP5.85. In all grid cells, at least 6 out of the 9 model simulations agree on the sign of the change as indicated by the fraction of grid cells (100%) in the bottom right corner (by chance, 25% not spatially clustered grid cells would be expected to agree).*

Table 2. *Quantification of Tmean change: As Figure 8, the table presents the historical mean temperature and projected changes in Tmean for three future periods (centred on 2030, 2055, and 2080) under three SSP scenarios. Values are given as the best estimate ± one standard deviation. Changes shown in bold are considered statistically significant, meaning that neither the best estimate nor its uncertainty range overlaps with zero.*

Tmean	Historical	Change to 2030	Change to 2055	Change to 2080
SSP1.26	19.28 ± 0.02 °C	**0.93 ± 0.24 °C**	**1.38 ± 0.39 °C**	**1.43 ± 0.47 °C**
SSP3.70		**0.91 ± 0.26 °C**	**2.07 ± 0.44 °C**	**3.33 ± 0.69 °C**
SSP5.85		**1.01 ± 0.21 °C**	**2.36 ± 0.61 °C**	**4.08 ± 1.08 °C**

In line with scientific understanding, temperature extremes (Figure 4, Table 3, Figure S1) increase more than temperature means. Specifically, the temperature of the hottest 5day period per year increases more than annualmean dailymean temperatures (compare Tables 2 and 3). Even at the aggregated Rwandanregion scale, where extreme values are averaged out compared to individual locations, the hottest 5day period per year could reach average values within the 2080 period of nearly 35.40 ± 1.76°C, meaning that each year would have at least one 5day period with an average of about 35°C across these days across the country. Individual years will be even hotter. For example, the hottest 5day period found in the model ensemble for the 2080 period has 38.6°C, to be understood as illustration rather than a specific threshold, as assessing the bounds for individual extremes requires different analysis. Individual locations and days will be even hotter. Individual years, locations, and days will also be cooler.

Table 3. *Quantification of extreme temperature change: The table presents the historical areamean TX5x value and projected changes for three future periods (centred on 2030, 2055, and 2080) under SSP12.6, SSP37.0, and SSP58.5. Values are reported as the best estimate ± one standard deviation. Changes are highlighted in bold when they are considered statistically significant, defined here as cases where the best estimate and its uncertainty range do not overlap with zero.*

TX5x	Historical	Change to 2030	Change to 2055	Change to 2080
SSP1.26	28.71 ± 0.14 °C	**1.12 ± 0.29 °C**	**1.60 ± 0.50 °C**	**1.68 ± 0.62 °C**
SSP3.70		**1.02 ± 0.45 °C**	**2.26 ± 0.57 °C**	**3.65 ± 0.87 °C**
SSP5.85		**1.17 ± 0.26 °C**	**2.67 ± 0.76 °C**	**4.64 ± 1.24 °C**

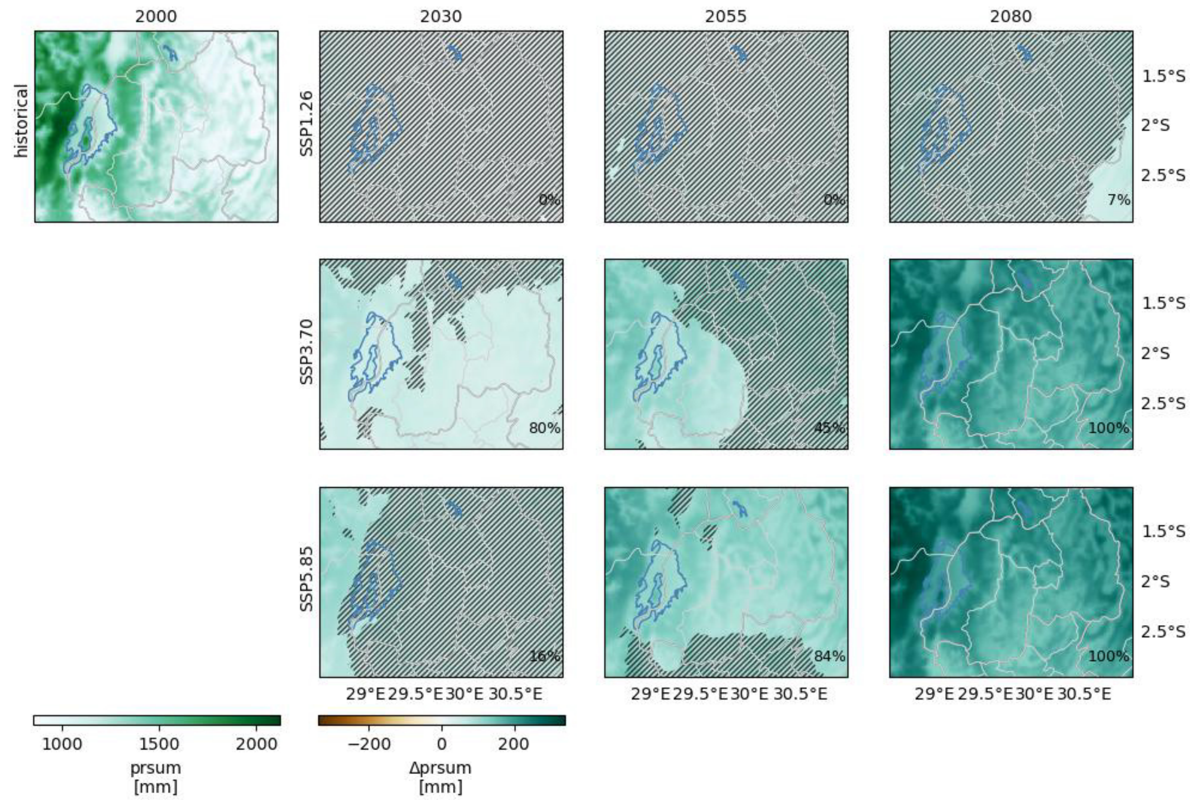

Figure 9: *Historical and projected changes in precipitation. Change of total annual precipitation (prsum) between the baseline period (19852014) and those centred around 2030 (20152044), 2055 (20402069), and 2080 (2065, 2094), showing the multimodel mean for the different climate change scenarios (from top to bottom) SSP1.26, SSP3.70, and SSP5.85. Hatching indicates where fewer than 6 out of the 9 model simulations agree on the sign of the change. The fraction of grid cells where 6 or more models agree on the sign is indicated in the bottom right corner (by chance, 25% not spatially clustered grid cells would be expected to agree). Where no hatching is visible this is because of 100% of all grid cells agreeing on the sign.*

Regarding total annual precipitation, the climate change signal (the multimodel mean line) diverges in the scenarios towards the end of the century, subject to large interannual variability and model uncertainty (Figure 5, Table 4). In the most ambitious mitigation scenario, there is limited model agreement on the sign of change (wettening or drying, in the annual average) and no significant change projected (Figure 9). In the other scenarios and especially towards the end of the century, all models agree on a precipitation increase. The spatial pattern of precipitation change is more heterogeneous than temperature change, with differences at high spatial resolution. Both the climatologically wetter areas within the western part of Rwanda, and the areas more to the east, are projected to get wetter.

Table 4. Quantification of prsum change.

prsum	Historical	Change to 2030	Change to 2055	Change to 2080
SSP1.26	1281.7 ± 23.5 mm	37.8 ± 42.0 mm	51.2 ± 84.4 mm	**71.3 ± 69.1 mm**
SSP3.70		**74.1 ± 58.2 mm**	112.2 ± 118.9	**215.5 ± 191.9**
SSP5.85		**84.4 ± 77.3 mm**	**138.0 ± 134.3 mm**	**222.9 ± 180.4**

As an example, for using the climate projection data for sectoral climate hazard analysis, we additionally show selected crop growingseasonal results. The findings show that the increase in precipitation may fall more into the later months of the year, impacting coffee (Figure 10) more than bean, maize, and sorghum (Figure 11), total precipitation changes during the growing season of which are only projected for the later time periods under SSP3.70 and SSP5.85.

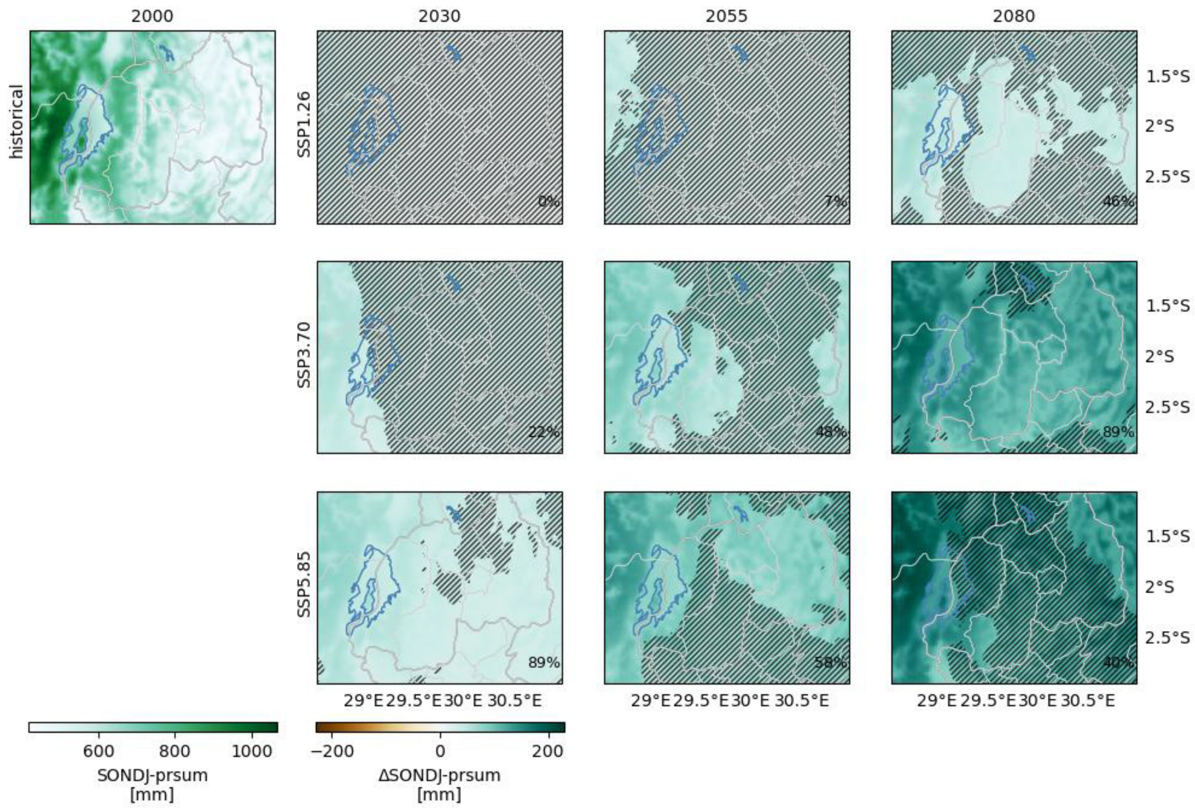

***Figure 10:** Historical and projected changes in total precipitation during the relevant months for coffee (as Figure 9, but for September to January instead of the full year).*

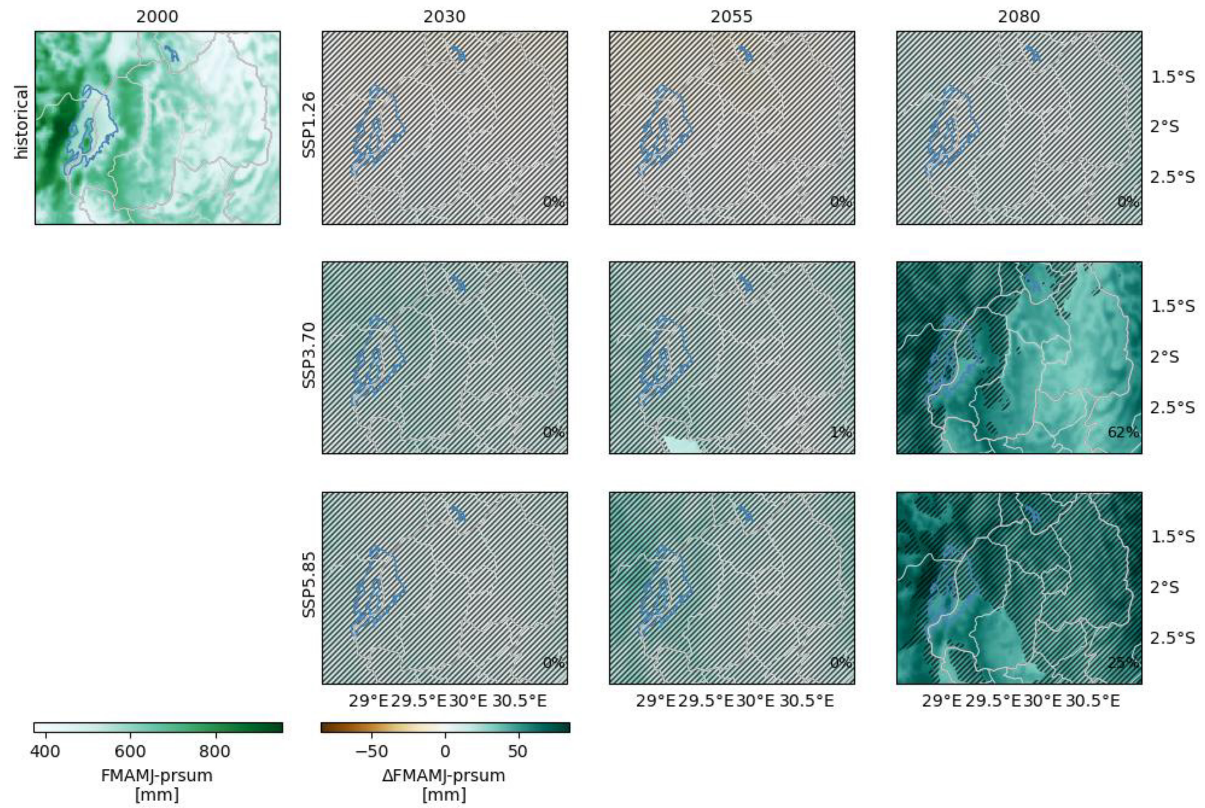

Figure 11: *Historical and projected changes in total precipitation during the relevant months for bean, maize, and sorghum (as Figure 9, but for February - June instead of the full year).*

The number of heavy precipitation days is highly variable, and a projected increase for the higheremission scenarios throughout the century is smaller than the simulated recent decrease (Figure 6). Projected increases in heavy precipitation are significant for the 2055 and 2080 period in SSP3.70 and SSP5.85 (Table 5), with fewer spatial differences within Rwanda (Figure 10) than for total precipitation.

Again, using agriculture as an example, this increase in heavy precipitation days is as for total precipitation projected to occur in both growing seasons, but affecting the coffee season sooner than the bean, maize, and sorghum season (figures not shown for conciseness but available upon request).

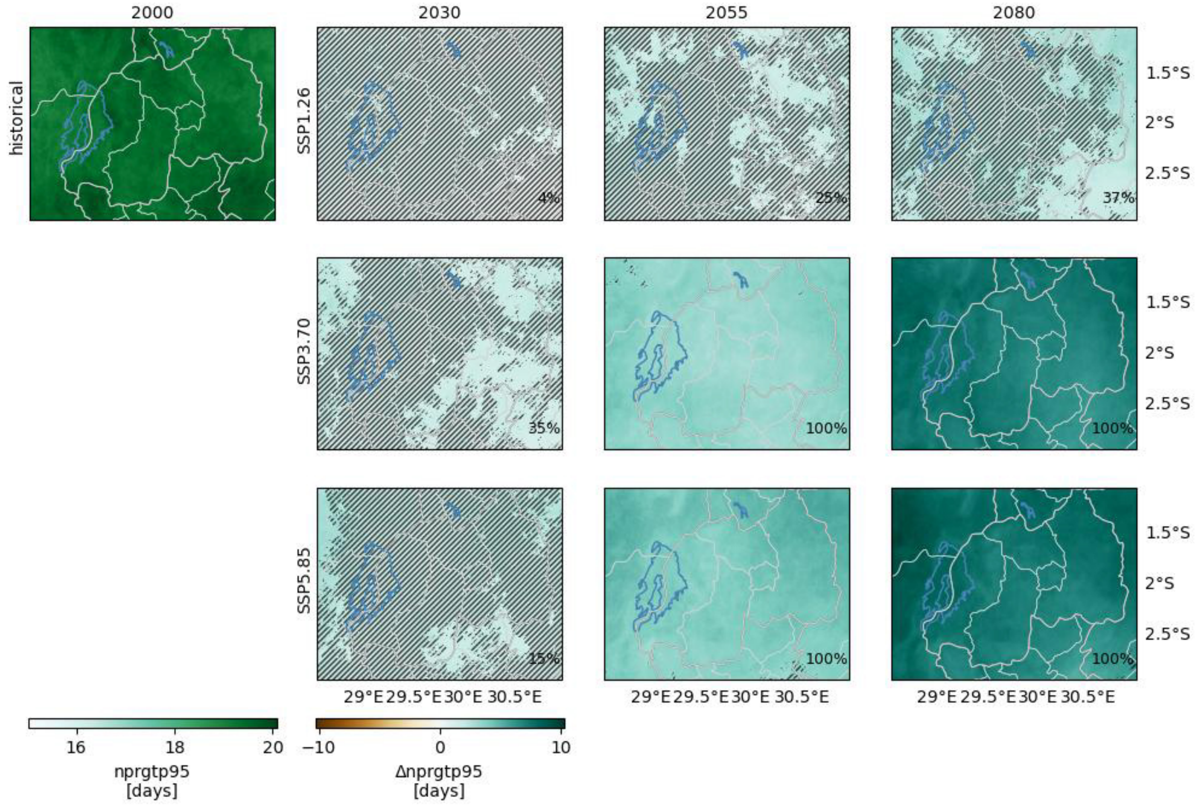

Figure 12: *Historical and projected changes in heavy precipitation. As Fig. 8, but for the number of heavyprecipitation days (nprgtp95).*

Table 5. *Quantification of changes in heavy precipitation.*

nprgtp95	Historical	Change to 2030	Change to 2055	Change to 2080
SSP1.26		0.02 ± 1.08 days	0.55 ± 2.10 days	1.16 ± 1.46 days
SSP3.70	20.49 ± 1.06 days	0.45 ± 1.42 days	**1.53 ± 1.20 days**	**5.27 ± 3.38 days**
SSP5.85		0.39 ± 1.72 days	**2.06 ± 1.81 days**	**5.33 ± 3.42 days**

The drought indices show a visually complementary, albeit not statistically significant change, subject to similar variability (Figure S2, Table S1).

5. Discussion and Conclusions

1. To summarise, the analysis found:
2. Significant projected increases in dailymean temperature annually in all climate change scenarios including the most ambitious SSP1.26.
3. Even larger projected increases in the temperature of the hottest day per year in terms of dailymaximum temperature, consistent with physical understanding.
4. A projected increase in total annual precipitation despite variability being generally larger for precipitation than for temperature.
5. A projected steady increase in the number of heavy-precipitation days visible in the SSP3.70 and SSP5.85 scenarios.
6. Uncertain changes in meteorological drought, noting also the models' and climate reanalysis' difficulty in reproducing the magnitude of the drought index from the weatherstation and satellitebased observations.
7. Rather homogeneous warming across the historically cooler and wetter hillier areas in Western Rwanda and the warmer and drier lower areas, and more spatially differentiated changes in all precipitationrelated indices.
8. In growing-seasonal analyses for the agricultural sector as an example of data use for sector-specific climate risk analysis, significant projected increases in daily-mean temperature, even larger increases in the temperature of the day with the highest daily-maximum temperature, and a projected increase in total annual precipitation especially in September-January rather than February-June.
9. Discrepancies between low precipitation in the observational gridded dataset from Meteo Rwanda and the global reanalysis product are large. Both satellite data and the reanalysis product used have substantial uncertainties that may contribute to this discrepancy. Comparison with other precipitation datasets such as the Climate Hazards Center InfraRed Precipitation with Station Data, version 2 (CHIRPS2) (Funk et al., 2015) and the analysis in a recent report focusing on observed historical changes (GIZ Rwanda & AIMS RIC, 2025) will be useful. While further investigation is hence needed to clarify this discrepancy, the temperature and mean to highprecipitation related findings withstand this scrutiny. Nonetheless, it adds a note of caution to the analysis of the produced climate projection data for risk assessments relating to lowprecipitation events, as the reanalysis product is what the climate model projections is biased corrected against. Absolute drought values computed from the climate model projections will hence significantly underestimate the drought hazard compared to the Meteo Rwanda observations; changes in drought might not be affected (but no significant change was found in the index analysed here anyway).
10. Note that as always, the case when using predefined climate projections, the climate scenarios do not cover the full range of possible climate futures. Moreover, the list of climate hazards is not exhaustive. Additional hazards associated with wind speeds, for

example, have not been addressed, and to assess the risk of flooding associated with the projected increase in heavyprecipitation days would require running a flood model, for example. The data are not analysed for worstcase scenario planning, but to show best estimates of projected changes, temporal and spatial averaging applied for illustration.

11. The analysis highlights the benefit of the downscaling to very high resolution for showing how historical climate differs within Rwanda given the eastern plains, the central plateau, the highlands, and the regions around Lake Kivu. The projected precipitation changes, too, show a spatial profile, which is additional to the areamean changes provided by the projections in their original/ISIMIP resolution. Temperature changes are more homogeneous across the Rwandan region, but the climatology of the downscaled data does reflect the orography, so that any local risks associated with resulting absolute temperatures in future, will be more accurate if assessed using the new dataset. Biases and uncertainties associated with the originally coarse spatial resolution of the climate models are not accounted for, such as those resulting from not resolving clouds and convection. However, the added granularity with regard to topography is valuable for considering spatial distributions of climate and climate change, and for modelling the impacts associated with these risks.

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Technical appendix

Supplementary figures and tables

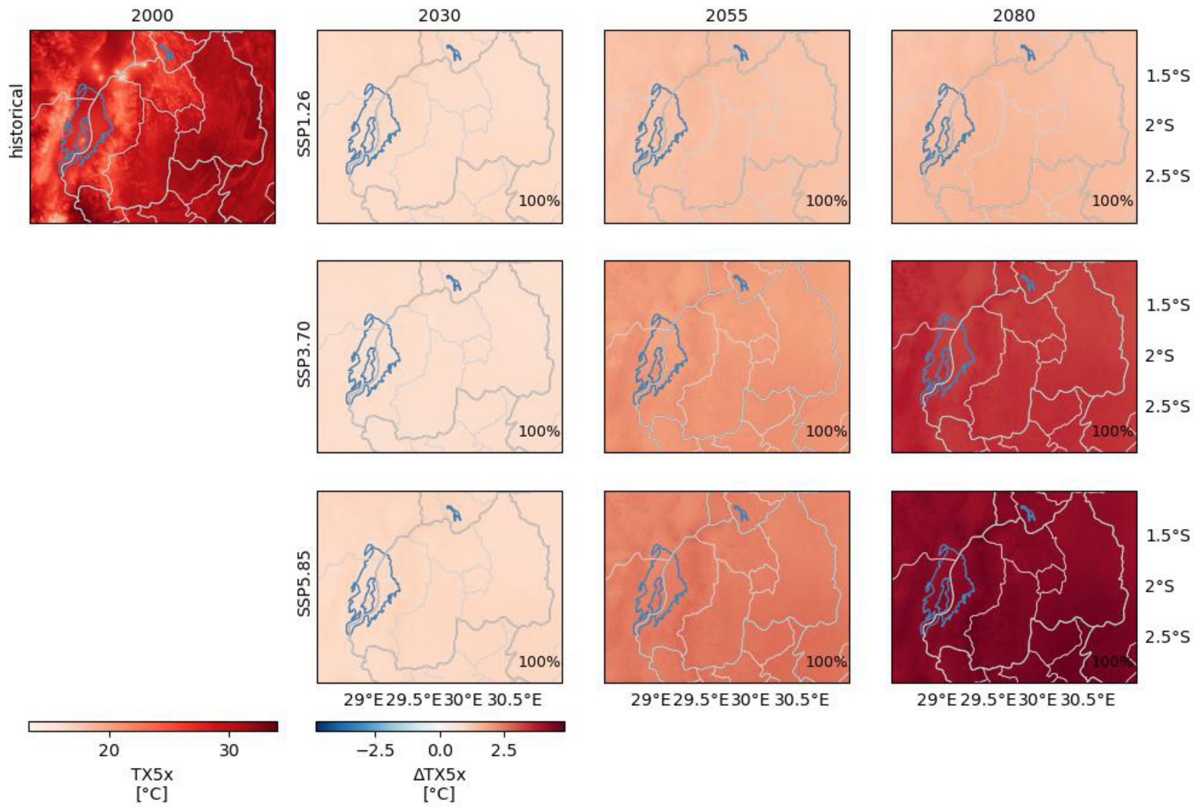

Figure S1. *Spatial map of changes in heat over the Rwandan region: As Fig. 6, but for the temperature of the hottest 5day period per year (TX5x).*

Table S1. *Quantification of changes in meteorological drought.*

n5daydry1mm	Historical	Change to 2030	Change to 2055	Change to 2080
SSP1.26	9.26 ± 0.81 days	0.2 ± 0.44 days	0.08 ± 0.49 days	0.27 ± 0.58 days
SSP3.70		0.34 ± 0.48 days	0.28 ± 0.68 days	0.38 ± 0.75 days
SSP5.85		0.36 ± 0.46 days	0.28 ± 0.64 days	0.36 ± 0.83 days

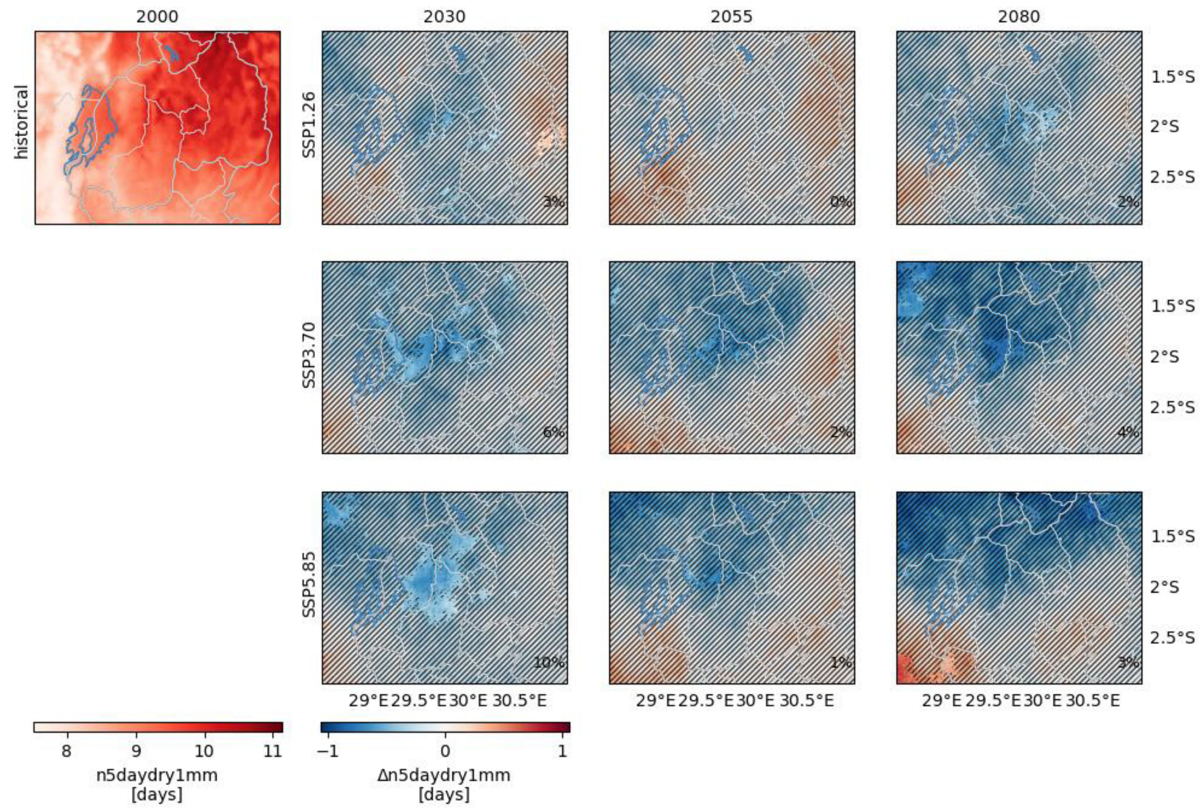

Figure S2*. Spatial map of changes in meteorological drought over the Rwandan region: As Figure 8, but for the number of dry spells (n5daydry1mm).*

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