



Royal Netherlands
Meteorological Institute
*Ministry of Infrastructure
and Water Management*

Climate Scenarios for Aruba, Cura-ao and Sint Maarten

Scientific basis, methodology and projected climate change for 2050 and 2100

Anneloes Teunisse, Iris Keizer, Rein Haarsma, Hylke de Vries, P@dzi Flores-Girigori, Lothar Irausquin, Sheryl Etienne-Leblanc, Joffrey Boekhoudt, Jonathan Zoetrum and Robert-Jan Moons

De Bilt, 2026| Scientific report; WR 26-03

Climate Scenarios for Aruba, Curaçao and Sint Maarten

Scientific basis, methodology and projected climate change
for 2050 and 2100

Anneloes Teunisse¹, Iris Keizer¹, Rein Haarsma¹, Hylke de Vries¹,
Pédzi Flores-Girigori², Lothar Irausquin³, Sheryl Etienne-Leblanc⁴,
Joffrey Boekhoudt⁵, Jonathan Zoetrum⁵, and Robert-Jan Moons²

¹Royal Netherlands Meteorological Institute (KNMI)

²International Panel on Deltas and Coastal Zones (IPDC)

³Departamento Meteorológico Aruba (DMA)

⁴The Meteorological Department of Sint Maarten (MDS)

⁵Meteorological Department Curaçao (MDC)

23 July 2026



Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Waterstaat



This report constitutes Deliverable 5 (D5) of the International Panel on Deltas and Coastal Zones (IPDC) project *Climate Scenarios and Digitization*. The project is coordinated by the IPDC Dutch Caribbean Coordinators Timo Kelder and Arno Nolte and managed by Robert-Jan Moons.

Research led by

Royal Netherlands Meteorological Institute (KNMI): Anneloes Teunisse, Iris Keizer, Rein Haarsma and Hylke de Vries.

In collaboration with

Departamento Meteorológico Aruba (DMA): Lothar Irausquin.

Meteorological Department Curaçao (MDC): Pédzi Flores-Girigori, Joffrey Boekhoudt and Jonathan Zoetrum.

The Meteorological Department of Sint Maarten (MDS): Sheryl Etienne-Leblanc.

In coordination with

National Climate Resilience Council (NCRC) of Aruba: Juliet Carvalhal and Ryan Peterson.

Ministry of Public Housing, Spatial Planning, Environment and Infrastructure (VROMI) of Sint Maarten: Raïtza Narain and Riddhi Samtani.

IPDC focal point of Curaçao: Pédzi Flores-Girigori.

Citation

Teunisse, A., Keizer, I., Haarsma, R., De Vries, H., Flores-Girigori, P., Irausquin, L., Etienne-Leblanc, S., Boekhoudt, J., Zoetrum, J., Moons, R. (2026). Climate Scenarios For Aruba, Curaçao and Sint Maarten: Scientific basis, methodology and projected climate change for 2050 and 2100. Scientific Report; WR-26-03. Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands.

Funding

Parts of this project received funding from the European Union’s Horizon 2020 Research and Innovation Programme under Grant Agreement No. 101073954 (PARATUS project; <https://www.paratus-project.eu>).

The following topics covered in this report were funded under this programme: ENSO bias and large-scale rainfall drivers (1.3), heat projections (2.2.2), extreme water levels (3.3.1) and marine heatwaves (3.3.2).

Executive summary

Climate change is already affecting Aruba, Curaçao, and Sint Maarten. According to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), human influence has unequivocally warmed the atmosphere, ocean, and land. Small islands are particularly vulnerable to climate change because of their limited land area, strong dependence on coastal zones and climate-sensitive sectors, and limited adaptive capacity. Aruba, Curaçao, and Sint Maarten are therefore exposed to a wide range of climate-related risks, including increasing heat stress, sea-level rise, and changes in precipitation patterns.

This report presents climate scenarios for Aruba, Curaçao, and Sint Maarten developed within the framework of the International Panel on Deltas and Coastal Areas (IPDC). The scenarios provide island-specific information to support adaptation planning and climate risk assessments in sectors such as water management, spatial planning, coastal protection, nature conservation, public health, energy, and tourism.

The scenarios combine observations from the islands with projections from global climate models and a robust scientific understanding of climate change. The methodology builds upon the KNMI'23 climate scenarios developed for the Netherlands and the Caribbean Netherlands, and incorporates local observations and expertise from Aruba, Curaçao, and Sint Maarten. They describe plausible climate conditions for 2050 and 2100 relative to the 1991–2020 reference period. Three global emissions scenarios are considered to represent uncertainties in future greenhouse gas emissions. These are combined with mild and strong drying scenarios to represent uncertainties in the regional climate response. The report provides projections for temperature, heat, rainfall, wind speed, sea level, extreme water levels, and marine heatwaves. Two important climate hazards – tropical cyclones and extreme rainfall – are not addressed in this report, as they require high-resolution modelling and methodologies that exceed the scope of this study.

All scenarios project continued warming throughout the twenty-first century. By 2100, temperatures are projected to increase by less than 1 °C under the lowest-emissions scenario and by approximately 3 °C under the highest-emissions scenario. The strongest warming occurs during the warmest months of the year, leading to more frequent hot days and higher maximum temperatures. As a result, heat conditions that are currently rare are expected to become increasingly common. Most scenarios indicate a drying tendency, although the magnitude of change remains uncertain. Depending on the scenario, annual precipitation changes range from limited changes to reductions of up to approximately 50 %. Relative decreases are largest during the dry season, while absolute reductions are greatest during the wet season. Projected changes in annual mean wind speed indicate a small increase for Aruba and Curaçao, whereas no changes are projected for Sint Maarten. Sea level will continue to rise throughout the twenty-first century and beyond. Relative to 1991–2020, sea level is projected to be approximately 20 cm higher by 2050. By 2100, projected sea-level rise ranges from about 50 cm under low emissions to around 80 cm under high emissions. Under low-likelihood, high-impact scenarios involving accelerated ice-sheet loss, substantially larger rises cannot be excluded. Sea-level rise will continue after 2100. Even under the low emissions scenario, sea level is projected to continue rising beyond 2100, exceeding one metre on sufficiently long timescales.

The magnitude of future climate change on Aruba, Curaçao, and Sint Maarten depends strongly on future global greenhouse gas emissions. Nevertheless, future increases in temperature and sea level are unavoidable. These findings highlight the importance of both global mitigation efforts and timely local adaptation to enhance the long-term resilience of the islands.

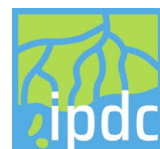
Acknowledgements

This technical report presents the climate scenarios for Aruba, Curaçao, and Sint Maarten, developed within the framework of the International Panel on Deltas and Coastal Zones (IPDC). The IPDC is an initiative funded by the Government of the Netherlands that provides technical assistance to small island states and developing countries worldwide. The programme addresses the full cycle of climate resilience building, including climate scenario development, climate risk assessments, adaptation planning, access to adaptation finance, and implementation support. The IPDC programme is facilitated by Deltares and Stichting Climate Adaptation Services. This work forms part of the IPDC Dutch Caribbean activity *Climate Scenarios and Digitization for Aruba, Curaçao and Sint Maarten*. The climate scenarios presented in this report are intended to support national climate risk assessments and the development of adaptation strategies and plans. The authors gratefully acknowledge the close collaboration with the meteorological services of Aruba, Curaçao, and Sint Maarten. Their observational data, climatological expertise, and knowledge of local conditions were essential for ensuring that the scenarios are scientifically robust and relevant to local needs. The authors further thank the IPDC Dutch Caribbean coordinators, Timo Kelder and Arno Nolte, and IPDC project manager Robert-Jan Moons for their guidance and support throughout the project. This work builds on the KNMI'23 climate scenarios for the Netherlands. The authors gratefully acknowledge KNMI and, in particular, the authors of the KNMI'23 climate scenarios for providing the scientific foundation on which this work is based. The authors also acknowledge the Government of the Netherlands for enabling this work through the IPDC programme. This collaboration has resulted in climate scenarios that combine scientific excellence with local expertise and context, thereby supporting climate adaptation and long-term planning in Aruba, Curaçao, and Sint Maarten.

For questions regarding this report, readers are encouraged to contact the meteorological departments of Aruba, Curaçao, or Sint Maarten.



Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Waterstaat



Contents

Executive summary	2
Acknowledgements	3
Glossary	6
1 Introduction	7
1.1 Why climate scenarios are relevant	8
1.2 Climate scenario approach	8
1.2.1 KNMI'23 framework	9
1.2.2 Updated global emissions scenarios	10
1.2.3 From KNMI'23 to IPDC scenarios	10
1.3 ENSO bias and large-scale rainfall drivers	10
1.4 Scope and limitations	11
1.5 Previous climate projection studies in the Caribbean	12
1.6 Structure of the report	13
2 Atmospheric climate scenarios	14
2.1 Methodology for atmospheric climate scenarios	14
2.1.1 Selection of socioeconomic scenarios (SSPs) and corresponding global warming levels .	14
2.1.2 Matched warming method	15
2.1.3 Two storyline scenarios to capture the spread in future precipitation	15
2.1.4 Statistical downscaling and bias correction	21
2.1.5 Calculation of the projected change	22
2.2 Results for atmospheric climate: observed climate and climate scenarios	24
2.2.1 Observed climate change	24
2.2.2 Atmospheric climate scenarios	28
3 Sea-level scenarios	42
3.1 Methodology for sea-level scenarios	42
3.1.1 Observations and model evaluation	42
3.1.2 Sea-level components and scenario construction	43
3.1.3 Low-likelihood high-impact scenarios	43
3.2 Results for sea-level scenarios	45
3.2.1 Observed sea-level change	45

3.2.2	Sea-level projections	47
3.3	Additional ocean-related climate indicators	52
3.3.1	Extreme water levels	52
3.3.2	Marine heatwaves	54
4	Main findings and discussion	58
4.1	Main findings	58
4.2	Physical interpretation	58
4.2.1	ENSO and Caribbean precipitation	58
4.2.2	Sea-level processes	59
4.2.3	Marine heatwaves and ocean processes	61
4.3	Uncertainties and limitations	61
4.3.1	Uncertainty in ENSO and precipitation projections	61
4.3.2	Methodological choices compared to KNMI'23 BES	61
4.3.3	Sea-level limitations	62
4.3.4	Limitations of the marine heatwave analysis	64
4.4	Implications for adaptation and future research	64
4.4.1	Coastal adaptation and sea-level rise	64
4.4.2	Extreme water levels and hurricanes	64
4.4.3	Climate extremes	65
4.4.4	Marine heatwaves and sea surface temperatures	65
4.4.5	Minimum and maximum temperatures	65
4.4.6	Trade winds and coastal upwelling	65
	Bibliography	66
A	Evaluation of observational datasets	70
A.1	Datasets	70
A.1.1	Station data	70
A.1.2	NOAA GSOD	71
A.1.3	ERA5-Land	71
A.1.4	Global Precipitation Climatology Centre (GPCC)	71
A.2	Comparison	72
A.2.1	Aruba	72
A.2.2	Sint Maarten	73
A.2.3	Curaçao	73
B	Supplementary climatology figures	80
B.1	Climatology 2050	80
B.2	Climatology 2100	84

Glossary

List of abbreviations that are used multiple times in this report

- **AMOC** – Atlantic Meridional Overturning Circulation
- **AR6** – Sixth Assessment Report of the IPCC
- **AVISO** – Archiving, Validation and Interpretation of Satellite Oceanographic data
- **CMIP6** – Coupled Model Intercomparison Project Phase 6
- **DMA** – Departamento Meteorológico Aruba
- **ENSO** – El Niño–Southern Oscillation
- **ERA5** – European Centre for Medium-Range Weather Forecasts (ECMWF) fifth-generation atmospheric reanalysis
- **GIA** – Global Isostatic Adjustment
- **GPCC** – Global Precipitation Climatology Centre
- **GSAT** – Global Surface Air Temperature
- **GSOD** – Global Surface Summary of the Day
- **IPCC** – Intergovernmental Panel on Climate Change
- **IPDC** – International Panel on Deltas and Coastal Areas
- **ITCZ** – Intertropical Convergence Zone
- **KNMI** – Royal Netherlands Meteorological Institute
- **KNMI’23** – Dutch climate scenarios published in 2023
- **LLHI** – Low-Likelihood, High-Impact
- **MDC** – Meteorological Department Curaçao
- **MDS** – The Meteorological Department of Sint Maarten
- **MHW** – Marine Heatwaves
- **NOAA** – National Oceanic and Atmospheric Administration
- **ODSL** – Ocean Dynamic Sea Level
- **PSMSL** – Permanent Service for Mean Sea Level
- **QDM** – Quantile Delta Mapping
- **SSP** – Shared Socioeconomic Pathways
- **SST** – Sea Surface Temperature
- **WMO** – World Meteorological Organization

Chapter 1

Introduction

Climate change is already affecting Aruba, Curaçao and Sint Maarten. The Intergovernmental Panel on Climate Change (IPCC) concluded in its Sixth Assessment Report (AR6) that human influence has unequivocally warmed the atmosphere, oceans and land (IPCC, 2021a). Global warming is occurring at an unprecedented rate, at least during the last 2,000 years. In 2024, the global mean temperature surpassed 1.5°C above pre-industrial levels (1850–1900) for the first time in a single calendar year, making it the warmest year on record (Copernicus Climate Change Service (C3S), 2024). Global mean sea level has been rising over the past century and the rate of rise has accelerated in recent decades.

Aruba, Curaçao and Sint Maarten are located in different parts of the Caribbean and therefore experience distinct climatic conditions (Figure 1.1). Aruba and Curaçao are situated in the southern Caribbean, close to the coast of Venezuela, and have a relatively dry, semi-arid climate influenced by the trade winds and regional upwelling systems. Sint Maarten is located in the northeastern Caribbean and experiences a wetter tropical climate. In contrast to Aruba and Curaçao, Sint Maarten lies within the Atlantic hurricane belt and is therefore more exposed to tropical cyclones.

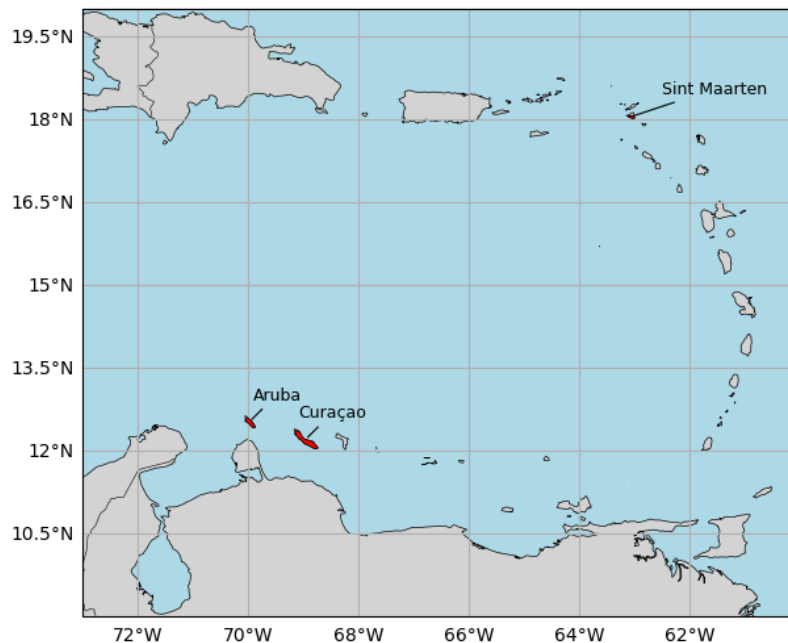


Figure 1.1: Location of Aruba, Curaçao and Sint Maarten within the Caribbean region. Aruba and Curaçao are located in the southern Caribbean near the Venezuelan coast, whereas Sint Maarten is situated in the northeastern Caribbean.

The geographical characteristics of the islands increase their exposure to hazards such as coastal flooding,

storm surge, erosion and saltwater intrusion (International Panel on Deltas and Coastal Areas (IPDC), 2024). In addition, mountainous terrain on parts of Sint Maarten may locally enhance rainfall extremes and flood risk. These physical vulnerabilities are amplified by socioeconomic factors, including high population density and the importance of tourism and fisheries for the local economy. The islands have already experienced the impacts of extreme weather and climate-related events. Hurricane Irma severely affected Sint Maarten in September 2017, while Curaçao experienced damaging floods in May 2024. In addition, increasing temperatures contribute to chronic heat stress (Cruz et al., 2025). On Curaçao, heat-related impacts have already resulted in the introduction of a heat plan in schools to protect students and teachers during the hottest months of the year.

Small islands are particularly vulnerable to climate change because of a combination of physical and socioeconomic factors (Mycioo et al., 2022). Limited land area, extensive coastlines and strong dependence on climate-sensitive sectors increase exposure to climate-related hazards. Tourism, fisheries and coastal infrastructure are especially sensitive to changes in temperature, precipitation and sea level. Rising sea levels increase the risk of coastal flooding, contribute to coastal erosion and salinization of freshwater resources, and can affect ecosystems and critical infrastructure (Martyr-Koller et al., 2021; Yu et al., 2019). For Aruba, Curaçao and Sint Maarten, sea-level rise poses a particular challenge because many economic activities, ecosystems and built-up areas are concentrated along the coast. Rising sea levels threaten beaches, coral reef ecosystems and low-lying coastal infrastructure (International Panel on Deltas and Coastal Areas (IPDC), 2024). These impacts are particularly relevant for tourism, which forms an important pillar of the economies of Aruba, Curaçao and Sint Maarten. Consequently, climate change poses both environmental and socioeconomic challenges to the islands.

1.1 Why climate scenarios are relevant

Climate adaptation requires information about how local climate conditions may evolve in the future. Climate scenarios do not provide predictions of what will happen, but rather describe a range of plausible future climates under different assumptions regarding greenhouse gas emissions and climate system responses. They help governments, businesses and communities to assess risks and develop adaptation strategies.

Climate information is particularly important for Aruba, Curaçao, and Sint Maarten, as many of their societal sectors are closely linked to weather and climate conditions. Water resources, coastal infrastructure, tourism, ecosystems, public health, and energy demand are all sensitive to changes in temperature, precipitation, and sea level. Since long-term investments can remain in place for decades, future climate conditions must be accounted for. Although global climate projections provide valuable information, their spatial resolution is generally too coarse to directly represent the local climate of small islands. Island-specific climate scenarios are therefore required to translate global climate change into information that is relevant for local decision making.

The climate scenarios presented in this report provide a scientific basis for adaptation planning on Aruba, Curaçao and Sint Maarten. They offer a consistent framework for assessing future climate risks and support policy development in areas such as water management, urban planning, coastal protection, nature conservation, health, energy and tourism.

1.2 Climate scenario approach

Most climate scenarios aim to describe plausible future climate conditions based on different assumptions regarding greenhouse gas emissions and the response of the climate system. They are not predictions, but internally consistent descriptions of possible future climates that can be used to assess risks and support adaptation planning.

Climate change is usually expressed in relation to a reference period. To reduce the impact of internal variability, periods of thirty years are usually considered. In this report, climate is defined as the thirty-year average state of a particular weather variable. The scenarios are presented for the years 2050 and 2100, these time horizons represent thirty-year reference periods centered around these years. Changes are expressed relative to the 1991–2020 reference period, which corresponds to the most recent World Meteorological Organization

(WMO) climate normal. During this reference period, the Global Mean Surface Air Temperature (GSAT) was already approximately 0.85°C warmer than during the pre-industrial period (1850–1900) (IPCC, 2021a).

The scenarios are developed for four climate variables: temperature, precipitation, wind speed and sea level. For the atmospheric variables, both different greenhouse gas emissions pathways and different regional precipitation storylines are considered. Sea-level rise is treated separately because it responds to climate change on much longer timescales and depends on different physical processes.

For each island, for the atmospheric scenarios, observational data from the main airport meteorological stations are used to represent the local climate. Consequently, the scenarios are representative of conditions near these stations. Spatial differences in climate may exist across the islands, particularly in areas with complex topography such as Sint Maarten.

1.2.1 KNMI’23 framework

The methodology used in this report follows the framework of the KNMI’23 climate scenarios for the Netherlands and the Caribbean Netherlands (Dorland et al., 2024; Wiel et al., 2024). Climate scenarios aim to describe the range of plausible future climates by explicitly accounting for the main sources of uncertainty in climate change projections. According to Hawkins et al., 2009, uncertainties in future climate change originate from three sources: internal climate variability, uncertainty in future anthropogenic forcing, uncertainty in the climate system’s response to a given level of forcing. Internal variability arises from natural fluctuations within the climate system and is inherently unpredictable on decadal and longer timescales. An important example for the Caribbean region is the El Niño–Southern Oscillation (ENSO), which strongly influences temperature, precipitation and hurricane activity.

Uncertainty in future anthropogenic forcing is related to unknown future greenhouse gas emissions and land-use changes. These are represented by the Shared Socioeconomic Pathways (SSPs), as adopted in the IPCC Sixth Assessment Report and in KNMI’23 (IPCC, 2021a; Brian C O’Neill et al., 2016). The climate scenarios presented here are based on output from global climate models participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6). Three emissions pathways are considered: SSP1-2.6, SSP2-4.5 and SSP5-8.5. SSP1-2.6 represents a low emissions pathway consistent with the ambitions of the Paris Agreement to limit global warming to well below 2°C and preferably 1.5°C above pre-industrial levels. SSP2-4.5 represents a moderate pathway and is used by local stakeholders as a reference for medium-term adaptation planning. SSP5-8.5 represents a high-end pathway with continued fossil-fuel use and limited mitigation and is included to assess long-term climate risks. Therefore, we will refer to SSP1-2.6 as the low emissions scenario, to SSP2-4.5 as the moderate emissions scenario and to SSP5-8.5 as the high emissions scenario.

In practice, the third source of uncertainty, the climate system’s response to a given level of forcing, is represented by the spread among climate models and is therefore often referred to as model uncertainty. KNMI’23 addresses this uncertainty using a storyline approach (Wiel et al., 2024). Instead of presenting only the full model ensemble, physically consistent groups of climate models are used to represent different regional climate responses. For the Caribbean, previous work showed that model uncertainty in future climate projections of precipitation is large, mainly because of differences in the simulated response of large-scale circulation and ENSO-related processes (Marta Brotons et al., 2024; Dorland et al., 2024). Therefore, the storyline approach in this study is based on precipitation and distinguishes between a relatively mild and relatively severe dry future climate. The uncertainty range for temperature and wind speed is consequently smaller than for precipitation. By the end of the century, however, differences between emissions scenarios become the dominant source of uncertainty for all variables.

Unlike the atmospheric scenarios presented in this report, which are constructed using matched global warming levels and a storyline approach, the sea-level scenarios are derived directly from the emissions scenarios. Consequently, uncertainties in the climate sensitivity and resulting temperature response are implicitly included in the projected sea-level rise. This distinction follows the KNMI’23 framework for the Netherlands and the Caribbean Netherlands (Le Bars et al., 2025), and is based on the sea-level framework presented in Chapter 9 of the IPCC Sixth Assessment Report (Fox-Kemper et al., 2021). In addition to standard scenarios, several low-likelihood high-impact (LLHI) scenarios are considered to illustrate plausible high-end outcomes relevant for long-term adaptation planning.

1.2.2 Updated global emissions scenarios

Since the publication of AR6 and KNMI'23, updated global emissions projections have become available (D. P. Van Vuuren et al., 2026). These indicate that the lowest and highest CMIP6 emissions pathways (SSP1-1.9, not used in this study, and SSP5-8.5) are currently considered less representative of the most likely future emissions development than previously assessed. However, these updates concern emissions pathways rather than the resulting climate projections themselves which include the uncertainty of the climate sensitivity of the global climate model. As updated emissions pathways have not yet been incorporated into a new generation of global climate model simulations, the KNMI'23 framework and the climate scenarios presented in this report remain relevant for climate risk assessment and adaptation planning. High-end regional climate changes may also arise under lower emissions pathways if climate sensitivity, carbon-cycle feedbacks, or regional climate responses are stronger than currently assumed. Future generations of climate scenarios are expected to incorporate updated emissions pathways (Selten et al., 2025).

1.2.3 From KNMI'23 to IPDC scenarios

The present report builds upon the KNMI'23 climate scenarios developed for Bonaire, Sint Eustatius and Saba (Dorland et al., 2024; Wiel et al., 2024). Because of the geographical proximity and similarities in climate, these scenarios provide the scientific foundation for the climate scenarios developed for Aruba, Curaçao and Sint Maarten. This study presents the first climate scenarios specifically developed for Aruba, Curaçao and Sint Maarten. Building on the KNMI'23 framework, the methodology was refined in close collaboration with the meteorological departments of the three islands to ensure that the scenarios are both scientifically robust and relevant for local stakeholders.

Several methodological improvements were introduced compared to the original KNMI'23 Caribbean scenarios. Firstly, locally observed meteorological data were used to improve the statistical downscaling and bias correction of the climate model output. Secondly, the seasonal definitions were adapted to match those used operationally by the meteorological services of each island, rather than applying a single Caribbean-wide definition. Thirdly, the selection of climate models used to construct the precipitation storylines was refined to better represent local climate characteristics.

In addition, a moderate emissions scenario (SSP2-4.5) was included following requests from local stakeholders. For many adaptation questions concerning the coming decades, stakeholders indicated that this scenario is currently used as a practical reference. Consequently, particular attention is given to the moderate emissions scenario when discussing results for 2050. For the end of the century, emphasis is placed on the high emissions scenario to illustrate possible long-term climate risks. These choices reflect stakeholder preferences and communication needs and should not be interpreted as implying that one emissions scenario is more likely than another.

Previous work for the Caribbean has shown that both precipitation storylines are associated with drying relative to the present climate, differing primarily in the magnitude of the projected drying (Marta Brotons et al., 2024; Dorland et al., 2024). Consequently, although the original KNMI'23 methodology distinguishes between *wet* and *dry* scenarios, this report adopts the terms *mild drying scenario* and *strong drying scenario* to better reflect the physical interpretation of the two precipitation storylines for Aruba, Curaçao and Sint Maarten.

The scenarios presented in this report were developed within a collaboration between KNMI, the Meteorological Department Aruba (DMA), the Meteorological Department Curaçao (MDC), the Department of Meteorological Services Sint Maarten (MDS), and the International Panel on Deltas and Coastal Areas (IPDC). This collaboration ensured that local expertise, observational datasets and stakeholder requirements were incorporated throughout the development of the scenarios.

1.3 ENSO bias and large-scale rainfall drivers

Future precipitation changes in the Caribbean are strongly influenced by large-scale atmosphere–ocean interactions. Previous studies have shown that projected drying in the Caribbean is primarily associated with changes in tropical circulation patterns and moisture transport (Marta Brotons et al., 2024; Dorland et al.,

2024).

As the tropical Pacific warms, many climate models simulate a shift towards more El Niño-like conditions. The strength of this trend varies considerably among the models (Marta Brotons et al., 2024). This shift weakens the Walker circulation and reduces moisture transport towards the Caribbean (Figure 1.2). During the dry season, additional drying may result from changes in the position of the Intertropical Convergence Zone (ITCZ) and stronger trade winds transporting relatively dry air into the region (Marta Brotons et al., 2024).

Walker circulation and seawater temperature

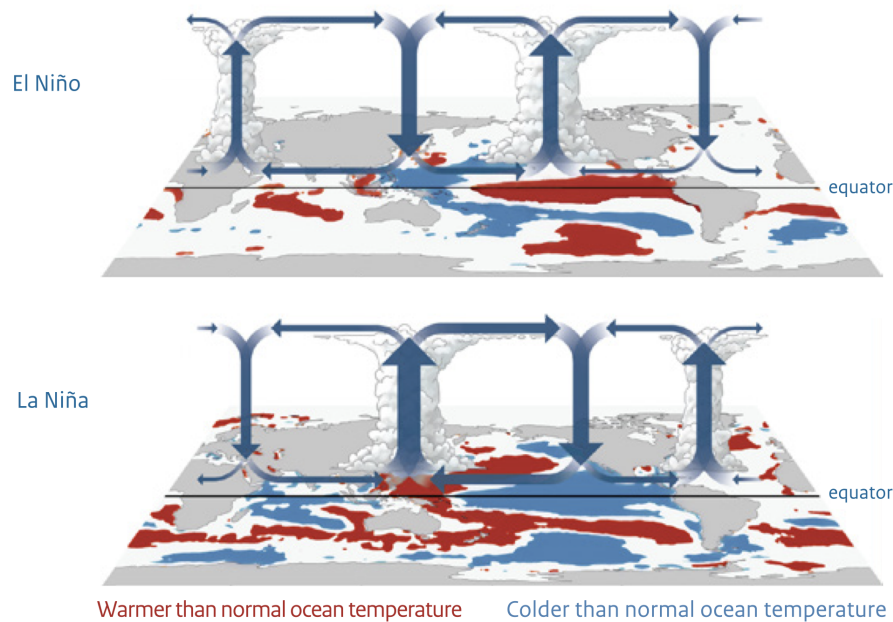


Figure 1.2: Schematic representation of the Walker circulation and tropical Pacific sea surface temperature anomalies during El Niño (top) and La Niña (bottom). El Niño conditions are generally associated with reduced convection and enhanced subsidence over the Caribbean, contributing to drier conditions in the region. Source: KNMI/NOAA.

However, substantial uncertainty remains regarding the response of the tropical Pacific to global warming. Several studies have identified persistent discrepancies between observed and simulated trends in the tropical Pacific (Seager, Henderson, et al., 2022). Recent observations have shown a tendency towards a La Niña-like trend, whereas many climate models simulate an El Niño-like mean-state response to global warming. Some studies attribute these differences to internal climate variability (Bayr et al., 2014; Plesca et al., 2018; Chung et al., 2019; Zhao et al., 2019), while others argue that they reflect systematic model biases (Seager, Cane, et al., 2019; Seager, Henderson, et al., 2022).

Because Caribbean precipitation is strongly linked to these large-scale processes, uncertainties in ENSO behaviour constitute one of the largest sources of uncertainty in future rainfall projections. This uncertainty motivates the precipitation-based storyline approach adopted in this report. The projected summer drying identified by the IPCC for the Caribbean (Figure 1.3) is consistent with the mechanisms described by Marta Brotons et al., 2024. A more extensive discussion of the physical mechanisms and associated uncertainties is provided in Chapter 4.

1.4 Scope and limitations

This report focuses on projected changes in temperature, precipitation, wind speed and sea level for Aruba, Curaçao and Sint Maarten. In addition, a selection of climate indicators, including hot days and marine

heatwaves, is analysed to provide further context for climate adaptation. Given the available project time and resources, not all aspects of climate change could be addressed within the scope of this study. Important topics such as tropical cyclones, heavy rainfall extremes, drought duration, ocean acidification and climate tipping points require dedicated methods and are therefore beyond the scope of the present study.

The climate scenarios presented in this report are intended to provide a scientifically robust basis for climate adaptation and risk assessment. They should therefore be regarded as a foundation for subsequent impact assessments rather than as a comprehensive assessment of all climate-related risks facing the islands.

1.5 Previous climate projection studies in the Caribbean

The present work builds upon a growing body of global and regional climate research concerning the Caribbean and Small Island Developing States. The IPCC AR6 Working Group II assessment identifies small islands as among the regions most vulnerable to climate change because of their exposure to sea-level rise, extreme weather, ecosystem degradation and socioeconomic constraints (IPCC, 2022).

The IPCC AR6 WG1 Regional Fact Sheet for Small Islands (IPCC, 2021b) concludes that warming has already been observed across Small Island regions and will continue under all future emissions scenarios. Rising temperatures are expected to increase heat stress and marine heatwaves, while sea level will continue to rise and exacerbate coastal flooding, shoreline retreat and saltwater intrusion. Future changes in tropical cyclone frequency remain uncertain, whereas the intensity of the strongest tropical cyclones is expected to increase in a warmer climate. For the Caribbean region, the IPCC identifies a progressive reduction in precipitation during the summer months under higher global warming levels (Figure 1.3). The strongest drying signal occurs during June–August, whereas projected changes in other months are generally smaller. These large-scale findings provide the broader context within which the island-specific scenarios presented in this report should be interpreted.

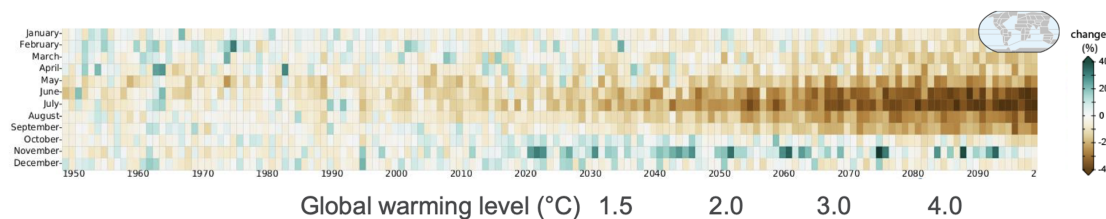


Figure 1.3: Projected monthly precipitation changes relative to 1995–2014 for the Caribbean Small Islands (CAR) region defined in IPCC AR6. Each column represents one year and each row a calendar month. Colours indicate projected precipitation anomalies relative to the reference period. The labels below the figure indicate the approximate global warming levels reached over time in the underlying CMIP6 simulations. The figure illustrates progressively stronger drying during the summer months (June–August) with increasing global warming. Source: IPCC, 2021b.

Sea-level scenarios for the Caribbean Netherlands were previously developed by Le Bars (Le Bars, 2022) and were subsequently incorporated into the KNMI’23 climate scenarios for Bonaire, Sint Eustatius and Saba (Dorland et al., 2024). These scenarios demonstrated that substantial regional differences in sea-level rise exist within the Caribbean and provided the methodological basis for the sea-level component of the present study. The current report extends this approach to Aruba, Curaçao and Sint Maarten.

The State of the Caribbean Climate report provides a comprehensive synthesis of observed trends and projected changes in temperature, rainfall and extremes across the Caribbean region (Mona, 2020). It draws on IPCC assessments, regional studies and regional climate modelling. It highlights ongoing warming, escalating heat stress, intensified droughts in certain areas, and heightened risks associated with heavy rainfall and tropical cyclones. Providing an important regional context for understanding future climate risks, the report recognises substantial sub-regional and island-scale analysis.

Additional regional studies (Van Meerbeek, 2020; Campbell et al., 2011; Michael A Taylor et al., 2013; Michael A. Taylor et al., 2018) consistently indicate continued warming and changes in precipitation across

the Caribbean. These studies provide an important regional context for the present work, but generally focus on larger spatial scales and therefore cannot fully represent island-specific climate processes.

For Curaçao, earlier assessments of climate change and its potential impacts were prepared by the Meteorological Department Curaçao (MDC) (Meteorological Department Curaçao, 2024). These assessments already highlighted continued warming, increasing heat stress and changes in precipitation patterns for the island. The present study builds upon these earlier efforts by applying the KNMI'23 framework and extending the analysis to Aruba and Sint Maarten.

Although previous studies provide important information on regional climate change, most analyses focus on the wider Caribbean and therefore cannot fully represent island-scale climate processes. Processes such as the Southern Caribbean Upwelling System, the Caribbean Low-Level Jet and local topography influence climate conditions differently on each island. The present study complements previous work by combining the KNMI'23 scenario framework with local observations and stakeholder input. This approach enables the development of island-specific climate scenarios for Aruba, Curaçao and Sint Maarten while remaining consistent with the large-scale signals identified in earlier Caribbean studies.

1.6 Structure of the report

This report presents the technical background of the IPDC climate scenario project for Aruba, Curaçao and Sint Maarten. In addition to this technical report, separate public reports have been prepared for each island in English and Dutch, with Papiamentu translations available for Aruba and Curaçao. These reports communicate the climate scenarios and their implications to a broader audience and are available through the KNMI website.¹

This technical report consists of two main parts. Chapter 2 describes the methodology, observations and results for the atmospheric variables temperature, precipitation and wind speed. Chapter 3 presents the methodology, observations and scenarios for sea level. The report concludes with a discussion of the main findings, uncertainties, implications for adaptation and recommendations for future research. Additional figures and the validation of observational datasets are provided in the appendices.

¹Public reports: Aruba (https://cdn.knmi.nl/system/data_center_publications/files/000/072/380/original/KNMI_Climate_Scenarios_Aruba_25-06.pdf), Curaçao (https://cdn.knmi.nl/system/data_center_publications/files/000/072/381/original/KNMI_Climate_Scenarios_Curacao_25-07.pdf) and Sint Maarten (https://cdn.knmi.nl/system/data_center_publications/files/000/072/382/original/KNMI_Climate_Scenarios_Sint_Maarten_25-08.pdf).

Chapter 2

Atmospheric climate scenarios

This chapter presents the climate scenarios for three key atmospheric variables: temperature, precipitation and wind speed. The first section outlines the methodology used to construct these climate scenarios. The subsequent section presents the results per variable, allowing inter-island comparisons.

2.1 Methodology for atmospheric climate scenarios

The methodology builds upon that used for the climate scenarios for Bonaire, Saba, and Sint Eustatius (Dorland et al., 2024), and the climate scenarios for Suriname (Koole et al., 2024) is used. An extensive description of this methodology can be found in Dorland et al., 2024 section 9.4.2. The methodology applied for the Caribbean scenarios builds upon the methodology used by KNMI for the scenarios of the Netherlands (Dorland et al., 2024 and Wiel et al., 2024). The methodology consists of five main steps:

1. **Selection of socioeconomic scenarios (SSPs) and corresponding global warming levels.**

Global warming levels are derived for the selected SSPs (SSP1-2.6, SSP2-4.5 and SSP5-8.5) and the IPCC AR6 assessed range of future global warming.

2. **Matched warming method.**

The selection of 30-year climate model periods is based on their global warming level, with the objective of ensuring that the regional projections correspond to the selected level of global warming, as determined in step 1.

3. **Definition of model groups.**

To represent uncertainty in future precipitation changes, climate models are grouped according to the magnitude of their projected drying response. This results in two physically consistent precipitation storylines: a mild and a strong drying scenario.

4. **Statistical downscaling and bias correction.**

Observational data is used to bias correct the model outputs ensuring a more precise alignment with the local climates of Aruba, Curaçao, and Sint Maarten.

5. **Calculation of projected changes.**

The long-term change in temperature, precipitation and wind speed are determined for each storyline scenario for the years 2050 and 2100 compared to the 1991–2020 reference period.

2.1.1 Selection of socioeconomic scenarios (SSPs) and corresponding global warming levels

The climate scenarios are based on global socioeconomic development scenarios, also known as Shared Socioeconomic Pathways (SSPs). Following KNMI'23, three emissions scenarios are considered: a low emissions

scenario (SSP1-2.6), a moderate emissions scenario (SSP2-4.5), and a high emissions scenario (SSP5-8.5). To assess the projected local climate response for the islands, output from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) is used. CMIP6 is an international multi-model initiative aimed at improving our understanding of the global climate response to anthropogenic forcing (Brian C O'Neill et al., 2016).

To ensure consistency with the IPCC AR6 assessed range of future global warming, the emissions scenario's time horizons are translated into corresponding Global Surface Air Temperature (GSAT) warming levels. These warming levels are subsequently used to evaluate the projected regional climate response in the CMIP6 models. This approach also reduces the influence of differences in climate sensitivity among models. The IPCC AR6 report provides an assessed range of GSAT change for different emissions scenarios and future time horizons relative to 1996–2015, thereby accounting for uncertainty in the global climate response to greenhouse gas forcing. The KNMI'23 global warming levels, based on the median of these assessed ranges, are given in Table 2.1. For a more detailed discussion of the selected warming levels, the reader is referred to Section 2.1.1 of Dorland et al., 2024. Climate sensitivity describes the amount of global warming associated with a doubling of atmospheric CO₂ concentrations. Because climate models differ in their climate sensitivity, individual models reach the same level of global warming at different times for the same emissions scenario. This effect is accounted for in the matched warming approach described in the next section.

		Time horizons	
Emissions scenario	Scenario name	2050	2100
SSP1-2.6	low (L)	0.9 (0.5-1.3)	0.8 (0.4-1.5)
SSP2-4.5	moderate (M)	1.1 (0.8-1.6)	1.9 (1.3-2.9)
SSP5-8.5	high (H)	1.5 (1.0-2.0)	4.0 (2.8-5.6)

Table 2.1: KNMI'23 global warming levels, based on the median value of the IPCC 'assessed range' of Global Surface Air Temperature change (Δ GSAT) relative to 1996–2015 [$^{\circ}$ C], for different emissions scenarios at the KNMI'23 time horizons. Values in parentheses indicate the 90 % confidence interval (5th–95th percentile). Table derived from the KNMI'23 climate scenarios (Dorland et al., 2024)

2.1.2 Matched warming method

A set of simulations from 29 CMIP6 models is used to assess the projected local climate response. The models are selected based on the availability of near-surface air temperature (tas), precipitation (pr), and near-surface zonal and meridional wind components (uas and vas) for the historical period and the period 2015–2115 for the three selected emissions scenarios described in Section 2.1.1. Following KNMI'23, no quality-based model selection was applied. Individual CMIP6 models differ in their climate sensitivity and therefore reach the same level of global warming at different times. The matched warming approach accounts for these differences by comparing model output at the same level of global warming rather than at the same future year. This reduces the influence of differences in climate sensitivity among models.

For each model, the 30-year period corresponding to the desired global warming level is selected from the high emissions scenario (Table 2.1). Using the high emissions scenario ensures that all target warming levels are reached within the simulation period. This procedure is referred to as *time sampling* (James et al., 2017; Hausfather et al., 2022). For models that do not exactly reach the target warming level, the projected regional climate response is linearly scaled to the desired Δ GSAT value. This procedure is referred to as *pattern scaling* (James et al., 2017). Together, time sampling and pattern scaling constitute the matched warming approach. By analysing climate change at a given level of global warming, rather than at a fixed point in time, the matched warming method provides a more robust estimate of regional climate change and reduces the influence of differences in climate sensitivity among models. Further details on the matched warming method are provided in Section 2.1.2 of Dorland et al., 2024.

2.1.3 Two storyline scenarios to capture the spread in future precipitation

The matched warming method reduces the influence of differences in global climate sensitivity among CMIP6 models. The remaining uncertainty arises from internal variability and uncertainty in the regional climate

response. The storyline approach adopted in this study builds on the analysis of Marta Brotons et al., 2024, who showed that uncertainty in future Caribbean precipitation projections is primarily associated with differences in the simulated circulation response.

Figures 2.1 (Aruba and Curaçao) and 2.2 (Sint Maarten), which will be discussed in detail below, show that the spread in projected precipitation responses across the CMIP6 ensemble is substantial. The upper panels show projected precipitation changes. The wide range of individual model projections (black dots) demonstrates that while some models project little change in precipitation, others project decreases exceeding 60 % by the end of the century. A similarly large spread in projected Caribbean precipitation changes is shown in Figure 1 of Marta Brotons et al., 2024, indicating that this uncertainty is a robust feature of the CMIP6 ensemble. This large spread motivates the use of a storyline approach (Shepherd et al., 2020).

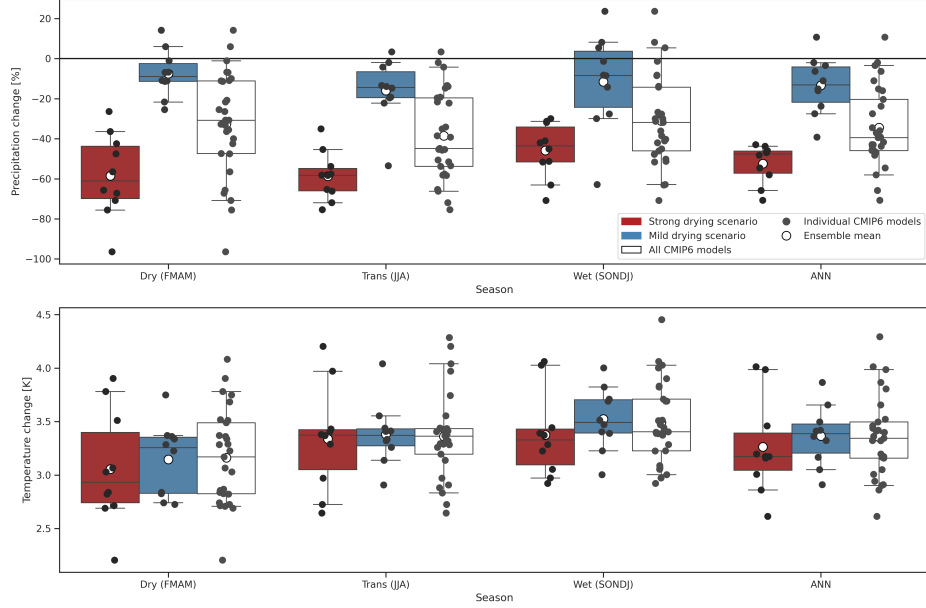


Figure 2.1: Box plots showing the spread in projected changes in precipitation (upper panel) and temperature (lower panel) for the dry season (February–May), transition season (June–August), wet season (September–December), and annual mean for Aruba and Curaçao for target year 2100 under the high emissions scenario. Results are shown for the strong drying scenario (red), the mild drying scenario (blue), and the complete ensemble (white). The central line in each box represents the median change, the box edges indicate the interquartile range (25th–75th percentile), and the whiskers represent the 5th and 95th percentiles. Individual models are shown as black dots, while the ensemble mean is indicated by a white circle.

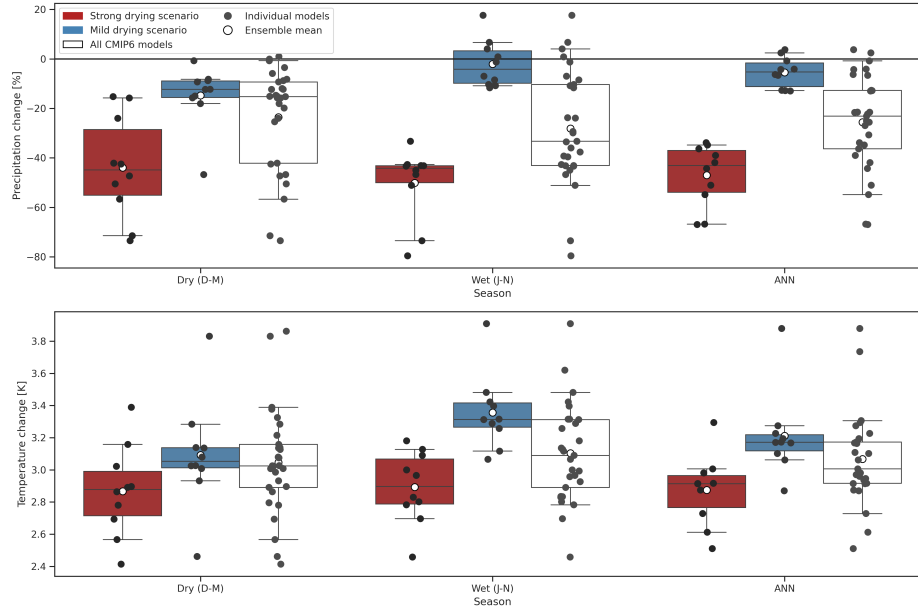


Figure 2.2: Box plots showing the spread in projected changes in precipitation (upper panel) and temperature (lower panel) for the dry season (December–May), wet season (June–November), and annual mean for Sint Maarten for target year 2100 under the high emissions scenario. Results are shown for the the strong drying scenario (red), the mild drying scenario (blue), and the complete ensemble (white). The central line in each box represents the median change, the box edges indicate the interquartile range (25th–75th percentile), and the whiskers represent the 5th and 95th percentiles. Individual models are shown as black dots, while the ensemble mean is indicated by a white circle.

Precipitation is selected as the central storyline variable because it exhibits a relatively large spread in projected change and because precipitation is a key climate variable for the Caribbean (Mona, 2020). Furthermore, Caribbean precipitation is strongly influenced by large-scale tropical circulation patterns, including ENSO (Giannini et al., 2000; Giannini et al., 2001; Marta Brotons et al., 2024; see Section 1.3). Using precipitation as the storyline variable therefore enables physically self-consistent scenarios while spanning a substantial part of the uncertainty in the regional climate response.

To represent this uncertainty, the 29 CMIP6 models are divided into two groups according to the magnitude of their projected drying response. These groups form the basis of the mild drying and strong drying scenarios, each containing ten models following KNMI’23. The grouping is defined using the high emissions scenario for the target year 2100 because this combination provides the largest signal-to-noise ratio and therefore minimizes the influence of internal variability on the group definition. The composition of the model groups is subsequently kept fixed for all other emissions scenarios and for the target year 2050, preserving physical consistency across time horizons and emissions scenarios.

The ten models with the weakest drying response near the islands form the basis of the mild drying scenario, whereas the ten models with the strongest drying response form the basis of the strong drying scenario. The two storylines are designed to cover the uncertainty in the precipitation response for Aruba and Curaçao jointly and for Sint Maarten separately. Aruba and Curaçao are treated jointly because they are geographically close (Figure 1.1) and share similar climatic characteristics. Sint Maarten is treated separately because it is located in the northeastern Caribbean and has therefore different climatic conditions. A more detailed description of the geographical and climatic characteristics of the islands is provided in Chapter 1. The grouping is based on a combined normalized precipitation trend index calculated over all seasons for the selected region. The division into the mild and strong drying scenarios remains consistent across seasons.

For Curaçao & Aruba we use a combined area from 10°N to 15°N and from 75°W to 65°W and for Sint Maarten we use the area between 16°N and 21°N and between 66°W and 56°W. The regions used for the model selection are determined from the correlation patterns shown in Figure 2.3. These maps show the Pearson correlation coefficient between projected precipitation changes over the islands and the surrounding

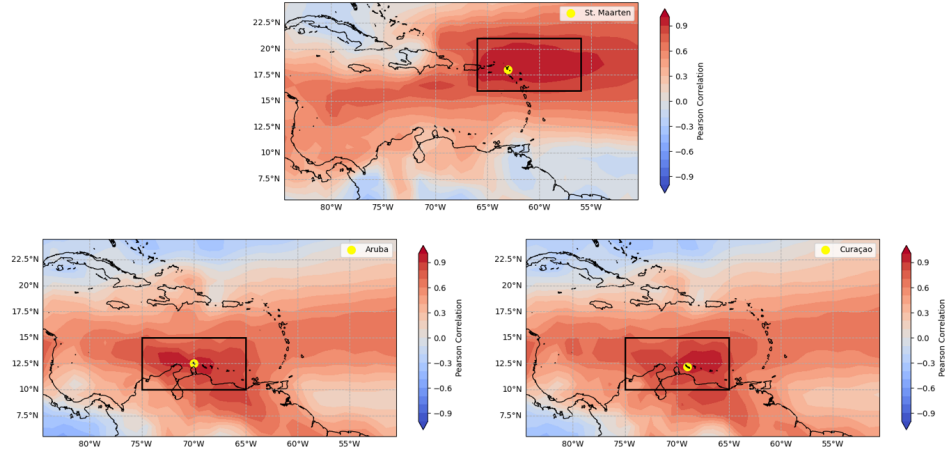


Figure 2.3: Pearson correlation coefficient between projected precipitation changes over the islands and projected precipitation changes across the surrounding Caribbean region during 2071–2100 (high emissions scenario). Panels (A) and (B) show the correlations for Aruba and Curaçao, respectively, while panel (C) shows the correlations for Sint Maarten. The black boxes indicate the regions selected for constructing the regional precipitation index used in the storyline model selection. For Aruba and Curaçao, the selected region spans 10°N–15°N and 75°W–65°W, whereas for Sint Maarten it spans 16°N–21°N and 66°W–56°W. The selected regions correspond to the areas exhibiting the highest correlations with projected precipitation changes over the islands.

Caribbean region during 2071–2100. The selected regions correspond to the areas with the strongest correlations and therefore provide representative indicators of the precipitation response near the islands. For Aruba and Curaçao a combined region is chosen. Figures 2.4 and 2.5 show the resulting model ranking and the corresponding drying scenarios.

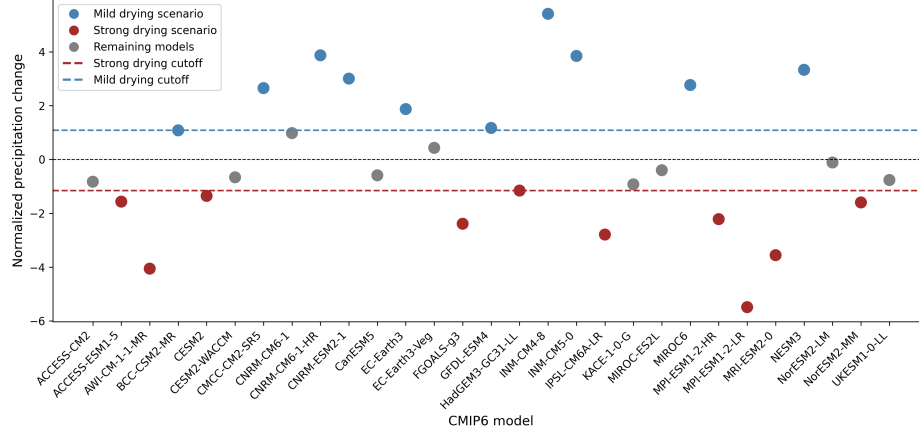


Figure 2.4: Projected precipitation change in 2100 under the high emissions scenario relative to the CMIP6 ensemble mean (normalized values) for the area (10°N–15°N, 75°W–65°W) around Aruba and Curaçao, shown for each individual model. The models are grouped according to the magnitude of their projected drying response. Models used for the mild drying scenario are shown in blue, models used for the strong drying scenario in red, and models not included in either scenario in grey. The dotted lines separate the ten models with the weakest drying response and the ten models with the strongest drying response from the remaining CMIP6 models.

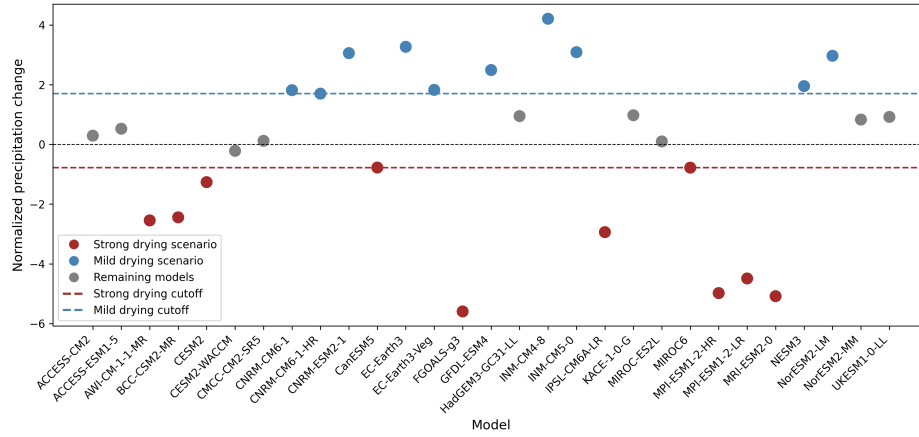


Figure 2.5: Projected precipitation change in 2100 under the high emissions scenario relative to the CMIP6 ensemble mean (normalized values) for the area (16°N–21°N, 66°W–56°W) around Sint Maarten, shown for each individual model. The models are grouped according to the magnitude of their projected drying response. Models used for the mild drying scenario are shown in blue, models used for the strong drying scenario in red, and models not included in either scenario in grey. The dotted lines indicate the selection thresholds for both scenario groups.

The characteristics of the model groups underlying the drying storyline scenarios are shown in Figures 2.1 and 2.2. These figures are fundamental to the interpretation of the storyline approach, as they illustrate which part of the model uncertainty is captured by the two drying scenarios. The upper panels show projected precipitation changes and the lower panels show projected temperature changes for the individual CMIP6 models (dots), the complete ensemble (white box plots), and the mild drying scenario (blue) and strong drying scenario (red). All results correspond to the high emissions scenario for the target year 2100 and represent the climatological period 2085–2115.

For precipitation, the drying scenarios are clearly separated for most seasons, indicating that the storyline approach captures a substantial part of the uncertainty in future precipitation change. Considerable spread nevertheless remains within each group and some outlier models are present, illustrating that the storylines do not encompass the full spread of the CMIP6 ensemble. The climate scenarios are based on the mean response of the drying scenarios rather than on individual models. Consequently, the white dots, the ensemble mean, shown in Figures 2.1 and 2.2 correspond to the values that are ultimately used in the scenario tables.

Figures 2.6 and 2.7 show the spatial precipitation change patterns associated with the drying scenarios respectively Aruba and Curaçao combined and for Sint Maarten separately. The differences between the strong (left panels) and mild (right panels) drying scenarios are not confined to the island itself but extend over a larger part of the Caribbean, indicating that the storyline separation reflects differences in large-scale circulation patterns rather than local effects only.

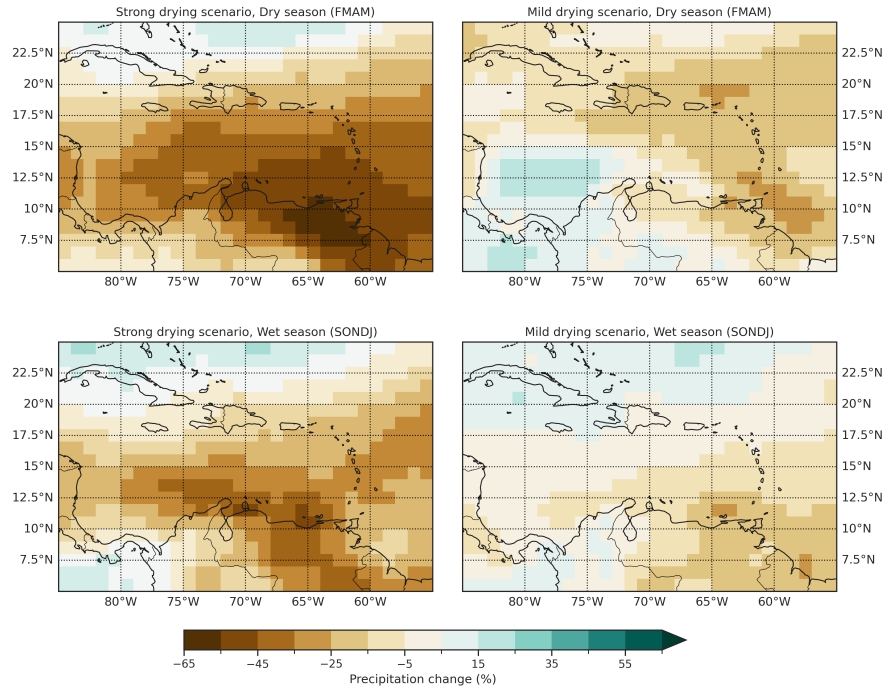


Figure 2.6: Precipitation change patterns based on CMIP6 data for 2100 in the high emissions scenario in the Caribbean. The seasons and model groups for the drying scenarios are based on Aruba and Curaçao. The left column represents the strong drying scenario and the right column the mild drying scenario. The top two graphs show the dry season (February-May) and the bottom two graphs show the wet season (September-January).

The lower panels in Figures 2.1 and 2.2 show the projected change in temperature. The CMIP6 models project substantial temperature increases for all seasons and all models. The panels show that the separation between the drying scenarios is much smaller for temperature than for precipitation. This is inherent to the adopted method for constructing the storylines. Nevertheless, a positive association between precipitation and temperature is apparent across the model groups, particularly for Sint Maarten. The mild drying scenario generally exhibits stronger warming, and vice versa. This positive association may reflect differences in the

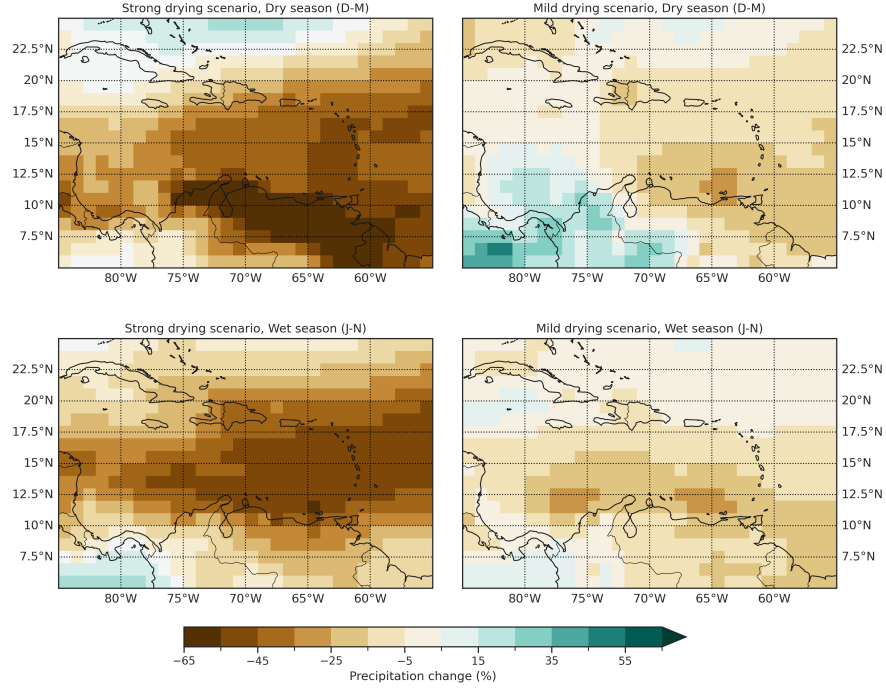


Figure 2.7: Precipitation change patterns based on CMIP6 data for 2100 in the high scenario in the Caribbean. The seasons and model groups for the drying scenarios are based on Sint Maarten. The left column represents the strong drying scenario and the right column the mild drying scenario. The top two graphs show the dry season (December-May) and the bottom two graphs show the wet season (June-November).

simulated regional and large-scale circulation response across the selected model groups, including changes in the trade winds, Walker circulation, ITCZ and Atlantic meridional overturning circulation, as well as associated cloud feedbacks. However, the physical mechanisms underlying this association have not been investigated in this study. Because the grouping is based on precipitation, only part of the uncertainty in temperature and wind speed is represented by the storyline approach. By the end of the century, the uncertainty in temperature is dominated by differences in emissions scenarios.

Figures 2.1 and 2.2 are only shown for the high emissions scenario, they mainly illustrate uncertainty associated with internal variability and the regional climate response. Uncertainty associated with future greenhouse gas emissions is not represented in these figures as the storyline approach combined with using multiple emissions scenarios separates uncertainty in the regional climate response from uncertainty in future emissions. Based on the drying scenarios, six climate scenarios are obtained for each island by combining two precipitation storylines with three emissions scenarios.

2.1.4 Statistical downscaling and bias correction

As a next step, the CMIP6 output is statistically downscaled for each island. This step is required because the CMIP6 models have a relatively coarse horizontal resolution. After regridding to a common grid, the CMIP6 data have a spatial resolution of approximately $1^\circ \times 1^\circ$ (about 109 by 111 km), which does not resolve the individual islands. Following the methodology used in KNMI'23 for Bonaire, Sint Eustatius, and Saba (Dorland et al., 2024), a statistical downscaling approach is adopted.

For each island, the nearest CMIP6 grid point is selected for near-surface air temperature (tas), precipitation (pr), and the near-surface zonal and meridional wind components (uas and vas). Observational data are subsequently used to correct systematic biases in the simulated distributions by applying Quantile Delta Mapping (QDM; Cannon et al., 2015). QDM uses the cumulative distribution functions (CDFs) of the

observations and model simulations to adjust the model output while preserving the simulated climate change signal. The same transformation derived for the historical period is subsequently applied to the future simulations, resulting in bias-corrected future climate projections for each island.

Figure 2.8 illustrates the effect of the QDM procedure for Aruba. The black curves represent the observational distributions, the solid blue curves the raw historical CMIP6 simulations, and the dashed blue curves the bias-corrected historical simulations. The solid red curves show the raw future CMIP6 simulations and the dashed red curves the bias-corrected future simulations. The figure demonstrates that the historical model distributions are shifted towards the observed distributions, while the projected climate change signal between the historical and future simulations is preserved. Similar results are obtained for Curaçao and Sint Maarten.

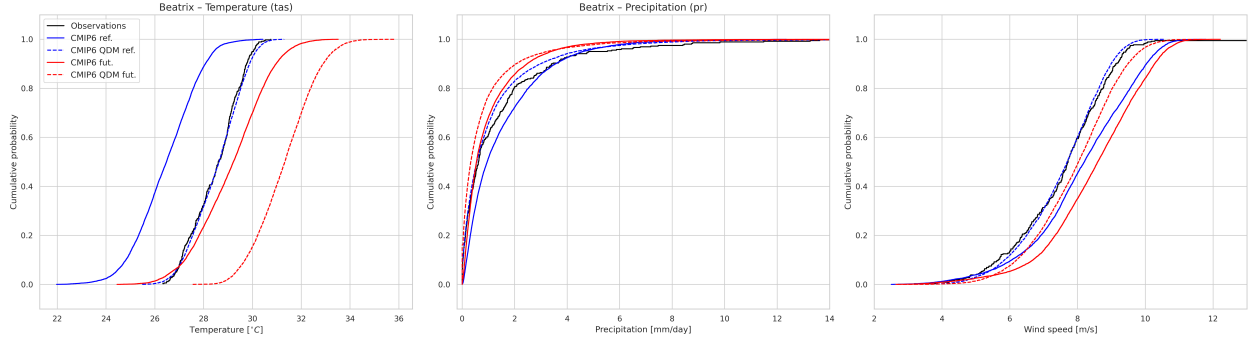


Figure 2.8: Empirical cumulative distribution functions for daily temperature (left), precipitation (middle), and wind speed (right) for Aruba. Observations are shown in black, raw historical CMIP6 simulations in solid blue, bias-corrected historical simulations in dashed blue, raw future simulations in solid red, and bias-corrected future simulations in dashed red. The QDM procedure shifts the model distributions towards the observed climatology while preserving the simulated climate change signal.

Different observational datasets are used for the three islands. For Sint Maarten, daily observations provided by MDS are used. Daily precipitation totals and daily mean values for temperature and wind speed are available. These observations were compared to the NOAA Global Surface Summary of the Day (GSOD) dataset (WMO station ID 78866) for quality control.

For Aruba, no complete daily observational dataset was available for the full 1991–2020 reference period. DMA provided hourly observations for 2005–2020, which were compared to the NOAA GSOD dataset (WMO station ID 78982). This comparison showed that the GSOD data adequately represent daily mean temperature and wind speed and daily precipitation totals and can therefore be used for bias correction.

For Curaçao, no local observational dataset was available and the NOAA GSOD dataset (WMO station ID 78988) was used directly. Further details on the validation of the observational datasets are provided in Appendix A.

2.1.5 Calculation of the projected change

After applying the matched-warming approach, selecting the drying scenarios, and statistically downscaling the CMIP6 simulations, projected climate changes are calculated as the final step of the scenario development process. For each island, six climate scenarios are obtained by combining three emissions scenarios (low, moderate and high) with two precipitation storylines (mild and strong drying). Projected changes are calculated for annual conditions as well as for the wet, dry and transition seasons separately.

The respective meteorological departments were consulted for the definition of the seasons. On Sint Maarten, seasonality is linked to the hurricane season, with a dry season from December–May and a wet season from June–November. Aruba and Curaçao have three seasons: a wet season (September–January), a dry season (February–May), and a transition season (June–August). Projected changes are expressed relative to the 1991–2020 reference period and are calculated for two time horizons: 2050 and 2100, represented by 30-year climatological averages centred around the target years. For each scenario combination, the mean response of the corresponding model group is used.

Scenario values are calculated for near-surface air temperature (*tas*), precipitation (*pr*), and near-surface wind speed derived from the zonal and meridional wind components (*uas* and *vas*). Temperature changes are expressed as absolute differences (°C), whereas precipitation and wind speed changes are expressed as relative changes with respect to the reference period.

The resulting climate scenarios are communicated in both this technical report and accompanying public reports. Figure 2.9 provides an example of the scenario tables used in the public reports, showing the projected climate conditions for Aruba in 2050. Similar tables are produced for all islands and time horizons.

Climate scenarios for 2050

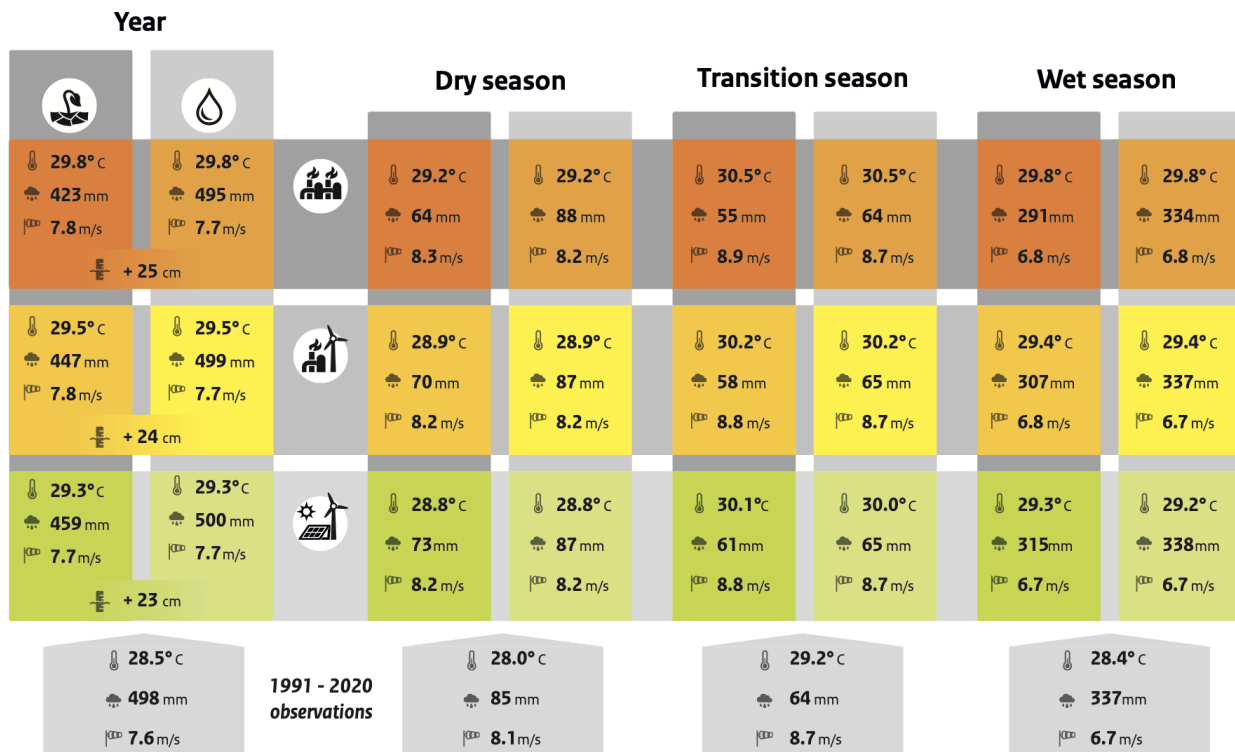


Figure 2.9: Example of the scenario figures for Aruba in 2050 for annual conditions and the three seasons under the six scenario combinations as published in the climate scenario communication reports accompanying this technical report.

2.2 Results for atmospheric climate: observed climate and climate scenarios

This section presents climate scenarios for temperature, precipitation, and wind speed. The results are presented by variable, enabling an inter-island analysis. These results will be published in the corresponding user reports for each island. This section does not discuss the drivers of climate change in the Caribbean. For a more detailed analysis, see Marta Brotons et al., 2024, as well as Section 9.4.6 of Dorland et al., 2024

2.2.1 Observed climate change

Observational records are available for the three islands for several decades (see Section 2.1.4). For Aruba and Curaçao, the analysis is based on the NOAA Global Surface Summary of the Day (GSOD) dataset. For Sint Maarten, daily observations provided by the island’s meteorological service are used. Figures 2.10, 2.11, and 2.12 show the annual temperature and wind speed averages and precipitation sums for the period 1985–2024.

During the 1991–2020 reference period, the mean annual temperature was 28.5 °C for Aruba, 28.1 °C for Curaçao, and 27.3 °C for Sint Maarten. The mean annual wind speed was 7.6 *m/s* for Aruba, 5.9 *m/s* for Curaçao, and 4.5 *m/s* for Sint Maarten. The annual precipitation total was 498 *mm* for Aruba, 618 *mm* for Curaçao, and 1112 *mm* for Sint Maarten. This indicates that Aruba is the warmest, windiest and driest island whereas Sint Maarten is the coolest, rainiest and has the lowest wind speeds.

Figures 2.10, 2.11, and 2.12 show that the mean temperature is increasing on all three islands. The increase in daily minimum temperature appears to be larger than the increase in daily maximum temperature. Years with relatively high temperatures, such as 1998, 2010, 2016, and 2024, coincide with strong El Niño events (NOAA Climate Prediction Center, 2025), consistent with the known influence of ENSO on Caribbean temperatures. However, only the temperature trend on Aruba is statistically significant.

The average wind speed shows considerable variability, with notably low wind speeds recorded in 2005 and 2010 across all three of the islands. These years coincided with particularly active Atlantic hurricane seasons with 28 and 19 named storms, respectively (NOAA National Hurricane Center, 2006 and NOAA National Hurricane Center, 2011). Hurricanes may disrupt the easterly trade winds, leading to reduced wind speeds in regions outside the storm’s path (Teunisse, 2024). A downward trend is apparent for Aruba and Curaçao. For Curaçao, this downward trend is statistically significant and largest. For Aruba, the downward trend is not significant due to large year-on-year variations. No clear long-term trend is visible in the wind speed data for Sint Maarten. Of the two islands showing a downward trend, only Curaçao’s decrease in wind speed is statistically significant.

There is significant interannual variability in precipitation across all three islands, with no statistically significant long-term trends. The variability from year to year is so large that it exceeds the magnitude of the fitted linear trends. As the observational analysis is based on data from a single station on each island, any detected trends should be interpreted with caution. Local effects, changes in instrumentation and changes in observational practices may influence the records. Further validation of the observational datasets is therefore recommended.

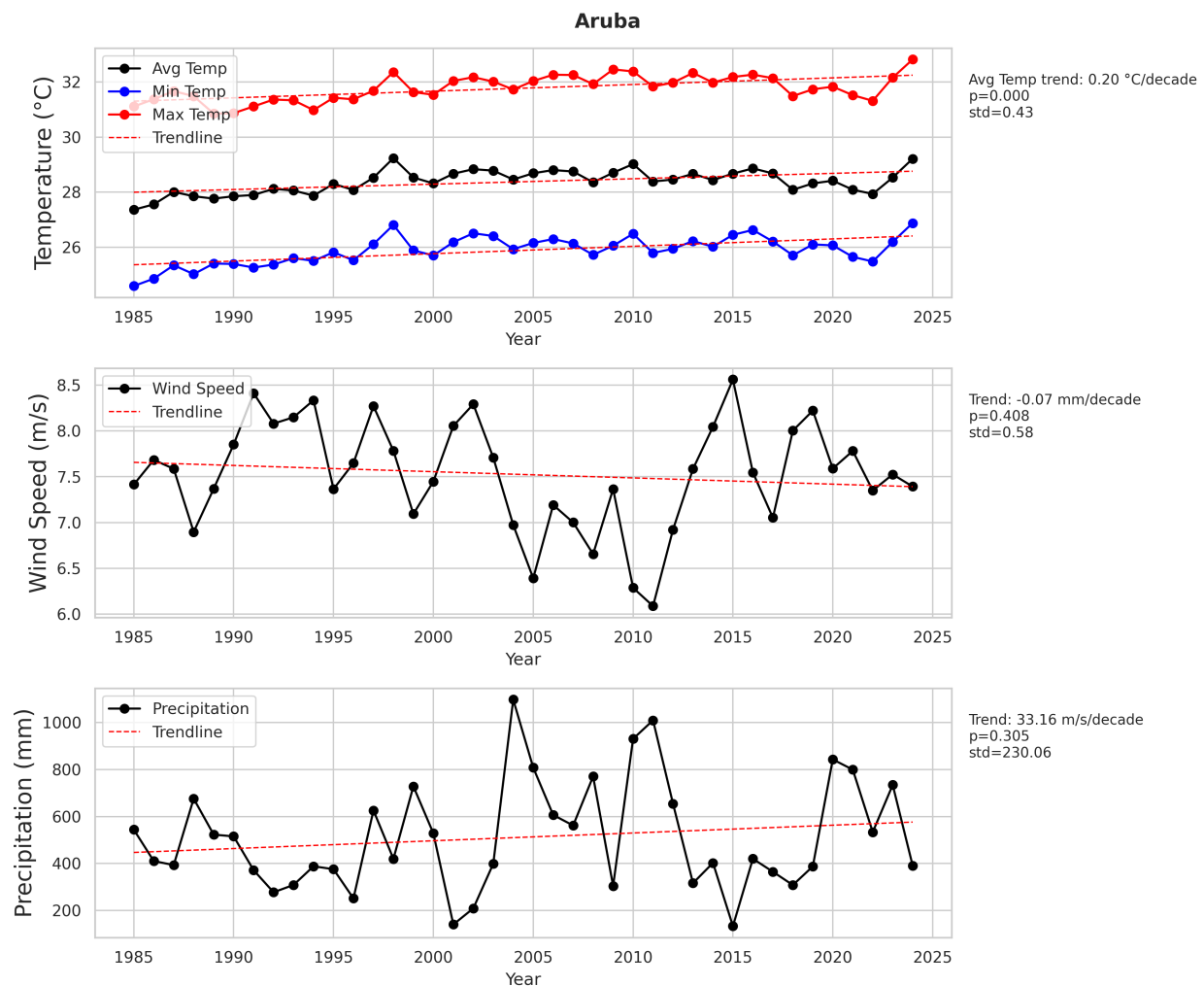


Figure 2.10: Yearly average temperature (mean, minimum, and maximum), wind speed, and total precipitation at Aruba from 1985 to 2024. The markers show the annual values and the dashed red lines indicate the linear regression trend lines. Based on NOAA GSOD data.

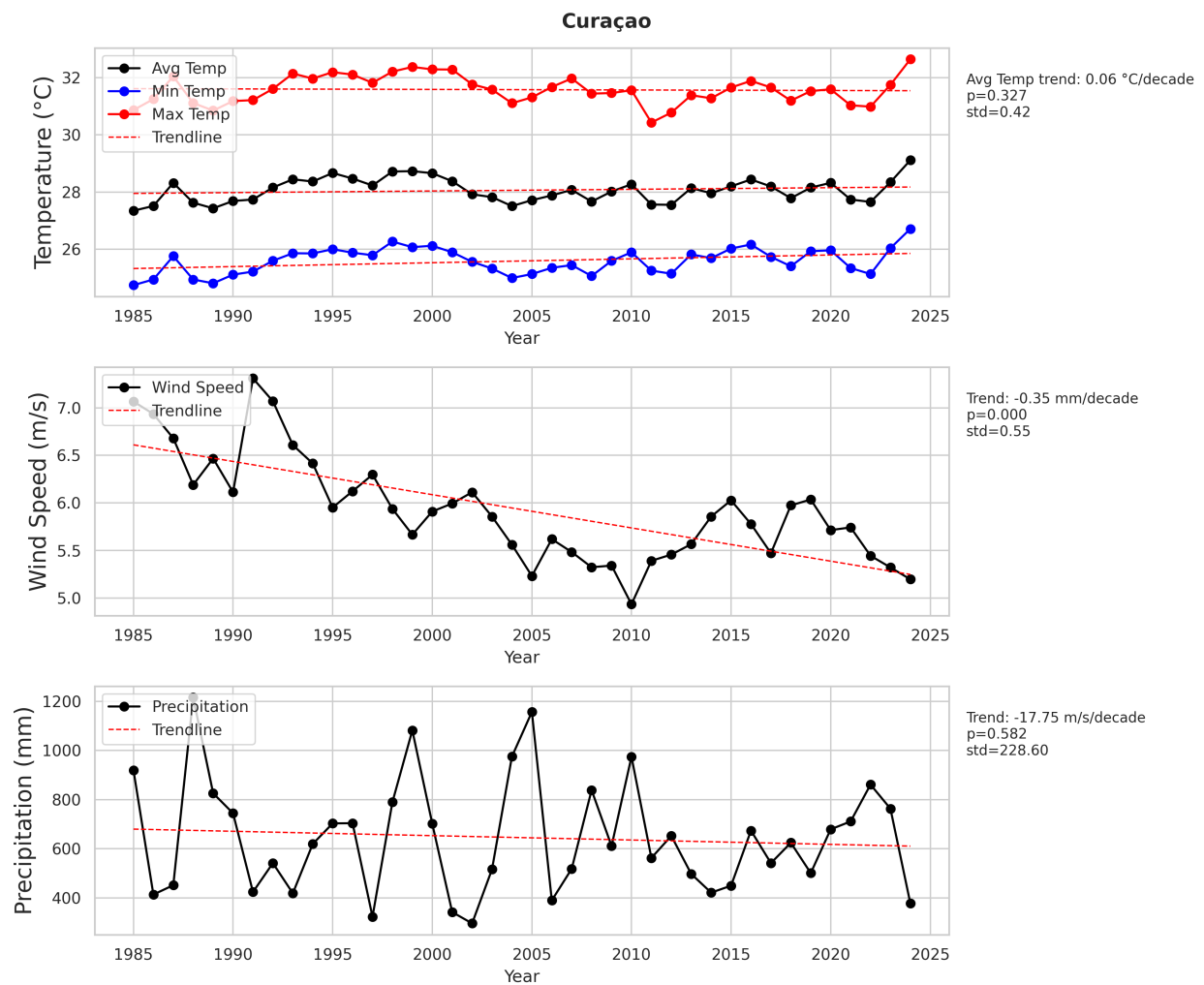


Figure 2.11: Yearly average temperature (mean, minimum, and maximum), wind speed, and total precipitation at Curaçao from 1985 to 2024. The markers show the annual values and the dashed red lines indicate the linear regression trend lines. Based on NOAA GSOD data.

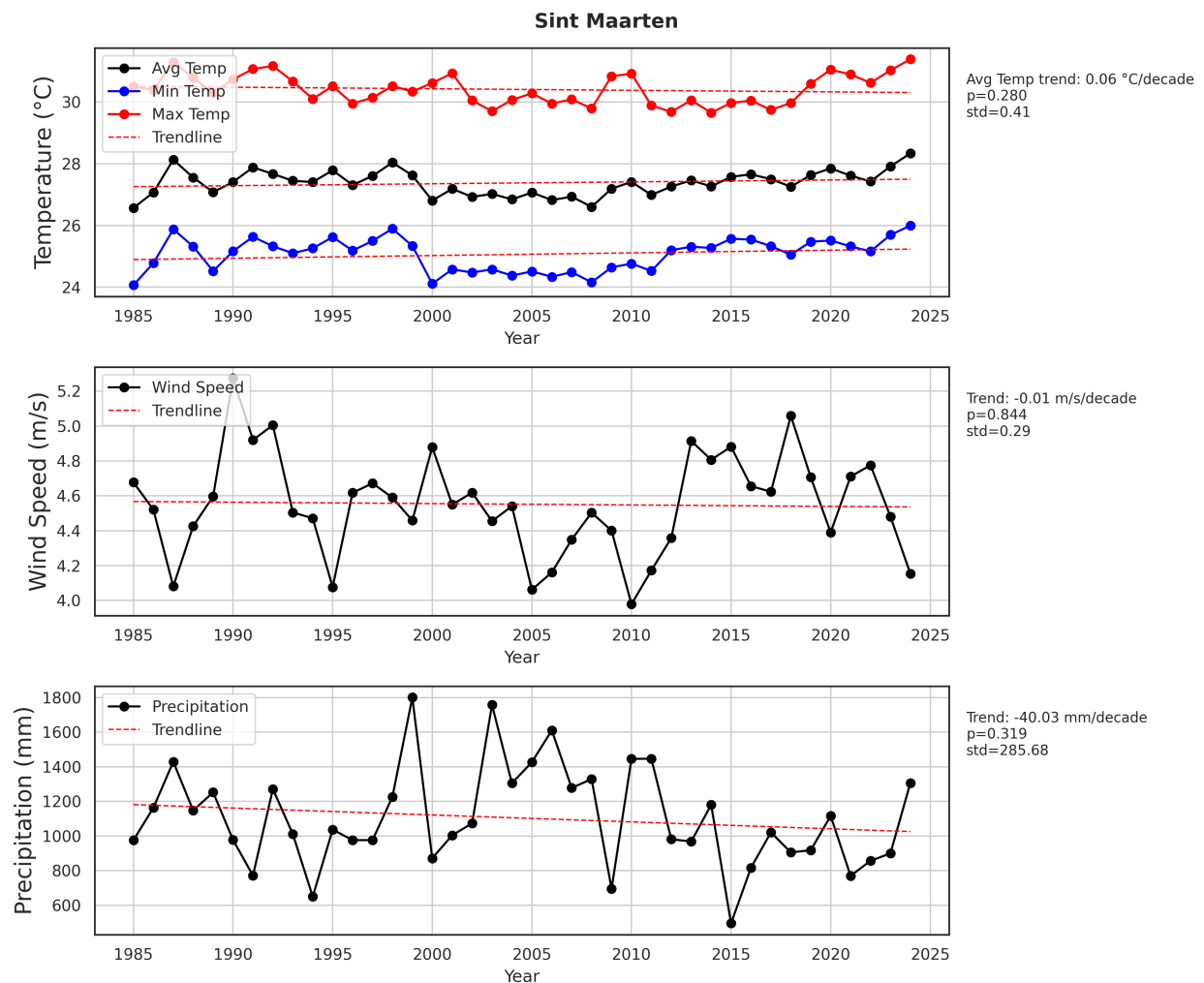


Figure 2.12: Yearly average temperature (mean, minimum, and maximum), wind speed, and total precipitation at Sint Maarten from 1985 to 2024. The markers show the annual values and the dashed red lines indicate the linear regression trend lines. Based on data of the Juliana airport station

2.2.2 Atmospheric climate scenarios

This section presents the projected changes in temperature, precipitation and wind speed in Aruba, Curaçao and Sint Maarten. First, the projected annual mean changes are discussed for each variable, followed by the corresponding climate scenario tables for 2050 and 2100.

As the seasonal cycle has a strong influence on many aspects of daily life on the islands, including water availability, ecosystems, heat exposure and other climate-sensitive activities, the analysis also covers projected changes in seasonality in addition to annual mean changes. The seasonal climatology figures compare the observed monthly climatology for the 1991–2020 reference period with the projected monthly climatology for two illustrative scenario combinations: moderate emissions scenario for 2050 and high emissions scenario for 2100. These scenarios are presented as illustrative examples because they provide useful reference cases for adaptation planning and long-term climate risk assessment. They are shown for illustrative purposes only and should not be interpreted as being more likely than the other scenarios.

Temperature scenarios

This section presents the projected changes in mean temperature on an annual and seasonal basis for Aruba, Curaçao, and Sint Maarten. First, the time series of projected annual mean temperature changes are discussed, followed by the seasonal temperature changes. Figure 2.13 shows the projected changes in annual mean temperature, as derived from the statistically downscaled CMIP6 simulations. The results for Aruba (A–C), Curaçao (D–F), and Sint Maarten (G–I) are shown for all models (left column), the mild drying scenario (middle column), and the strong drying scenario (right column). The emissions scenarios are shown in each panel up to 2100.

All emissions scenarios project continued warming for all three islands. Up to approximately 2040, the projected warming is similar across the emissions scenarios. After mid-century, the scenarios increasingly diverge, with the largest differences occurring by the end of the century. By 2050, the annual mean temperature increase is approximately 0.8 °C under the low emissions scenario and approximately 1.3 °C under the high emissions scenario. By 2100, warming is limited to approximately 0.7 °C under the low emissions scenario, whereas under the high emissions scenario the projected warming reaches approximately 3.0–3.3 °C relative to the 1991–2020 reference period (Tables 2.2, 2.3, and 2.4). Under the low emissions scenario, a slight decrease in temperature is projected after mid-century. This reflects the decline in global warming levels under this scenario, which assumes strong mitigation and net negative CO₂ emissions later in the century (IPCC, 2021a). Under the moderate and high emissions scenarios, warming continues throughout the century. The mild drying scenario generally projects slightly stronger warming than the strong drying scenario, consistent with the association between projected precipitation and temperature described in Section 2.1.1 and shown in Figures 2.1 and 2.2. However, the differences between the drying scenarios are small compared to the differences between emissions scenarios. The largest spread in projected temperature change is therefore associated with differences between emissions scenarios.

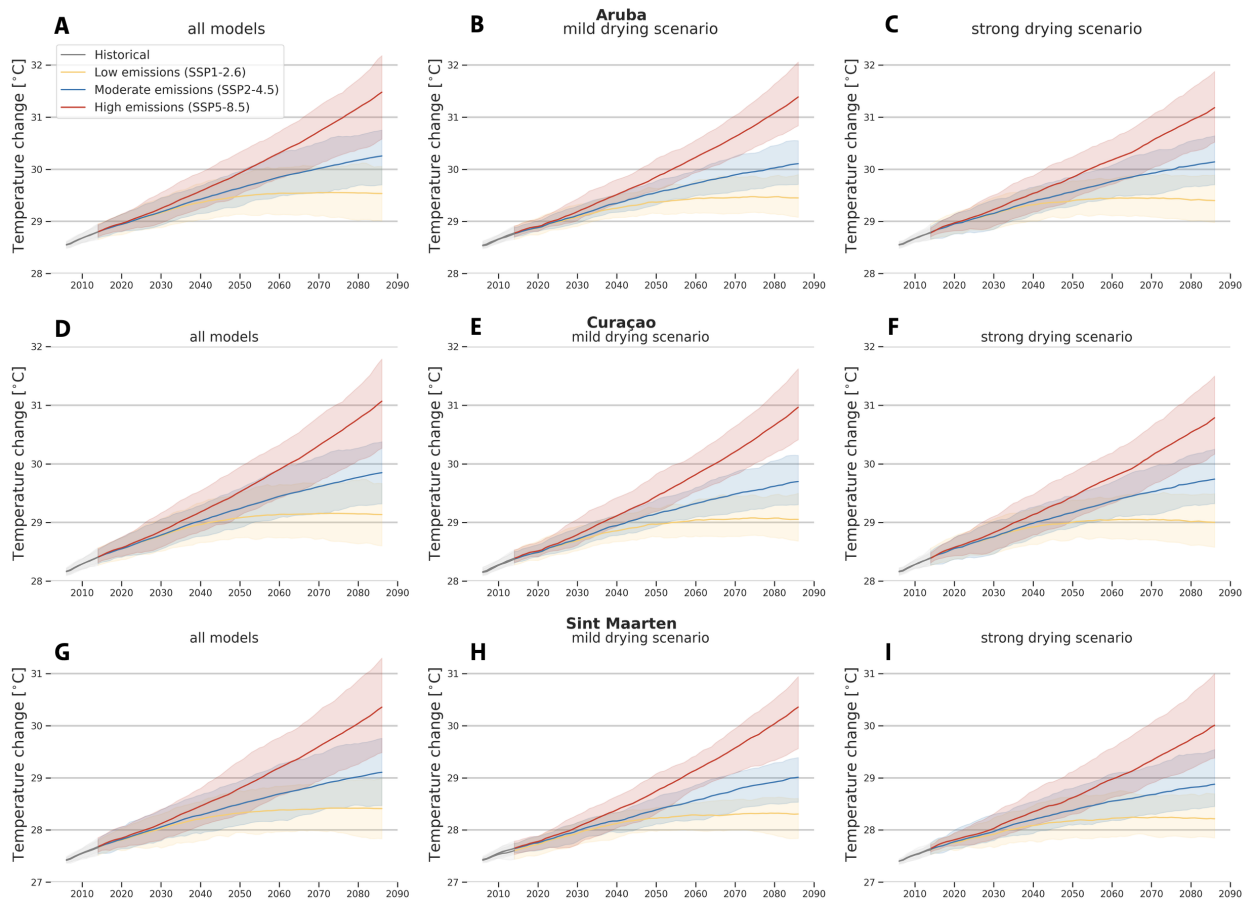


Figure 2.13: Projected changes in annual mean temperature for Aruba (A, B and C), Curaçao (D, E and F), and Sint Maarten (G, H and I) towards the 1991–2020 baseline, based on the 29 CMIP6 model that are statistically downscaled using the QDM method. The time series shown are forced by low- (yellow), moderate- (blue), and high-emissions scenario (red). The historical period is shown in grey. The lines show the 30-year rolling average multi-model mean while the shaded areas show the 90 % spread.

Seasonal changes are shown in Figures 2.14 and 2.15. These figures show the observed monthly climatology for the reference period 1991–2020 and the projected monthly climatology for two illustrative scenario combinations: moderate emissions for 2050 and high emissions for 2100. Monthly changes for all emissions scenarios and both time horizons are provided in Appendix B. All islands show similar seasonal temperature cycles, with the highest temperatures occurring in August and September. Sint Maarten has a cooler reference climate than Aruba and Curaçao. For all islands, temperature variations are small throughout the year. Aruba and Curaçao experience a relative cooling in July. The seasonal temperature cycle of Aruba and Curaçao reflects the combined influence of the annual cycle in solar radiation, the seasonal evolution of the Atlantic Warm Pool, and regional ocean-atmosphere interactions associated with the Caribbean Low-Level Jet and Venezuelan coastal upwelling. A dip in solar radiation and peak in upwelling results in the cool dip in July. Due to the more northern position of Sint Maarten, it is not affected by these dynamics.

The projected warming occurs throughout the year, while the overall shape and timing of the seasonal temperature cycle remain largely unchanged. For most scenarios and time horizons, the monthly temperature curves shift upwards almost in parallel, indicating little change in the annual temperature range. Consequently, an increasing number of future monthly mean temperatures exceed the 1991–2020 warmest monthly mean temperature (September). By 2050 under the moderate emissions scenario, this already applies to several months of the year for Aruba and Curaçao. Under the high-emissions scenario by 2100, monthly mean temperatures remain above the 1991–2020 warmest month throughout the entire year for both islands. For Sint Maarten, even the coolest months by the end of the century are projected to be comparable to the warmest month in the reference climate (August and September). This indicates that climatic conditions

Table 2.2: Projected changes in mean temperature for Aruba relative to the 1991–2020 reference period for the target years 2050 and 2100. Results are shown for the mild and strong drying scenarios combined with the emissions scenarios. Temperature changes are rounded to one decimal place; changes in interannual variability are rounded to two decimals.

Season	Indicator	1991–2020 Observations	2050						2100					
			Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild	Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild
Annual	Mean temperature	28.5 °C	0.8 °C	0.8 °C	1.0 °C	1.0 °C	1.3 °C	1.3 °C	0.7 °C	0.7 °C	1.6 °C	1.6 °C	3.0 °C	3.3 °C
	Interannual variability	0.31 °C	-0.02 °C	-0.01 °C	-0.02 °C	0.00 °C	-0.01 °C	0.01 °C	-0.02 °C	-0.01 °C	-0.00 °C	0.03 °C	0.08 °C	0.15 °C
Dry season	Mean temperature	28.0 °C	0.8 °C	0.8 °C	0.9 °C	0.9 °C	1.2 °C	1.2 °C	0.7 °C	0.7 °C	1.5 °C	1.5 °C	2.9 °C	3.1 °C
Wet season	Mean temperature	28.4 °C	0.8 °C	0.8 °C	1.0 °C	1.0 °C	1.3 °C	1.3 °C	0.8 °C	0.7 °C	1.6 °C	1.7 °C	3.1 °C	3.5 °C
Transition season	Mean temperature	29.3 °C	0.8 °C	0.8 °C	1.0 °C	1.0 °C	1.3 °C	1.3 °C	0.7 °C	0.7 °C	1.6 °C	1.6 °C	3.1 °C	3.3 °C

Table 2.3: Projected changes in mean temperature for Curaçao relative to the 1991–2020 reference period for the target years 2050 and 2100. Results are shown for the mild and strong drying scenarios combined with the emissions scenarios. Temperature changes are rounded to one decimal place; changes in interannual variability are rounded to two decimals.

Season	Indicator	1991–2020 Obs	2050						2100					
			Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild	Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild
Annual	Mean temperature	28.1 °C	0.8 °C	0.8 °C	1.0 °C	0.9 °C	1.3 °C	1.3 °C	0.7 °C	0.7 °C	1.6 °C	1.6 °C	3.0 °C	3.3 °C
	Interannual variability	0.36 °C	-0.02 °C	-0.01 °C	-0.02 °C	-0.01 °C	-0.01 °C	0.01 °C	-0.02 °C	-0.01 °C	0.00 °C	0.03 °C	0.09 °C	0.15 °C
Dry season	Mean temperature	27.6 °C	0.7 °C	0.7 °C	0.9 °C	0.9 °C	1.2 °C	1.2 °C	0.7 °C	0.7 °C	1.5 °C	1.5 °C	2.8 °C	3.0 °C
Wet season	Mean temperature	28.1 °C	0.8 °C	0.8 °C	1.0 °C	1.0 °C	1.3 °C	1.3 °C	0.8 °C	0.7 °C	1.6 °C	1.6 °C	3.1 °C	3.4 °C
Transition season	Mean temperature	28.9 °C	0.8 °C	0.8 °C	1.0 °C	0.9 °C	1.3 °C	1.3 °C	0.7 °C	0.7 °C	1.6 °C	1.6 °C	3.1 °C	3.3 °C

currently associated with the warmest time of the year are projected to become commonplace during much larger parts of the year, or even year-round under the high-emissions scenario for Aruba and Curaçao. Only under the high-emissions scenario by 2100 does warming become more seasonally differentiated, with slightly larger increases during the wet season.

Overall, the three islands show similar temperature responses: warming occurs throughout the year and the magnitude of warming is primarily determined by the emissions scenario.

Table 2.4: Projected changes in mean temperature for Sint Maarten relative to the 1991–2020 reference period for the target years 2050 and 2100. Results are shown for the mild and strong drying scenarios combined with the emissions scenarios. Temperature changes are rounded to one decimal place; changes in interannual variability are rounded to two decimals.

Season	Indicator	1991–2020 Obs	2050						2100					
			Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild	Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild
Annual	Mean temperature	27.3 °C	0.8 °C	0.8 °C	0.9 °C	0.9 °C	1.2 °C	1.3 °C	0.7 °C	0.7 °C	1.5 °C	1.6 °C	3.0 °C	3.3 °C
	Interannual variability	0.36 °C	-0.01 °C	0.03 °C	-0.01 °C	0.04 °C	-0.01 °C	0.06 °C	-0.01 °C	0.02 °C	-0.01 °C	0.08 °C	0.02 °C	0.17 °C
Dry season	Mean temperature	26.3 °C	0.8 °C	0.7 °C	0.9 °C	0.9 °C	1.2 °C	1.2 °C	0.7 °C	0.7 °C	1.5 °C	1.5 °C	3.0 °C	3.2 °C
Wet season	Mean temperature	28.4 °C	0.8 °C	0.8 °C	0.9 °C	1.0 °C	1.2 °C	1.3 °C	0.7 °C	0.7 °C	1.5 °C	1.7 °C	3.0 °C	3.4 °C

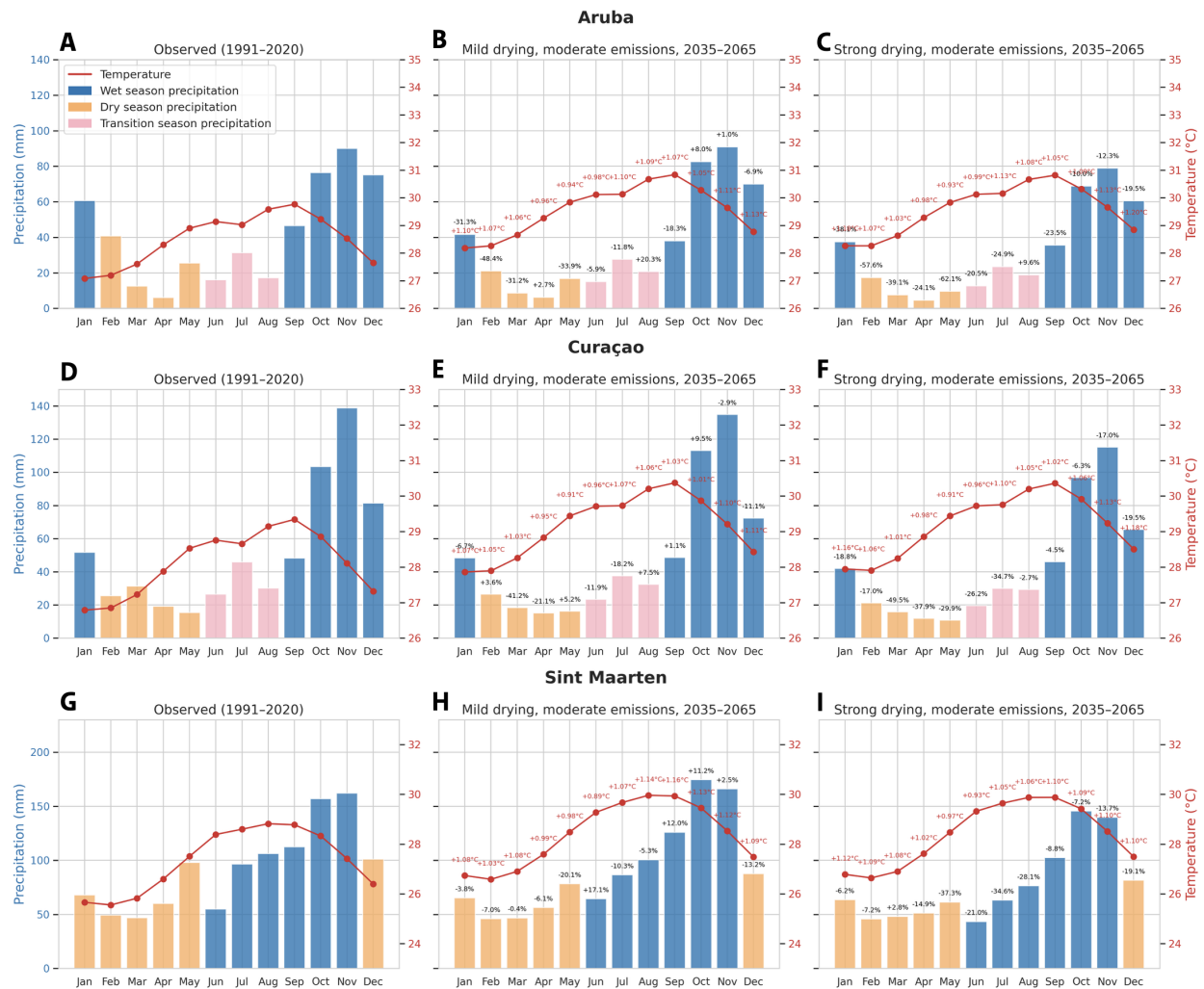


Figure 2.14: Climatology of Aruba (A–C) Curaçao (D–F) and Sint Maarten (G–I) according to the observations (A, D, G) from NOAA GSOD (1991–2020), monthly means and in a future climate (2035–2065) based on CMIP6, with a distinction between the mild drying scenario (B–H) and strong drying scenario (C, F, I) based on the moderate emissions scenario (SSP2-4.5).

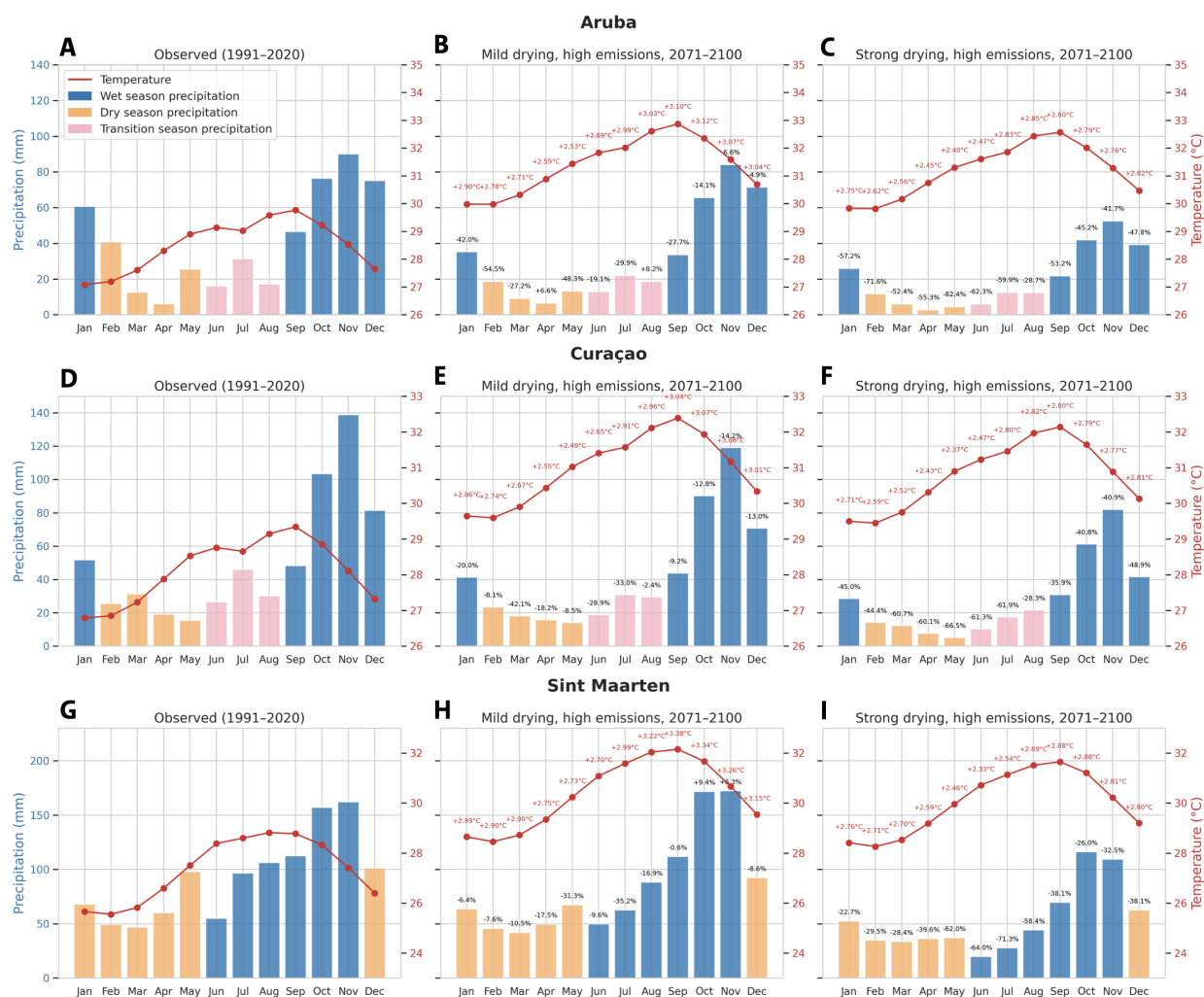


Figure 2.15: Climatology of Aruba (A–C) Curaçao (D–F) and Sint Maarten (G–I) according to the observations (A, D, G) from NOAA GSOD (1991–2020), monthly means and in a future climate (2071–2100) based on CMIP6, with a distinction between the mild drying scenario (B– H) and strong drying scenario (C, F, I) based on the high emissions scenario (SSP5-8.5).

Heat projections

Tropical regions are considered particularly vulnerable to heat stress because current climatic conditions already lie relatively close to combinations of temperature and humidity associated with adverse impacts on human health (Mora, Dousset, et al., 2017). The temperature scenarios presented in Section 2.2.1 indicate an increase in annual mean temperature of approximately 0.7–3.3 °C by the end of the century, depending on the island, emissions scenario and drying scenario. This section provides an illustrative assessment of future heat exposure by analysing changes in the frequency of hot days between the reference period and future climate periods. For this purpose, the 95th percentile of daily mean temperature during the 1991–2020 reference period was used as a threshold for extreme heat. The number of days exceeding this 1991–2020 threshold is subsequently calculated for the reference period, 2050 (2035–2065), and 2100 (2071–2100).

Figure 2.16 shows that the number of days exceeding the reference-period 95th percentile increases substantially on all three islands and under all emissions scenarios. By definition, approximately 5 % of days in the 1991–2020 reference period exceed this threshold, corresponding to about 18 days per year. By mid-century, the number of exceedances increases markedly, while towards the end of the century the differences between emissions scenarios become much larger, reflecting the divergence in projected warming after approximately 2050.

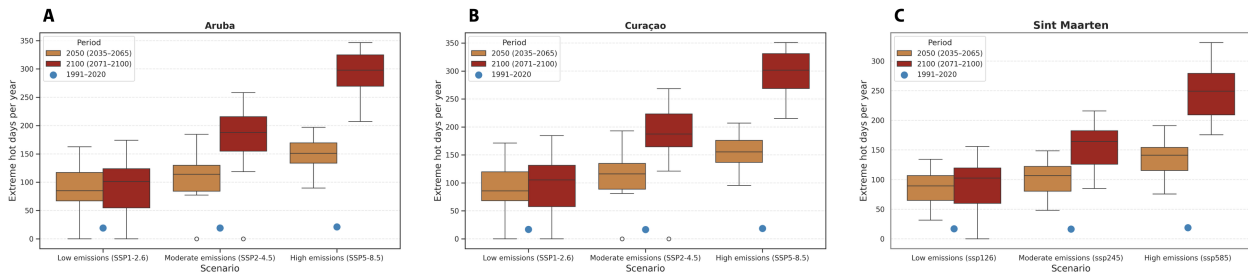


Figure 2.16: Number of days per year exceeding the 95th percentile of daily mean temperature in the 1991–2020 reference period for Aruba (A), Curaçao (B), and Sint Maarten (C). Blue markers indicate the reference-period value. Box plots show the distribution across the CMIP6 ensemble for 2050 (2035–2065; orange) and 2100 (2071–2100; red) under the low-, moderate- and high emissions scenarios.

Although there is considerable spread between individual models, especially for the high emissions scenario in 2100, the direction of change is robust across the ensemble. Under the high emissions scenario, the median projections indicate that days exceeding the reference-period 95th percentile may occur during most of the year by 2100. Conditions that are currently considered rare are therefore projected to become much more frequent in the future.

Aruba and Curaçao show very similar responses, while Sint Maarten generally exhibits somewhat fewer extreme hot days. Nevertheless, the projected increase is substantial for all islands. Because natural temperature variability in the Caribbean is relatively small, relatively modest increases in mean temperature can lead to a rapid emergence of climatic conditions outside the historical range (Mora, Frazier, et al., 2013). Consequently, temperatures that are currently experienced only rarely are projected to occur much more frequently in the future. The threshold used here is defined relative to the 1991–2020 climate and therefore describes changes relative to this reference period climate rather than a fixed physiological or impact-based heat-stress threshold.

Rainfall scenarios

Changes in atmospheric circulation and moisture transport associated with global warming are expected to affect precipitation patterns worldwide (IPCC, 2021a). Previous studies indicate an overall tendency towards drying in the Caribbean region (IPCC, 2021a, Mona, 2020 and Van Meerbeeck, 2020), although uncertainty in future precipitation projections remains large (Marta Brotons et al., 2024).

This section discusses projected precipitation changes for Aruba, Curaçao, and Sint Maarten. First, the long-term evolution of precipitation is described based on the statistically downscaled CMIP6 simulations. Subsequently, projected changes in the seasonal cycle are discussed. Figure 2.17 shows projected changes in

annual precipitation relative to the 1991–2020 reference period for all islands and for the drying scenarios under the low, moderate, and high emissions scenarios.

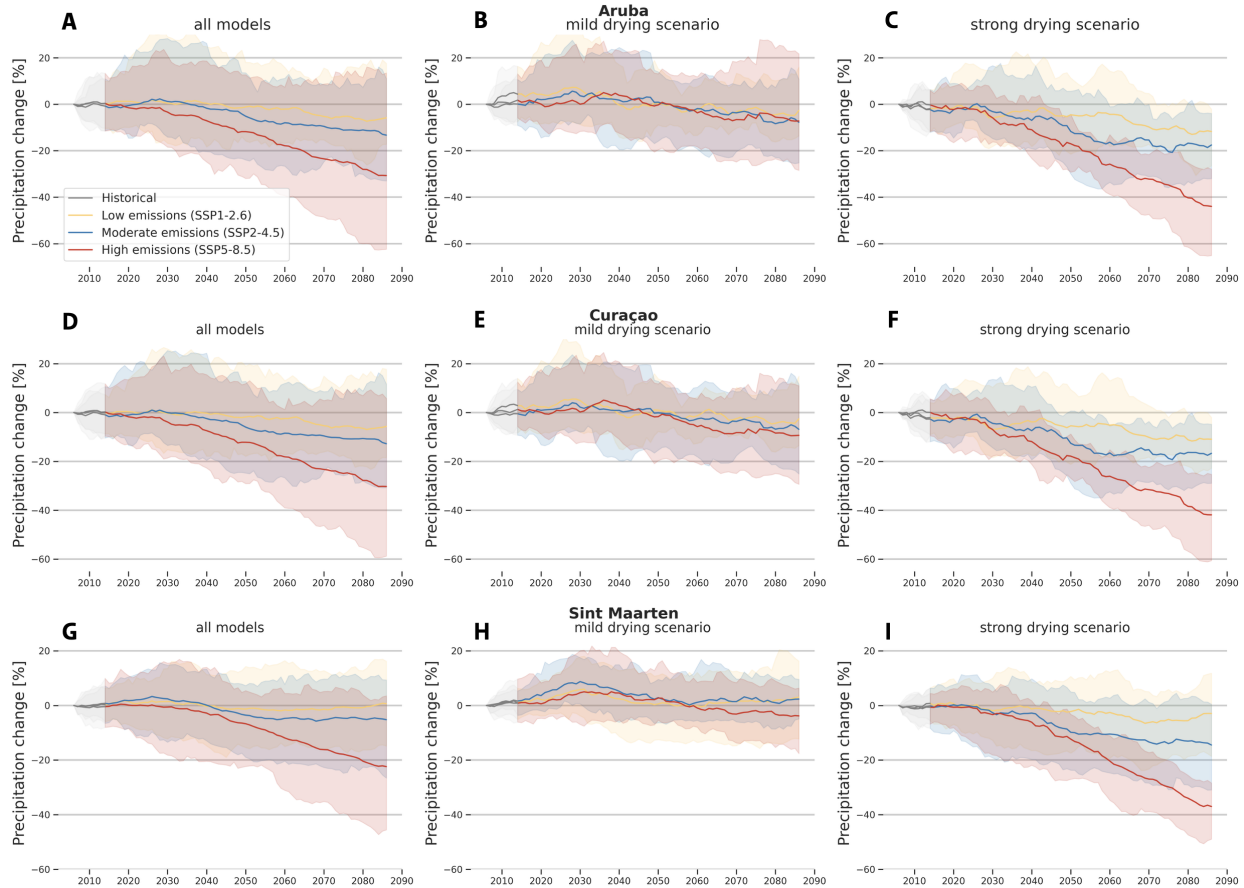


Figure 2.17: Projected changes in precipitation for Aruba (A–C), Curaçao (D–F), and Sint Maarten (G–I) towards the 1991–2020 baseline, based on the 29 CMIP6 models that are statistically downscaled using the QDM method. The time series shown are forced by the low (yellow), moderate (blue), and high emissions scenario (red). The historical period is shown in grey. The lines show the 30-year rolling average multi-model mean while the shaded areas show the 90 % spread.

Future precipitation projections show considerable uncertainty. This uncertainty originates from both strong interannual variability and differences between climate models, which are known to be particularly large for Caribbean precipitation projections (Marta Brotons et al., 2024). For all islands, an important distinction exists between the drying scenarios. The strong drying scenario consistently projects stronger drying, whereas the mild drying scenario generally projects smaller decreases and, for some scenarios on Sint Maarten, even slight increases in annual precipitation. In the first half of the century, differences between drying scenarios contribute more to the spread in projected precipitation than differences between emissions scenarios.

Aruba and Curaçao show very similar precipitation responses, which is expected given their geographical proximity and the relatively coarse horizontal resolution of global climate models. For both islands, the ensemble mean indicates decreasing annual precipitation in nearly all scenarios. The magnitude of drying increases with increasing greenhouse-gas emissions and is substantially larger for the strong drying scenario. By 2100 under the high emissions scenario, annual precipitation decreases by approximately 50 % in the strong drying scenario, whereas reductions remain around 10 % in the mild drying scenario (Tables 2.5 and 2.6). Under the low emissions scenario, projected changes are considerably smaller, with annual precipitation remaining close to reference-period values in the mild drying scenario and 7 % or 8 % in the strong drying scenario.

For Sint Maarten, projections show less drying than for Aruba and Curaçao. The low emissions scenarios as

well as the mild drying scenarios show little change in annual precipitation ranging between an increase of about +3% and a decrease of about -5% in 2100 (Table 2.7). In the strong drying scenario decreases reach about -17% in the moderate emissions scenario and about -46% in the high emissions scenario, resulting in a large spread between drying scenarios.

Uncertainty in future precipitation is large for all islands. Under the high emissions scenario, the strong drying scenarios project strong reductions in annual precipitation by the end of the century, whereas changes remain comparatively modest in the mild drying scenarios. These differences illustrate the importance of considering multiple drying scenarios when assessing future hydroclimatic risks.

Table 2.5: Projected changes in precipitation for Aruba relative to the 1991–2020 reference period for the target years 2050 and 2100. Results are shown for the drying scenarios combined with the emissions scenarios. Changes in precipitation and interannual variability are expressed relative to the 1991–2020 reference period and rounded to one and two decimal places, respectively.

Season	Indicator	1991–2020 Observations	2050						2100					
			Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild	Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild
Annual	Annual precipitation	498.0 mm	-7.9 %	0.4 %	-10.2 %	0.1 %	-15.2 %	-0.6 %	-6.9 %	0.4 %	-20.6 %	-1.7 %	-51.3 %	-7.8 %
	Interannual variability	252.47 mm	-3.92 %	5.53 %	-5.46 %	6.48 %	-9.04 %	8.14 %	-3.23 %	5.02 %	-13.11 %	9.52 %	-33.05 %	14.13 %
Dry season	Seasonal precipitation	85.0 mm	-14.6 %	2.5 %	-17.8 %	2.9 %	-24.2 %	3.7 %	-13.0 %	2.3 %	-30.3 %	4.3 %	-59.6 %	6.5 %
Wet season	Seasonal precipitation	337.4 mm	-7.0 %	0.2 %	-9.1 %	-0.1 %	-13.7 %	-1.0 %	-6.0 %	0.3 %	-18.8 %	-2.0 %	-48.6 %	-8.0 %
Transition season	Seasonal precipitation	64.5 mm	-7.0 %	1.1 %	-9.5 %	0.7 %	-15.2 %	-0.6 %	-5.9 %	1.3 %	-21.8 %	-2.5 %	-59.9 %	-15.0 %

Table 2.6: Projected changes in precipitation for Curaçao relative to the 1991–2020 reference period for the target years 2050 and 2100. Results are shown for the drying scenarios combined with the emissions scenarios. Changes in precipitation and interannual variability are expressed relative to the 1991–2020 reference period and rounded to one and two decimal places, respectively.

Season	Indicator	1991–2020 Observations	2050						2100					
			Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild	Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild
Annual	Annual precipitation	617.7 mm	-9.0 %	0.1 %	-11.2 %	-0.3 %	-16.0 %	-1.4 %	-8.0 %	0.2 %	-21.0 %	-2.8 %	-48.7 %	-11.3 %
	Interannual variability	215.77 mm	-4.66 %	3.05 %	-6.07 %	3.36 %	-9.17 %	3.67 %	-3.99 %	2.85 %	-12.51 %	3.68 %	-28.11 %	2.86 %
Dry season	Seasonal precipitation	91.5 mm	-15.4 %	-1.0 %	-18.6 %	-1.0 %	-24.7 %	-0.9 %	-13.8 %	-1.0 %	-30.5 %	-0.6 %	-56.8 %	3.5 %
Wet season	Seasonal precipitation	409.9 mm	-7.8 %	0.2 %	-9.9 %	-0.2 %	-14.3 %	-1.3 %	-6.8 %	0.4 %	-19.0 %	-2.8 %	-46.2 %	-11.7 %
Transition season	Seasonal precipitation	102.7 mm	-8.3 %	1.6 %	-10.7 %	1.2 %	-16.2 %	-0.2 %	-7.1 %	1.7 %	-22.2 %	-2.4 %	-55.5 %	-16.7 %

Table 2.7: Projected changes in precipitation for Sint Maarten relative to the 1991–2020 reference period for the target years 2050 and 2100. Results are shown for the drying scenarios combined with the emissions scenarios. Changes in precipitation and interannual variability are expressed relative to the 1991–2020 reference period and rounded to one and two decimal places, respectively.

Season	Indicator	1991–2020 Observations	2050						2100					
			Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild	Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild
Annual	Annual precipitation	1112.4 mm	-5.8 %	3.5 %	-7.7 %	3.6 %	-12.2 %	3.5 %	-4.9 %	3.3 %	-17.2 %	2.8 %	-46.1 %	-3.7 %
	Interannual variability	307.73 mm	-0.41 %	13.05 %	-1.39 %	14.70 %	-4.03 %	16.91 %	-0.03 %	12.07 %	-7.35 %	17.88 %	-24.37 %	13.45 %
Dry season	Seasonal precipitation	409.7 mm	-5.6 %	-1.6 %	-7.4 %	-2.0 %	-11.5 %	-2.8 %	-4.8 %	-1.4 %	-16.2 %	-3.7 %	-43.8 %	-8.4 %
Wet season	Seasonal precipitation	689.1 mm	-7.1 %	5.7 %	-9.3 %	6.1 %	-14.1 %	6.3 %	-6.1 %	5.4 %	-19.4 %	5.6 %	-48.7 %	-1.0 %

Figures 2.14 and 2.15 show the monthly climatology for the reference period 1991–2020 and the projected monthly climatology for two illustrative scenario combinations: the moderate emissions scenario for 2050 and the high emissions scenario for 2100. For the projected monthly precipitation climatology under all emissions scenarios and both time horizons, see Appendix B.

Aruba and Curaçao exhibit very similar seasonal precipitation cycles, with rainfall concentrated in October and November and relatively dry conditions during the first half of the year (Figures 2.14A and D). The timing of the seasonal cycle remains largely unchanged in the projections, while the magnitude of monthly precipitation changes. Relative changes are generally largest during the 1991–2020 dry and transition seasons,

where monthly rainfall totals are low, indicating increasingly dry conditions during these months. In contrast, the largest absolute reductions in monthly precipitation occur during the wet season, particularly under the high-emissions scenario by the end of the century. As a result, annual precipitation decreases substantially while the seasonal cycle is largely preserved.

Compared to Aruba and Curaçao, Sint Maarten has a wetter climate throughout the year, with a pronounced wet season associated with the Atlantic hurricane season (Figures 2.14G and 2.15G). The timing of the wet season remains similar in all scenarios, but its magnitude differs considerably between the two drying scenarios. In the mild drying scenario (Figures 2.14H and 2.15H), wet-season precipitation remains relatively close to present-day conditions, with modest increases in some months and decreases in others. In contrast, the strong drying scenario (Figures 2.14I and 2.15I) projects reductions during most months of the year. As for Aruba and Curaçao, the largest relative changes occur during the dry season, whereas the largest absolute reductions occur during the wet season, substantially reducing rainfall during the peak of the hurricane season and leading to lower annual precipitation totals.

Overall, the projections indicate a tendency towards drier conditions on all three islands while largely preserving the timing of the present-day seasonal cycle. The projected changes therefore affect both the intensity of the dry season, through large relative reductions in rainfall, and the annual water balance, through substantial decreases in wet-season precipitation. In contrast to temperature, uncertainty in projected monthly precipitation is primarily determined by the regional drying scenario rather than by the greenhouse-gas emissions scenario. This is particularly evident for Sint Maarten, where differences between the drying scenarios during the wet season exceed those between emissions scenarios. Higher greenhouse-gas emissions generally amplify drying towards the end of the century, especially under the strong drying scenario.

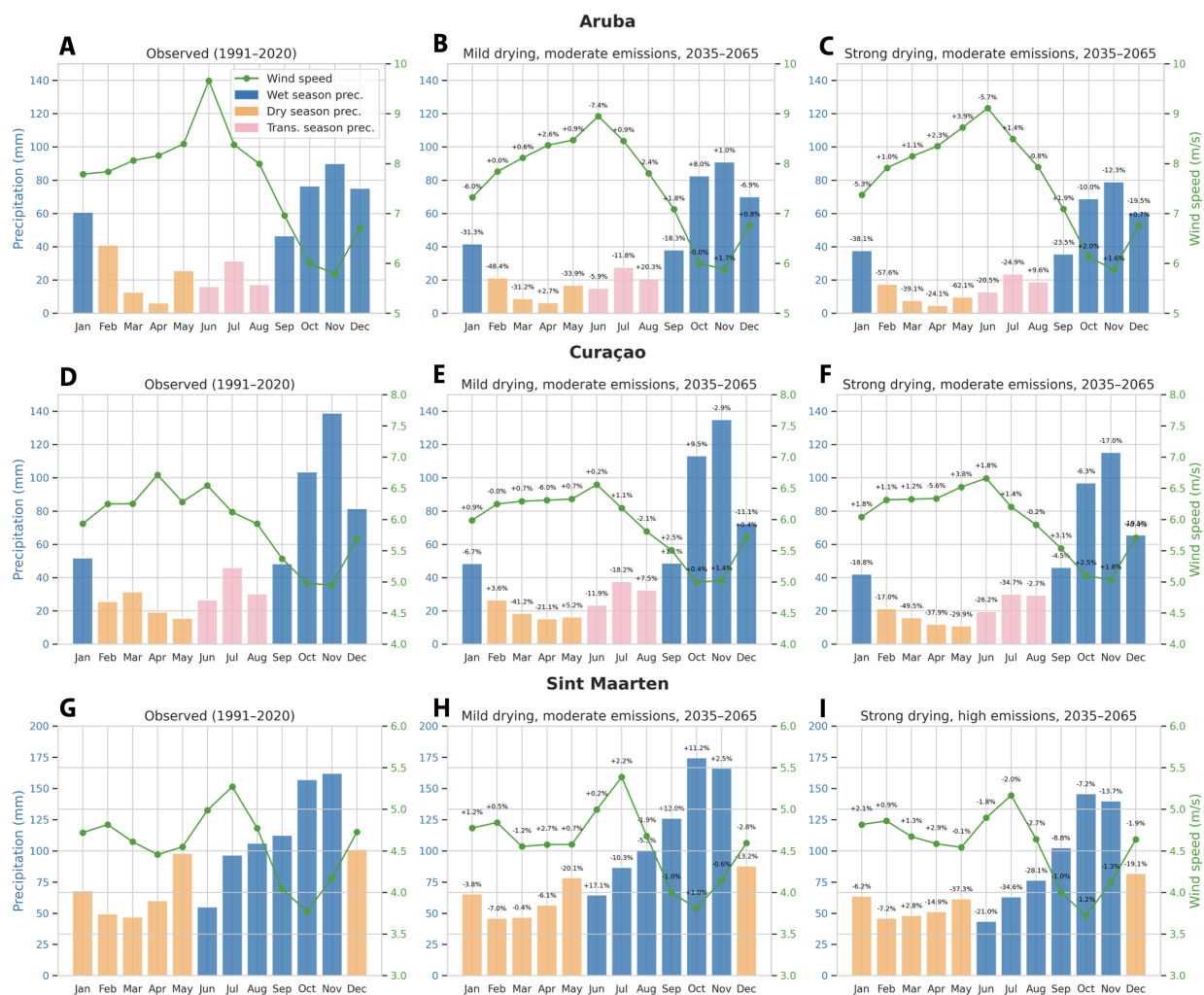


Figure 2.18: Precipitation and wind climatology of Aruba (A–C) Curaçao (D–F) and Sint Maarten (G–I) according to the observations (A, D, G) from NOAA GSOD (1991–2020), monthly means and in a mid-century climate (2035–2065) based on CMIP6, with a distinction between the mild drying scenario (B–H) and strong drying scenario (C, F, I) based on the moderate emissions scenario (SSP2-4.5).

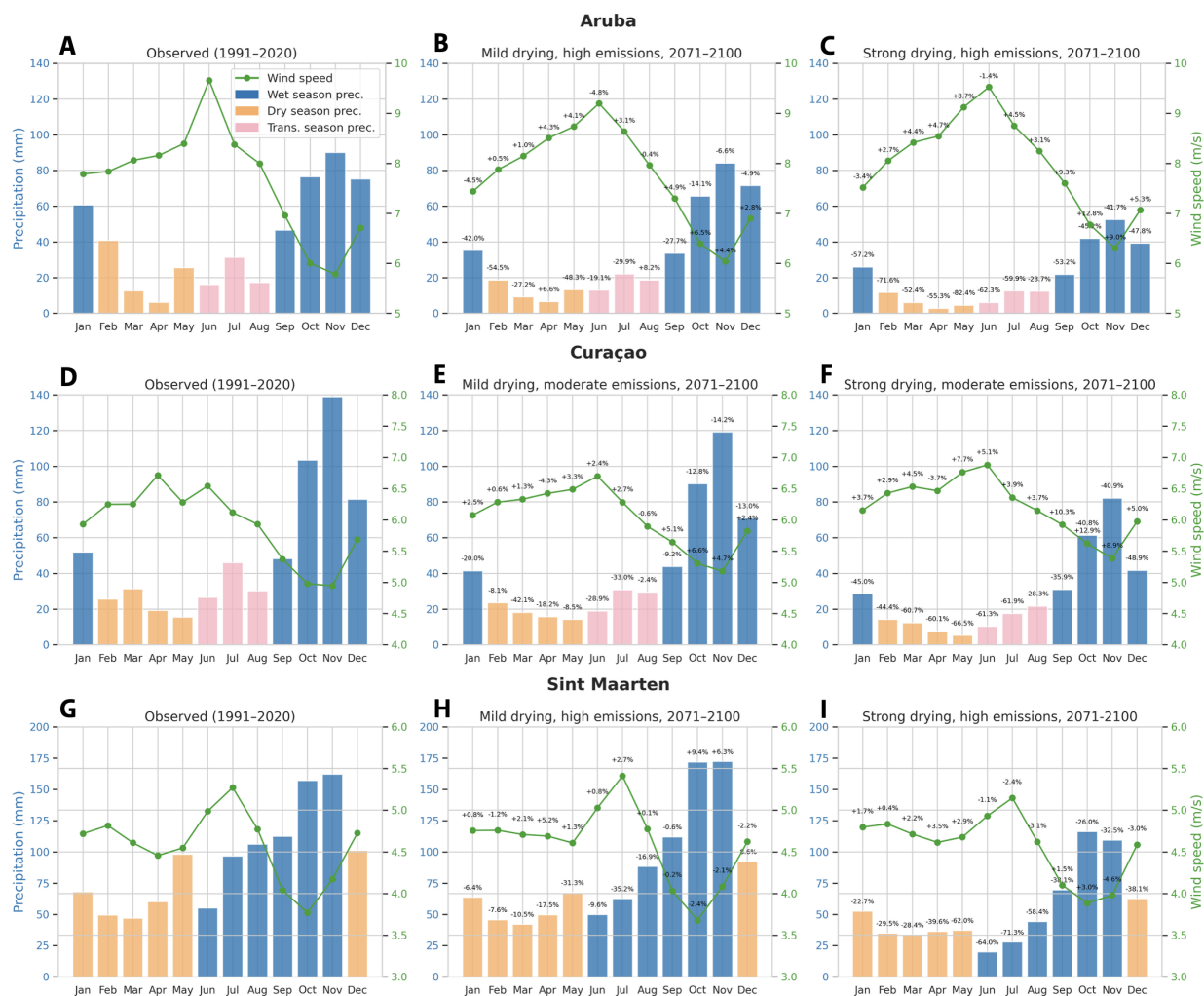


Figure 2.19: Precipitation and wind climatology of Aruba (A– C) Curaçao (D– F) and Sint Maarten (G– I) according to the observations (A, D, G) from NOAA GSOD (1991–2020), monthly means and in a end-of-century climate (2071-2100) based on CMIP6, with a distinction between the mild drying scenario (B– H) and strong drying scenario (C, F, I) based on the high emissions scenario (SSP5-8.5).

Wind speed scenarios

Projected changes in wind speed are considerably smaller than the projected changes in temperature and precipitation. The ensemble mean projects a slight increase in annual mean wind speed for Aruba and Curaçao throughout the twenty-first century (Figure 2.20). The magnitude of this increase depends on both the emissions and the drying scenarios, with the largest changes occurring under the high emissions and strong drying scenario, reaching approximately 3–8 % by the end of the century (Tables 2.8 and 2.9). Under the low emissions scenario, projected changes remain small.

Aruba and Curaçao show very similar projected responses, with the strong drying scenarios consistently producing slightly larger increases in wind speed than the mild drying scenarios. In contrast, projected changes for Sint Maarten remain close to zero throughout the century (Figure 2.20G–I). Differences between scenarios are generally small compared to the spread between climate models, indicating that no robust long-term increase or decrease in annual mean wind speed can be identified for Sint Maarten. Overall, projected changes in annual mean wind speed are small compared to the spread between climate models. Consequently, confidence in the magnitude of future wind-speed changes remains relatively low.

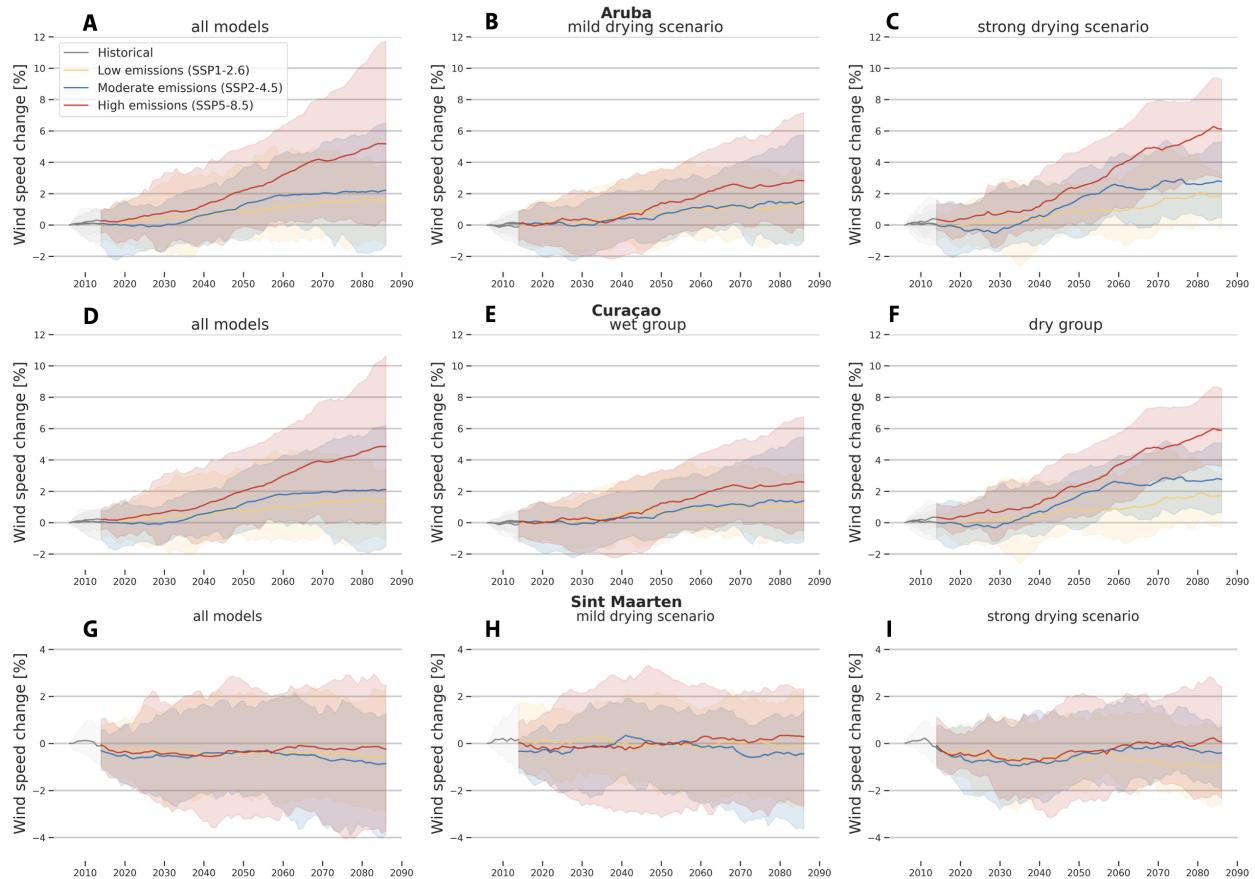


Figure 2.20: Projected changes in wind speed for Aruba (A–C), Curaçao (D–F), and Sint Maarten (G–I) relative to the 1991–2020 reference period, based on the 29 CMIP6 models that are statistically downscaled using the QDM method. The time series are forced by the low (yellow), moderate (blue), and high emissions scenario (red). The historical period is shown in grey. Lines indicate the 30-year rolling average multi-model mean and shaded areas represent the 90 % spread.

Table 2.8: Projected changes in wind speed for Aruba relative to the 1991–2020 reference period for the target years 2050 and 2100. Results are shown for the drying scenarios combined with the emissions scenarios. Changes in wind speed and interannual variability are expressed relative to the 1991–2020 reference period and rounded to one and two decimal places, respectively.

Season	Indicator	1991–2020 Observations	2050						2100					
			Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild	Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild
Annual	Mean wind speed	7.6 m/s	1.3 %	0.6 %	1.6 %	0.7 %	2.4 %	1.1 %	1.1 %	0.5 %	3.3 %	1.5 %	7.8 %	3.4 %
	Interannual variability	0.77 m/s	1.59 %	1.04 %	1.62 %	1.21 %	1.41 %	1.49 %	1.54 %	0.95 %	0.94 %	1.70 %	-2.15 %	2.20 %
Dry season	Mean wind speed	8.1 m/s	1.1 %	0.5 %	1.4 %	0.7 %	2.1 %	1.0 %	1.0 %	0.5 %	2.7 %	1.3 %	6.1 %	2.8 %
Wet season	Mean wind speed	6.7 m/s	1.4 %	0.8 %	1.8 %	1.0 %	2.8 %	1.4 %	1.2 %	0.7 %	3.8 %	1.9 %	9.7 %	4.4 %
Transition season	Mean wind speed	8.7 m/s	1.5 %	0.3 %	1.9 %	0.4 %	2.6 %	0.7 %	1.3 %	0.2 %	3.4 %	1.0 %	7.4 %	3.0 %

Table 2.9: Projected changes in wind speed for Curaçao relative to the 1991–2020 reference period for the target years 2050 and 2100. Results are shown for the drying scenarios combined with the emissions scenarios. Changes in wind speed and interannual variability are expressed relative to the 1991–2020 reference period and rounded to one and two decimal places, respectively.

Season	Indicator	1991–2020 Observations	2050						2100					
			Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild	Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild
Annual	Mean wind speed	5.9 m/s	1.3 %	0.5 %	1.6 %	0.7 %	2.4 %	1.0 %	1.1 %	0.4 %	3.2 %	1.3 %	7.4 %	3.2 %
	Interannual variability	0.57 m/s	0.46 %	1.02 %	0.10 %	1.11 %	-0.96 %	1.20 %	0.58 %	0.95 %	-2.37 %	1.17 %	-9.35 %	0.58 %
Dry season	Mean wind speed	6.4 m/s	1.3 %	0.6 %	1.6 %	0.7 %	2.2 %	1.0 %	1.1 %	0.5 %	2.8 %	1.3 %	6.0 %	2.7 %
Wet season	Mean wind speed	5.4 m/s	1.4 %	0.7 %	1.9 %	0.9 %	2.8 %	1.3 %	1.2 %	0.6 %	3.9 %	1.8 %	9.6 %	4.3 %
Transition season	Mean wind speed	6.2 m/s	1.2 %	0.1 %	1.5 %	0.2 %	2.1 %	0.4 %	1.1 %	0.1 %	2.8 %	0.6 %	6.2 %	2.0 %

Table 2.10: Projected changes in wind speed for Sint Maarten relative to the 1991–2020 reference period for the target years 2050 and 2100. Results are shown for the drying scenarios combined with the emissions scenarios. Changes in wind speed and interannual variability are expressed relative to the 1991–2020 reference period and rounded to one and two decimal places, respectively.

Season	Indicator	1991–2020 Observations	2050						2100					
			Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild	Low Strong	Low Mild	Moderate Strong	Moderate Mild	High Strong	High Mild
Annual	Mean wind speed	4.5 m/s	-0.4 %	-0.1 %	-0.4 %	-0.1 %	-0.4 %	-0.1 %	-0.4 %	-0.1 %	-0.3 %	-0.1 %	0.4 %	0.4 %
	Interannual variability	0.28 m/s	-0.63 %	0.16 %	-1.03 %	0.27 %	-2.02 %	0.55 %	-0.46 %	0.11 %	-3.19 %	0.90 %	-8.64 %	3.16 %
Dry season	Mean wind speed	4.6 m/s	-0.2 %	-0.3 %	-0.2 %	-0.3 %	-0.1 %	-0.3 %	-0.2 %	-0.3 %	0.0 %	-0.3 %	1.0 %	0.1 %
Wet season	Mean wind speed	4.5 m/s	-0.7 %	-0.0 %	-0.7 %	-0.0 %	-0.8 %	-0.0 %	-0.6 %	-0.0 %	-0.7 %	0.0 %	-0.3 %	0.3 %

Wind speed exhibits a clear seasonal cycle on all three islands, although the observed cycles differ in shape and magnitude (Figures 2.18A,D,G and 2.19A,D,G). Aruba has the highest observed wind speeds and shows a pronounced maximum in June, followed by a marked decline towards October and November. The observed seasonal cycle for Curaçao is flatter, with relatively high wind speeds during the first half of the year and lower values in October and November. Sint Maarten has lower wind speeds overall and peaks around February and July and two minima around April and October. On all three islands, wind speeds are lowest around October or November.

To illustrate projected changes in seasonality, Figures 2.18 and 2.19 show the monthly climatology for the 1991–2020 reference period and the projected monthly climatology for two illustrative scenario combinations: the moderate emissions scenario for mid-century and the high emissions scenario for the end of the century. Projected monthly wind-speed climatologies for all emissions scenarios and both time horizons are provided in Appendix B.

For Aruba and Curaçao, the ensemble-mean projections indicate generally small increases in monthly wind speed, although the magnitude and even the sign of the change vary between months and scenario combinations. The seasonal tables show that the relative increase is generally larger during the wet season than

during the dry season, particularly under the high-emissions scenario and the strong drying scenario (Tables 2.8 and 2.9). Because present-day wind speeds are relatively low during much of the wet season, these increases slightly reduce the contrast between the windier and calmer parts of the year. Nevertheless, the overall timing and shape of the seasonal cycle are largely preserved.

The projected monthly changes are larger under the high emissions scenario at the end of the century than under the moderate emissions scenario at mid-century. This difference is clearest for Aruba and Curaçao in the strong drying scenario. Even in these scenario combinations, however, the projected changes remain modest relative to the present-day seasonal cycle and to the spread between climate models.

For Sint Maarten, projected changes in monthly wind speed remain close to zero. The two drying scenarios produce somewhat different monthly responses, but these differences are small relative to the model spread and do not indicate a consistent change in the timing or amplitude of the seasonal cycle. No robust change in wind seasonality can therefore be identified for Sint Maarten.

The strong drying scenario generally produces both larger precipitation reductions (Section 2.2.2) and slightly larger increases in wind speed than the mild drying scenario. This association indicates that the precipitation-based scenario selection also separates models according to aspects of their simulated regional circulation response. A change in the Caribbean Low-Level Jet provides one possible physical interpretation, as stronger trade winds have previously been associated with reduced precipitation over parts of the Caribbean (Wang, 2007; Michael A. Taylor et al., 2018). However, the Caribbean Low-Level Jet was not explicitly analysed in this study, and this mechanism cannot be confirmed from the present results.

Overall, the projected wind-speed changes are modest compared with the projected changes in temperature and precipitation. The ensemble mean indicates a slight tendency towards stronger winds on Aruba and Curaçao, especially under the high emissions and strong drying scenario, whereas no robust long-term change emerges for Sint Maarten. For all three islands, the projected changes are small relative to the spread between climate models, resulting in low confidence in their precise magnitude.

Chapter 3

Sea-level scenarios

This chapter presents the sea-level scenarios for Aruba, Curaçao and Sint Maarten. The methodology section (Section 3.1) describes the observational datasets, the contributing processes, the regional model selection, and the low-likelihood high-impact (LLHI) scenarios used to construct the projections. The results section (Section 3.2) presents observed sea-level change together with projected sea-level rise for 2050, 2100 and 2300. Finally, Section 3.3 presents additional ocean-related climate indicators, including observed extreme water levels and marine heatwaves. These analyses complement the sea-level scenarios by placing the projected changes in the context of present-day variability and broader changes in the marine environment. In particular, the marine heatwave analysis provides context for potential impacts on the coral reef ecosystems and marine parks that are of ecological and socio-economic importance to the islands.

3.1 Methodology for sea-level scenarios

The sea-level scenarios for Aruba, Curaçao and Sint Maarten are constructed by combining observations with process-based projections of the individual contributors to sea-level rise. First, observational datasets are used to evaluate historical sea-level changes near the islands. Subsequently, projections are derived for the different components contributing to sea-level rise and combined into regional sea-level scenarios for three emissions pathways. In addition, low-likelihood high-impact (LLHI) scenarios are considered to illustrate plausible high-end outcomes.

3.1.1 Observations and model evaluation

Observational sea-level records are used to quantify historical sea-level change near Aruba, Curaçao and Sint Maarten and to evaluate whether the satellite altimetry data adequately represent regional sea-level variability. Satellite altimetry provides spatially consistent observations of sea-level variability across the Caribbean region, while available tide gauge records are used to assess the consistency of the altimetry data near the islands.

Monthly satellite altimetry data for the period 1993–2023 were obtained from the Copernicus Marine Data Store. Satellite altimetry measures sea level using radar observations and provides spatially continuous estimates of sea-level anomalies. To compare local sea-level trends with global mean sea level, global mean sea-level anomaly data for the period 1993–2024 were obtained from AVISO.

Available tide gauge observations were downloaded from the Permanent Service for Mean Sea Level (PSMSL). For Sint Maarten, the longest nearby record is available from Lime Tree Bay on St. Croix (U.S. Virgin Islands), covering the period 1977–2024. For Curaçao, shorter observations are available from Bullen Bay for the period 2013–2018. No long-term tide gauge records are available for Aruba.

The agreement between tide gauge and satellite observations is used to evaluate whether the satellite altimetry adequately represents regional sea-level variability and long-term trends. Following this evaluation, the altimetry data are used to derive historical sea-level trends for each island, which provide a reference for the

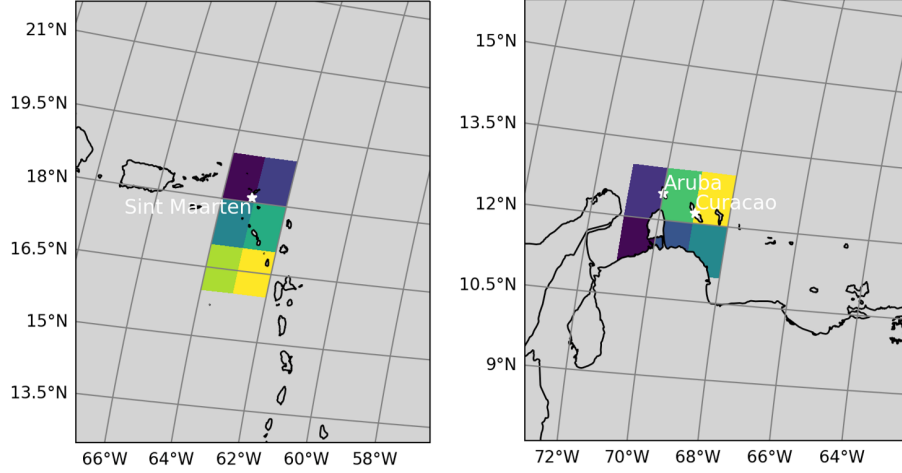


Figure 3.1: CMIP6 regions used to calculate regional sea-level change for Sint Maarten (left) and for Aruba and Curaçao (right). Colours indicate the grid cells included in the regional averages.

assessment of the projected sea-level changes.

3.1.2 Sea-level components and scenario construction

Future sea-level change is represented using a sea-level budget approach, in which total sea-level rise is calculated as the sum of the individual physical processes contributing to sea-level change. This approach follows the framework presented in Chapter 9 of the IPCC Sixth Assessment Report and forms the basis of the KNMI Climate Scenarios'23 (Fox-Kemper et al., 2021; Dorland et al., 2024 and Le Bars et al., 2025). Because the present-day sea-level budget can largely explain the observed sea-level rise, the same process-based framework is applied to estimate future sea-level change.

The contributors considered in this study are global thermosteric sea level, ocean dynamic sea level (ODSL), glaciers, the Greenland Ice Sheet, the Antarctic Ice Sheet, land water storage and glacial isostatic adjustment (GIA). Global thermosteric sea-level rise results from the thermal expansion of seawater caused by ocean warming, whereas ODSL reflects regional changes in ocean circulation, temperature and salinity. Contributions from glaciers and the ice sheets account for both changes in ice mass and their associated spatial fingerprints. Land water storage represents changes in terrestrial water reservoirs, while GIA describes long-term vertical land motion caused by solid Earth adjustment. Global thermosteric sea level and ODSL are derived directly from CMIP6 ocean model output. Because of the relatively coarse spatial resolution of CMIP6, regional averages over larger areas surrounding the islands are used to calculate the sea-level scenarios (Figure 3.1). Owing to their geographical proximity and the absence of substantial differences in the governing sea-level processes, Aruba and Curaçao share the same sea-level scenarios. Contributions from glaciers and the Greenland and Antarctic Ice Sheets are obtained from process-based ice models, while land water storage and GIA are derived from dedicated hydrological and solid Earth models.

Sea-level projections are calculated annually and are presented for three time horizons (2050, 2100 and 2300) and low, moderate and high emissions scenarios. Together, these combinations result in nine sea-level scenarios for each island.

3.1.3 Low-likelihood high-impact scenarios

In addition to the standard sea-level scenarios, low-likelihood high-impact (LLHI) scenarios are considered for the years 2100 and 2300. These scenarios represent physically plausible processes that are either not fully represented or remain highly uncertain in the standard process-based projections. Although their probability cannot be robustly quantified, they provide insight into potential high-end sea-level rise outcomes that may be relevant for long-term adaptation planning. The LLHI scenarios are discussed more extensively in Dorland

et al., 2024 section 4.3.4.

Three LLHI scenarios are included in this study. The first is the physical evidence scenario, which is based on an expert assessment of the maximum physically plausible sea-level rise under the high emissions scenario (Wal et al., 2022). The second scenario considers Marine Ice Cliff Instability, a mechanism that may lead to accelerated mass loss from the Antarctic Ice Sheet (R. M. DeConto and Pollard, 2016; R. M. DeConto, Pollard, et al., 2021). The third scenario is based on Structured Expert Judgement, in which expert assessments of future Greenland and Antarctic Ice Sheet contributions are used. In this study, the 95th percentile of the expert estimates is used to represent a high-end outcome.

3.2 Results for sea-level scenarios

This section first describes the observed sea-level changes around the islands and subsequently presents projected sea-level rise for different time horizons. Besides changes in mean sea level, potential implications for extreme water levels and marine heatwaves are discussed. Together, these analyses provide insight into both gradual and episodic changes affecting the coastal and marine environment of Aruba, Curaçao and Sint Maarten.

3.2.1 Observed sea-level change

Satellite altimetry observations indicate that sea level has been rising near Aruba, Curaçao and Sint Maarten over the past decades. Available tide gauge observations compare well with the satellite records, supporting the use of the altimetry dataset to characterize regional sea-level variability and long-term trends (Figure 3.2).

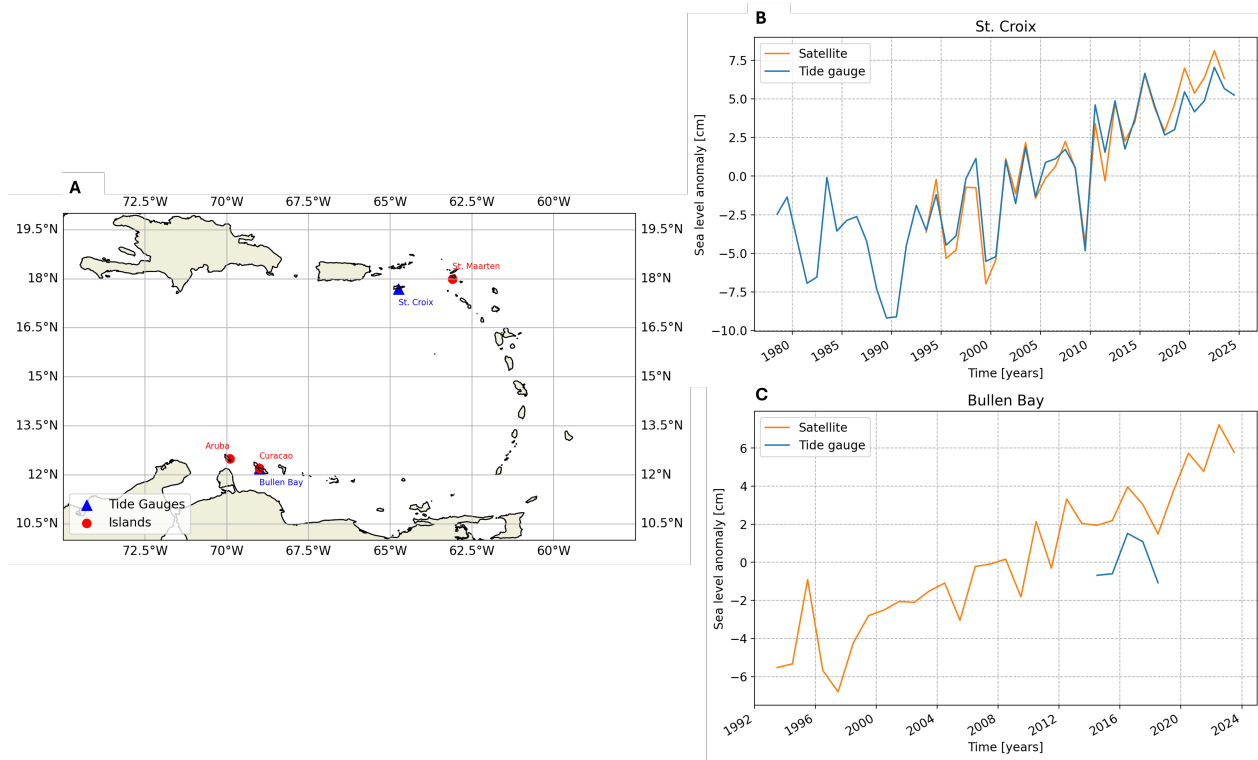


Figure 3.2: Location of the islands and the tide gauges used for comparison with satellite altimetry (A). Sea-level anomalies relative to the 1993–2023 mean derived from satellite altimetry and tide gauge observations for Bullen Bay, Curaçao (B), and St. Croix, U.S. Virgin Islands (C).

For Sint Maarten, the nearby tide gauge at St. Croix shows good agreement with the satellite observations. For Curaçao, the shorter Bullen Bay record exhibits an offset relative to the altimetry data. This difference is expected because tide gauges and satellite altimetry use different vertical reference systems, implying that absolute water levels are not directly comparable. Although the Bullen Bay record is too short to assess long-term trends, the observations indicate that the satellite data adequately capture temporal variability.

The satellite observations reveal increasing sea-level trends for all three islands during the period 1993–2023 (Figure 3.3; Table 3.1). Aruba and Curaçao show very similar trends owing to their geographical proximity, whereas Sint Maarten exhibits a somewhat smaller trend. Comparison with the global mean sea-level trend indicates that the observed rise near Aruba and Curaçao exhibit trends comparable to the global mean trend, whereas Sint Maarten shows a somewhat smaller trend.

Spatial variations in observed sea-level trends are visible throughout the Caribbean region (Figure 3.4). These

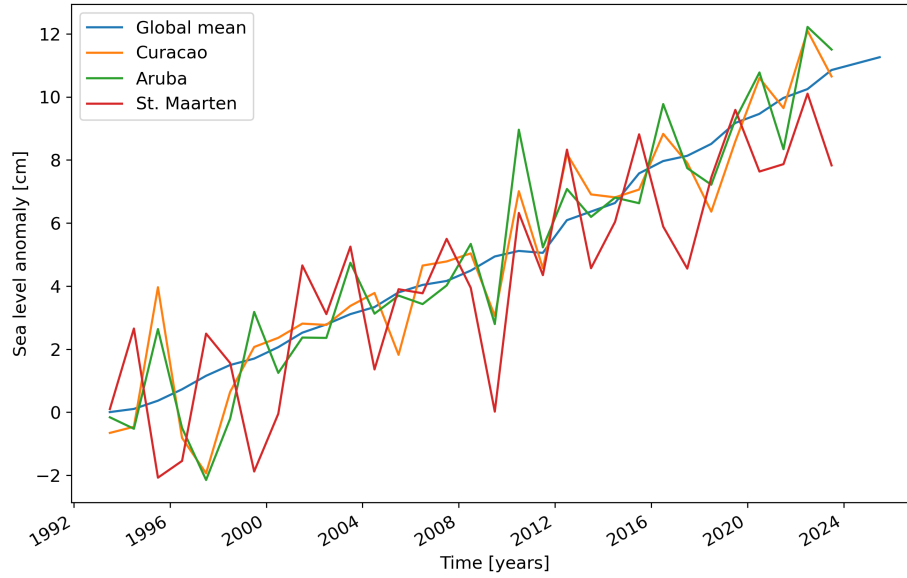


Figure 3.3: Annual mean sea-level anomalies relative to the 1993–2023 mean for Aruba, Curaçao, Sint Maarten and the global mean based on satellite altimetry observations (1993–2024).

Table 3.1: Observed sea-level trends derived from tide gauge and satellite altimetry observations. Trends are expressed in cm decade^{-1} and uncertainties represent the standard error of the linear trend estimate.

Dataset	Type	Period	Trend (cm decade^{-1})	Standard error
Bullen Bay	Tide gauge	2013–2018	-0.1	3.6
St. Croix	Tide gauge	1977–2024	3.8	0.5
Curaçao	Altimetry	1993–2023	3.8	0.3
Aruba	Altimetry	1993–2023	3.9	0.3
Sint Maarten	Altimetry	1993–2023	3.1	0.4
Global mean	Altimetry	1993–2023	3.6	0.1

regional differences are primarily associated with ocean dynamic processes and may reflect both natural climate variability and long-term changes in ocean circulation. The observed trends therefore provide the present-day context for the future sea-level projections discussed in the following sections.

Overall, the observations indicate that sea level around all three islands has been rising throughout the satellite era. Aruba and Curaçao exhibit trends close to, or slightly above, the global mean trend, whereas the trend near Sint Maarten is somewhat lower. Given the relatively short observational record and the influence of natural variability, these differences should not be interpreted as robust long-term differences between the islands.

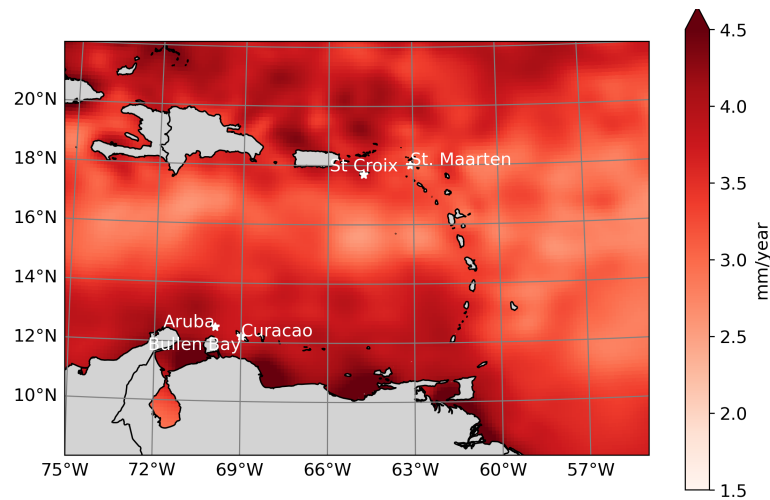


Figure 3.4: Linear trends in sea level derived from satellite altimetry observations for the period 1993–2023 expressed in mm yr^{-1} .

3.2.2 Sea-level projections

Building on the observed sea-level changes presented in Section 3.2.1, this section presents the projected sea-level rise for Aruba, Curaçao and Sint Maarten relative to the 1991–2020 reference period. Projections are provided for low, moderate and high emissions scenarios and for the target years 2050, 2100 and 2300. In addition to the standard projections, low-likelihood high-impact (LLHI) scenarios are included to illustrate plausible high-end outcomes associated with accelerated ice-sheet mass loss. Finally, the relative contributions of the different physical processes to the projected sea-level rise are discussed.

Sea-level projections until 2050

Projected sea-level rise is presented for three time horizons. The near-term period around 2050 is particularly relevant for current adaptation planning, as many infrastructure and coastal management decisions taken today will remain in place for several decades.

The observational records presented in Section 3.3.1 show that the sea level around Aruba, Curaçao and Sint Maarten has been rising for several decades. The sea-level projections indicate a continuation and gradual acceleration of this rise during the first half of the twenty-first century (Figure 3.5).

By 2050, median sea-level rise relative to the 1995–2015 reference period is projected to range between approximately 21 and 25 cm, depending on the island and emissions scenario (Tables 3.2 and 3.3). Differences between the three emissions scenarios remain small, amounting to only a few centimetres. The largest contributor to total sea-level rise in 2050 is global thermosteric expansion, the thermal expansion of seawater as the oceans warm. This contribution dominates by 2050 because the oceans respond relatively rapidly to increasing global temperatures, whereas the large ice sheets respond on much longer timescales. The largest sources of uncertainty are associated with the Antarctic Ice Sheet contribution and ocean dynamic sea-level change.

The limited scenario dependence by mid-century reflects the delayed response of the ocean and cryosphere to past and present greenhouse gas emissions. Many contributors to sea-level rise are already committed by historical warming and will continue to contribute during the coming decades regardless of future emissions (Pardaens et al., 2011). In addition, the temperature pathways of the different emissions scenarios remain relatively similar until around 2050 (Section 2.2.1), which further limits differences in projected sea-level rise.

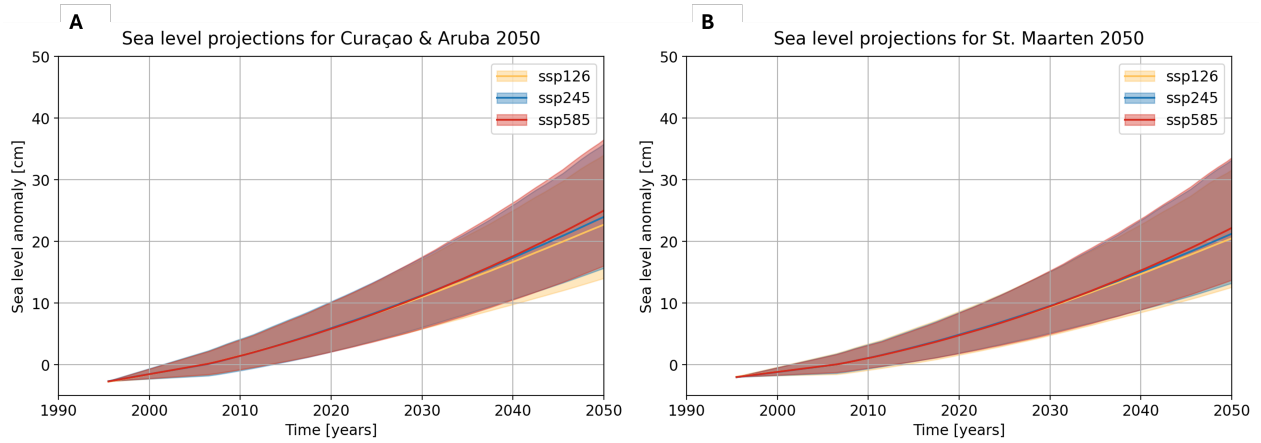


Figure 3.5: Projected sea-level change relative to the 1995–2015 reference period for Aruba and Curaçao (A) and Sint Maarten (B) up to 2050 under the low, moderate and high emissions scenario. Shading indicates the 5–95 % uncertainty range.

Table 3.2: Projected sea-level rise for Aruba and Curaçao relative to the 1995–2015 reference period for the target year 2050. Results are shown for the low, moderate and high emissions scenario. Values represent the median projection with the 5–95 % uncertainty range in parentheses.

Component	Low emissions	Moderate emissions	High emissions
Global thermosteric sea level	8 (5 to 10) cm	8 (6 to 11) cm	9 (6 to 12) cm
Ocean dynamic sea level	4 (-2 to 10) cm	4 (-2 to 10) cm	3 (-3 to 10) cm
Glaciers	3 (2 to 5) cm	4 (2 to 5) cm	4 (3 to 6) cm
Land water storage	1 (1 to 2) cm	1 (1 to 2) cm	1 (1 to 2) cm
Greenland Ice Sheet	2 (1 to 3) cm	3 (2 to 4) cm	3 (2 to 5) cm
Antarctic Ice Sheet	4 (0 to 14) cm	4 (-1 to 15) cm	4 (-1 to 14) cm
Glacial isostatic adjustment	0 (0 to 0) cm	0 (0 to 0) cm	0 (0 to 0) cm
Total sea-level rise	23 (14 to 34) cm	24 (16 to 36) cm	25 (16 to 37) cm

Table 3.3: Projected sea-level rise for Sint Maarten relative to the 1995–2015 reference period for the target year 2050. Results are shown for the low, moderate and high emissions scenarios. Values represent the median projection with the 5–95 % uncertainty range in parentheses.

Component	Low emissions	Moderate emissions	High emissions
Global thermosteric sea level	8 (5 to 10) cm	8 (6 to 11) cm	9 (6 to 12) cm
Ocean dynamic sea level	2 (-3 to 6) cm	1 (-4 to 6) cm	0 (-6 to 5) cm
Glaciers	3 (2 to 5) cm	4 (2 to 5) cm	5 (3 to 6) cm
Land water storage	1 (1 to 2) cm	1 (1 to 2) cm	1 (1 to 2) cm
Greenland Ice Sheet	2 (1 to 3) cm	2 (1 to 4) cm	3 (2 to 4) cm
Antarctic Ice Sheet	4 (0 to 14) cm	4 (-1 to 16) cm	4 (-1 to 14) cm
Glacial isostatic adjustment	1 (1 to 1) cm	1 (1 to 1) cm	1 (1 to 1) cm
Total sea-level rise	21 (13 to 32) cm	22 (13 to 34) cm	23 (14 to 34) cm

In summary, projected sea-level rise until 2050 is relatively insensitive to the emissions scenario. By mid-century, all three islands are projected to experience approximately 20–25 cm of sea-level rise relative to the reference period. This limited scenario dependence reflects the delayed response of the ocean and cryosphere to historical greenhouse gas emissions.

Sea-level projections until 2100

Towards the end of the century, differences between emissions scenarios become increasingly important. These long-term projections illustrate how future sea-level rise depends on the extent of global warming and provide information on the range of possible outcomes relevant for long-term adaptation.

By 2100, projected sea-level rise becomes strongly dependent on the emissions scenario (Figure 3.6). Under the low emissions scenario, median sea-level rise relative to the 1995–2015 reference period reaches 48 cm for Aruba and Curaçao and 46 cm for Sint Maarten (Tables 3.4 and 3.5). Under the high emissions scenario, projected sea-level rise increases to 82 cm around Aruba and Curaçao and 78 cm around Sint Maarten.

The divergence between scenarios after mid-century reflects the increasing influence of future greenhouse gas emissions on ocean warming and land-ice loss. Under the low emissions scenario, sea-level rise continues throughout the century but the rate of rise remains relatively limited. Under the high emissions scenario, the rate of sea-level rise accelerates substantially, reaching median values of approximately 15 mm yr^{-1} by 2100.

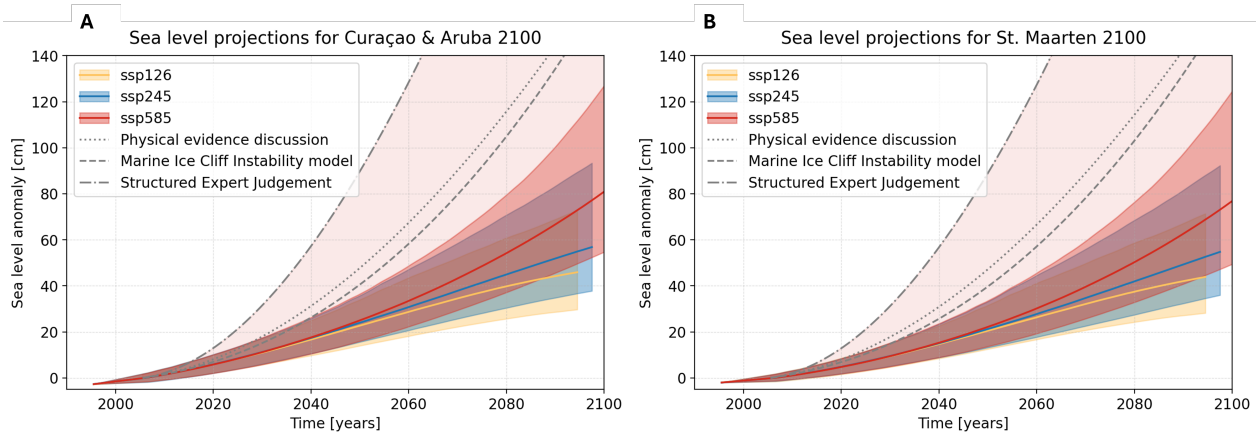


Figure 3.6: Projected sea-level change relative to the 1995–2015 reference period for Aruba and Curaçao (A) and Sint Maarten (B) up to 2100 under the low, moderate and high emissions scenarios. Dotted lines indicate the low-likelihood high-impact scenarios discussed in Section 3.2.2. For visual clarity, the low and moderate emissions scenarios are truncated before 2100.

Table 3.4: Projected sea-level rise for Aruba and Curaçao relative to the 1995–2015 reference period for the target year 2100. Values represent the median projection with the 5–95 % uncertainty range in parentheses.

Component	Low emissions	Moderate emissions	High emissions
Global thermosteric sea level	15 (10 to 20) cm	21 (14 to 27) cm	32 (22 to 42) cm
Ocean dynamic sea level	5 (-1 to 11) cm	5 (-2 to 12) cm	5 (-4 to 14) cm
Glaciers	7 (4 to 11) cm	10 (6 to 14) cm	14 (9 to 20) cm
Land water storage	2 (1 to 4) cm	2 (1 to 4) cm	2 (1 to 4) cm
Greenland Ice Sheet	6 (3 to 10) cm	8 (5 to 13) cm	14 (8 to 25) cm
Antarctic Ice Sheet	11 (0 to 38) cm	12 (-1 to 48) cm	14 (-3 to 56) cm
Glacial isostatic adjustment	1 (1 to 1) cm	1 (1 to 1) cm	1 (1 to 1) cm
Total sea-level rise	48 (31 to 77) cm	59 (39 to 97) cm	82 (55 to 128) cm

Table 3.5: Projected sea-level rise for Sint Maarten relative to the 1995–2015 reference period for the target year 2100. Values represent the median projection with the 5–95 % uncertainty range in parentheses.

Component	Low emissions	Moderate emissions	High emissions
Global thermosteric sea level	15 (10 to 20) cm	21 (14 to 27) cm	32 (22 to 42) cm
Ocean dynamic sea level	3 (-2 to 7) cm	3 (-3 to 9) cm	0 (-10 to 10) cm
Glaciers	7 (4 to 11) cm	10 (6 to 14) cm	14 (9 to 21) cm
Land water storage	3 (1 to 4) cm	3 (1 to 4) cm	3 (1 to 4) cm
Greenland Ice Sheet	6 (3 to 9) cm	7 (4 to 12) cm	13 (7 to 24) cm
Antarctic Ice Sheet	11 (0 to 40) cm	12 (-1 to 50) cm	14 (-3 to 58) cm
Glacial isostatic adjustment	1 (1 to 1) cm	1 (1 to 1) cm	1 (1 to 1) cm
Total sea-level rise	46 (29 to 76) cm	57 (37 to 97) cm	78 (50 to 126) cm

The projected sea-level budget for 2100 is shown in Figure 3.7. Global thermosteric expansion constitutes the largest contribution to sea-level rise in all scenarios and increases substantially with increasing greenhouse gas emissions. Contributions from glaciers and the Greenland Ice Sheet also increase under higher-emissions scenarios.

The Antarctic Ice Sheet represents one of the largest sources of uncertainty in the sea-level projections, as reflected by the wide uncertainty ranges in Tables 3.4 and 3.5. Under the low and moderate emissions scenario, the median Antarctic contribution exceeds the Greenland contribution, whereas both contributions become comparable under the high emissions scenario.

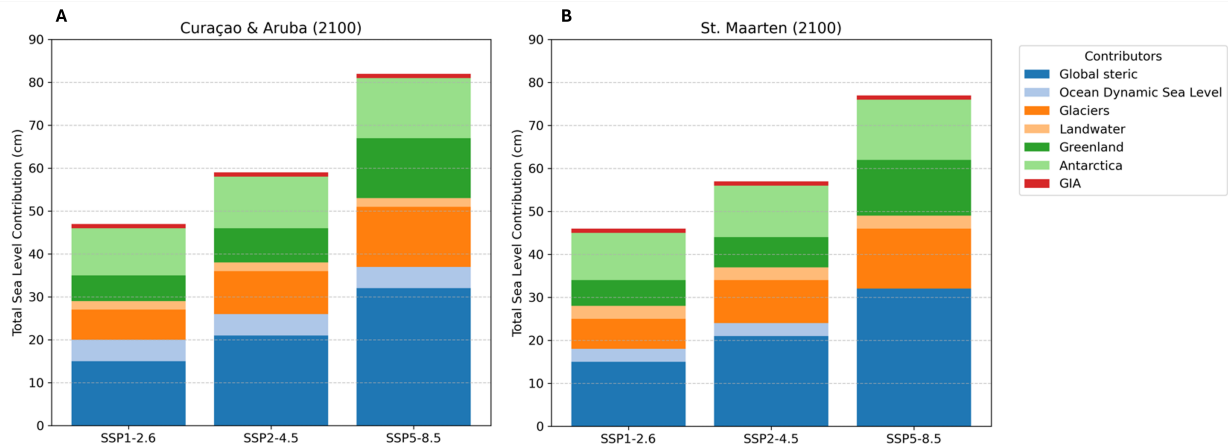


Figure 3.7: Median contributions to projected sea-level rise by 2100 for Aruba and Curaçao (A) and Sint Maarten (B) under the low, moderate and high emissions scenario relative to the 1995–2015 reference period.

Regional differences between the islands remain relatively small. Aruba and Curaçao experience slightly larger projected sea-level rise than Sint Maarten owing to differences in ocean dynamic sea level (ODSL). Figure 3.8 shows that these differences are negligible under the low and moderate emissions scenario, but become more pronounced under the high emissions scenario. The spatial ODSL pattern under the high emissions scenario is consistent with patterns reported in previous studies (Van Westen et al., 2020). These differences may be related to changes in large-scale ocean circulation, although the underlying mechanisms are not explicitly investigated in this study.

In contrast to the mid-century projections, sea-level rise by 2100 is strongly dependent on the emissions pathway. Higher greenhouse gas emissions result in substantially larger contributions from thermal expansion and land-ice melt, leading to a wider range of possible outcomes. Although regional differences between the islands are relatively small, Aruba and Curaçao experience slightly larger sea-level rise than Sint Maarten because of differences in ocean dynamic sea level.

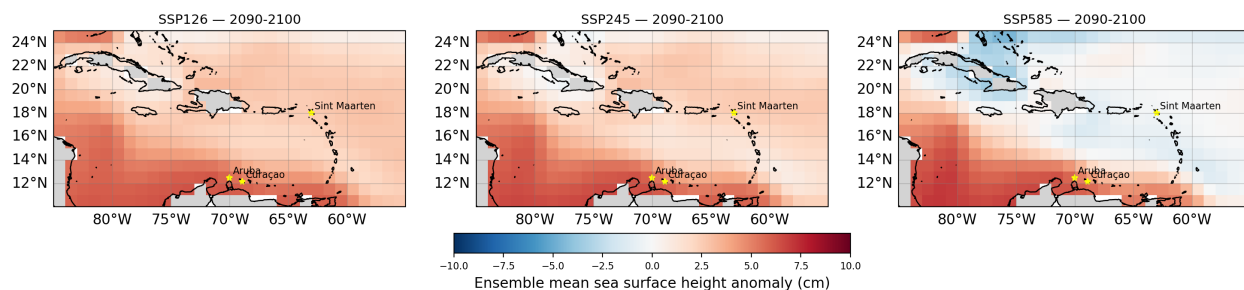


Figure 3.8: CMIP6 ensemble mean ocean dynamic sea-level anomaly for 2090–2100 under the low, moderate and high emissions scenario relative to the historical period.

Low-likelihood high-impact scenarios

In addition to the standard emissions scenarios, low-likelihood high-impact (LLHI) scenarios are considered. These scenarios represent physically plausible, but deeply uncertain, processes that are not fully captured by the standard sea-level projections. They are primarily intended to inform long-term adaptation strategies that seek to account for high-end risks.

Three LLHI scenarios are included in this study. The first is based on the physical plausibility assessment presented by Wal et al., 2022. The second is derived from simulations that include Marine Ice Cliff Instability, a mechanism that can accelerate Antarctic ice-sheet mass loss through structural failure of marine ice cliffs (R. M. DeConto and Pollard, 2016; R. M. DeConto, Pollard, et al., 2021). The third is based on Structured Expert Judgement and represents the 95th percentile of expert estimates of future ice-sheet contributions.

Unlike the standard emissions scenarios, the likelihood of these LLHI scenarios is not quantified. They should therefore not be interpreted as alternative best estimates, but rather as high-end storylines that illustrate the possibility of substantially larger sea-level rise. Their influence becomes particularly important after 2100, when uncertainties associated with ice-sheet dynamics dominate the overall uncertainty range. The LLHI scenarios are shown as dotted lines in Figures 3.6 and 3.9. They indicate that future sea-level rise could substantially exceed the standard emissions scenarios, particularly on multi-century timescales.

Sea-level projections until 2300

Sea level responds slowly to changes in the climate system and will continue to rise for centuries after 2100. Although projections for 2300 are highly uncertain, they provide insight into the long-term commitment associated with different emissions pathways. Figure 3.9 shows the projected sea-level evolution until 2300 for Aruba, Curaçao and Sint Maarten. In all scenarios, sea level continues to rise well beyond 2100. However, the magnitude of the rise depends strongly on future greenhouse gas emissions.

Under the low emissions scenario, projected sea-level rise by 2300 reaches approximately 0.7–1.9 m relative to the reference period. Under the high emissions scenario, substantially larger rises are projected, ranging from approximately 2.2 to 6.7 m. The uncertainty range increases considerably over time, reflecting the growing importance of long-term ice-sheet responses and other slow components of the climate system. Differences between the islands remain small compared to the overall uncertainty range. Similar to the 2100 projections, Aruba and Curaçao exhibit slightly higher sea-level rise than Sint Maarten owing to differences in ocean dynamic sea level, but these regional differences are minor relative to the spread between emissions scenarios.

Overall, the 2300 projections illustrate the long-term consequences of greenhouse gas emissions. Even under low emissions pathways, sea level continues to rise for centuries. Under higher-emissions scenarios, multi-metre sea-level rise becomes possible, emphasizing the importance of considering long-term adaptation and coastal planning.

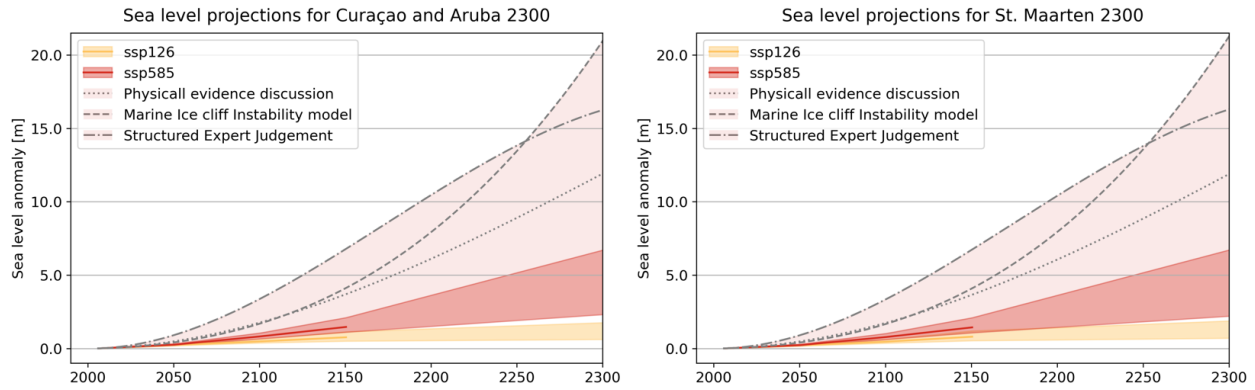


Figure 3.9: Projected sea-level change relative to the 1995–2015 reference period up to 2300 for Aruba and Curaçao (A) and Sint Maarten (B) under the low, moderate and high emissions scenario. Dotted lines indicate the low-likelihood high-impact scenarios discussed in Section 3.2.2.

3.3 Additional ocean-related climate indicators

In addition to the sea-level scenarios presented above, this section describes two ocean-related climate indicators that provide additional context for understanding climate risks on Aruba, Curaçao and Sint Maarten. Unlike the preceding sections, these analyses do not present additional climate scenarios or projections, but complement the sea-level scenarios by characterising present-day ocean conditions and hazards.

Section 3.3.1 analyses observed extreme water levels to place the projected sea-level rise in the context of present-day variability and coastal flooding. The second section describes observed marine heatwaves because of their relevance for the coral reef ecosystems and marine parks surrounding the islands, which are of considerable ecological and socioeconomic importance. Together, these analyses provide additional context for interpreting the projected impact of climate change on the coastal and marine environment.

3.3.1 Extreme water levels

Besides gradual sea-level rise, extreme water levels represent an important coastal hazard for the Caribbean islands (Dullaart et al., 2024). Coastal flooding results from the combined effects of mean sea level, astronomical tides, storm surge and wave setup. Understanding the relative contribution of these processes helps to place future sea-level rise in the context of extreme events. Storm surges are identified as an important climate risk for the islands (International Panel on Deltas and Coastal Areas (IPDC), 2024). Tropical cyclones passing through the Caribbean can generate elevated water levels and large waves, causing coastal flooding and erosion. Hurricane Irma, which severely affected Sint Maarten in September 2017, provides an example of the combined influence of these processes (National Hurricane Center, 2018).

Figure 3.10 shows the simulated tide and storm surge signal during the passage of Hurricane Irma using the Global Tide and Surge Model (GTSM), kindly provided by Dr. Sanne Muis (Deltares; Vrije Universiteit Amsterdam), based on the methodology described by Muis et al., 2020. To illustrate the relative contributions of storm surge, tides and waves during an extreme event, Hurricane Irma (2017) is used as a case study. A storm surge exceeding approximately 0.4 m occurred near Sint Maarten during landfall, whereas no substantial surge signal is visible for Aruba and Curaçao, reflecting the greater distance between these islands and the hurricane track. This storm surge provides a useful reference for interpreting the magnitude of projected future sea-level rise.

The influence of Hurricane Irma on wave conditions is shown in Figure 3.11. Whereas storm surge remained limited for Aruba and Curaçao because of their distance from the hurricane track, wave and swell heights increased substantially on all three islands, reaching values of approximately 5 m above normal sea level on Aruba and Curaçao and exceeding 6 m near Sint Maarten. These elevated wave conditions illustrate that swell generated by distant tropical cyclones can affect the wider Caribbean basin.

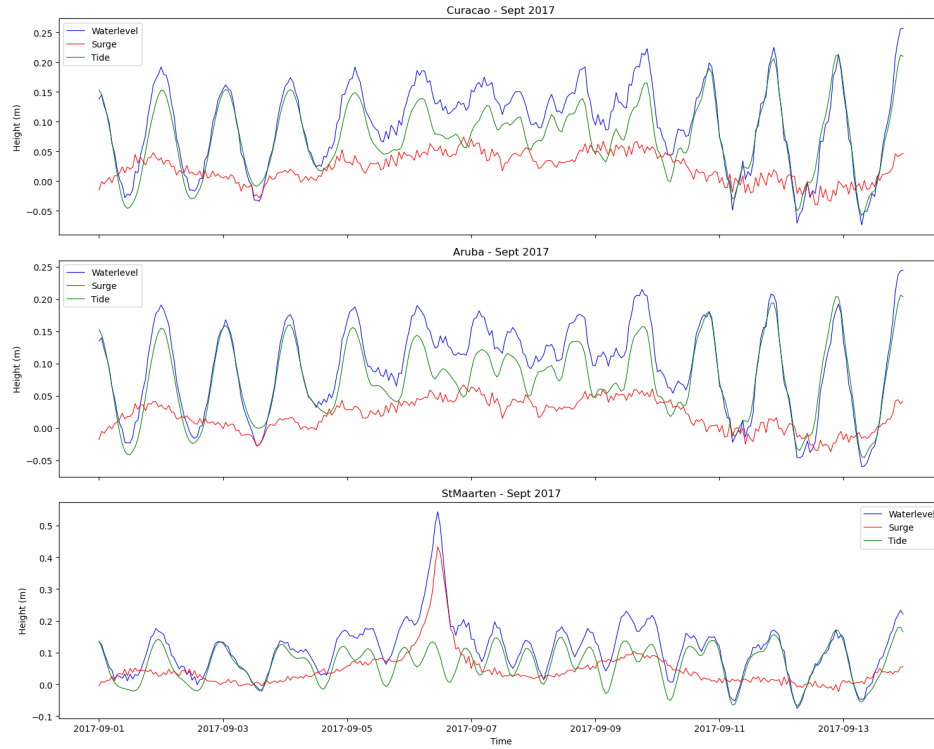


Figure 3.10: Simulated tide, storm surge and total water level (tide + surge) during the passage of Hurricane Irma (2017) for locations near Aruba, Curaçao and Sint Maarten. Data are derived from the Global Tide and Surge Model (GTSM).

Storm surge and waves affect coastal flooding in different ways. Storm surge often forms a dominant contribution to coastal inundation because it raises the mean water level for several hours to days (Idier et al., 2019). Wind waves and swell act on top of this elevated water level and can further enhance flooding and coastal erosion. The impacts experienced during an event therefore depend on the combination of all contributing processes. The approximately 0.4 m peak storm surge simulated during Hurricane Irma provides a useful benchmark for interpreting the projected sea-level rise. By 2100, projected mean sea-level rise exceeds this storm surge under all emissions scenarios (Tables 3.4 and 3.5). Future sea-level rise will increase the baseline upon which extreme events occur. Consequently, storm events comparable to Hurricane Irma would occur on top of a substantially higher mean sea level, increasing the likelihood and severity of coastal flooding.

Future coastal flood risk, however, is not determined by mean sea-level rise alone. Recent studies indicate that projected changes in storm surge and wave conditions may also contribute substantially to future extreme water levels. Dullaart et al., 2024 show that these changes are not negligible compared to projected mean sea-level rise for several Caribbean islands. Furthermore, climate change is projected to increase the intensity of the strongest tropical cyclones, although projected changes in their overall frequency remain uncertain (Knutson et al., 2020). Together, rising mean sea level and potential changes in storm surge and wave climate are therefore expected to increase future coastal flood risk.

Overall, the Hurricane Irma case study illustrates how the combined effects of tides, storm surge and waves can produce substantial coastal impacts during present-day extreme events. The approximately 0.4 m storm surge simulated during Hurricane Irma is exceeded by the projected mean sea-level rise by 2100 under all emissions scenarios, illustrating how substantially the baseline water level may increase during this century. Rising mean sea level, together with projected changes in tropical cyclone intensity, storm surge and wave climate, is therefore expected to result in higher extreme water levels and increased risks of coastal flooding and erosion for Aruba, Curaçao and Sint Maarten.

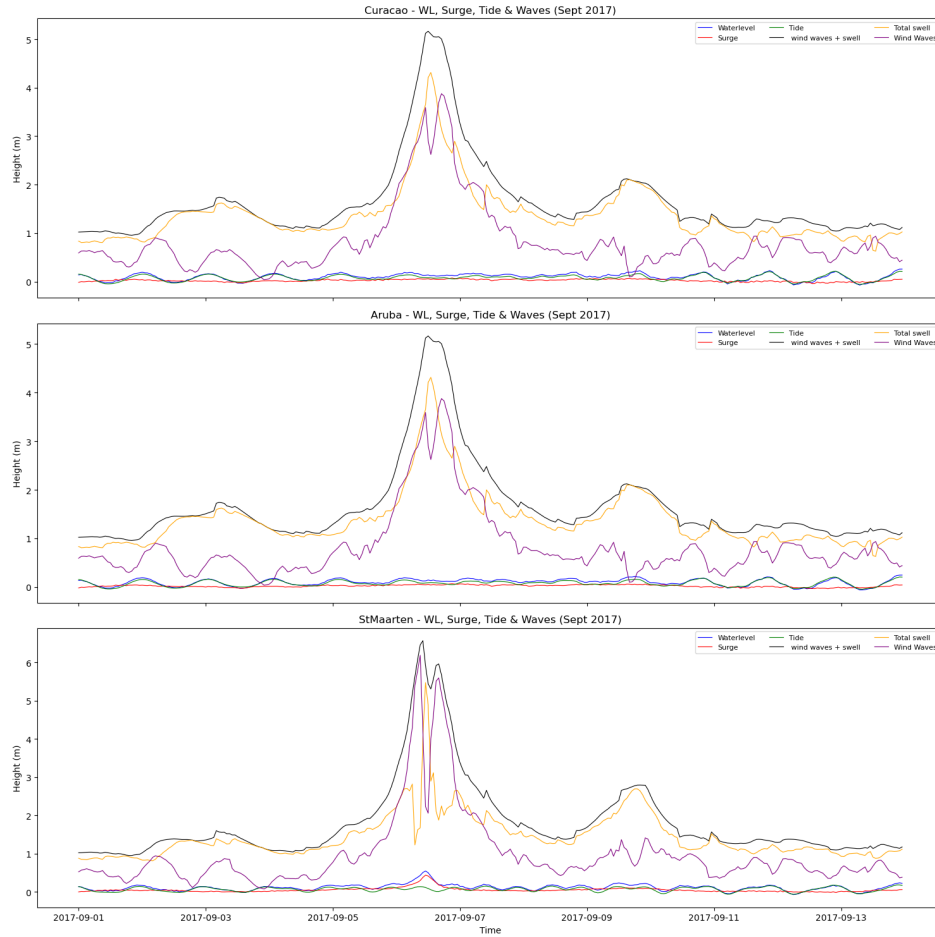


Figure 3.11: Water level, storm surge, tide and wave components during the passage of Hurricane Irma (2017) for locations near Aruba, Curaçao and Sint Maarten. Storm surge information is derived from GTSM, whereas wave characteristics are based on ERA5 reanalysis data.

3.3.2 Marine heatwaves

Changes in the marine environment are not limited to sea-level rise. Increasing ocean temperatures can lead to more frequent marine heatwaves, which may affect coral reefs, marine ecosystems and coastal communities. Although sea surface temperature scenarios were not included in the KNMI'23 Caribbean scenarios and the development of dedicated marine projections fell outside the scope of this project, an exploratory analysis of marine heatwaves was added because of their relevance for coral ecosystems, marine biodiversity and interactions with the climate over nearby islands (IPCC, 2022, Meesters et al., 2025, Wicquart et al., 2025 and Oliver, Benthuisen, et al., 2021).

Worldwide, marine heatwaves (MHWs) are increasing in frequency, duration and intensity (Oliver, Donat, et al., 2018, Oliver, Benthuisen, et al., 2021 and IPCC, 2021a). These periods of exceptionally high sea surface temperatures can have substantial impacts on marine ecosystems and may also influence local atmospheric conditions (Oliver, Benthuisen, et al., 2021). Recent studies indicate that marine heatwaves have already become more frequent and longer-lasting in the Caribbean Sea. Based on satellite observations for 1983–2012, the frequency of marine heatwaves increased by approximately 1.3 events per decade, while their average duration increased by about 1.5 days per decade. CMIP6 projections further suggest that continued ocean warming will substantially increase the duration and intensity of marine heatwaves during the twenty-first century, with marine heatwave conditions becoming nearly permanent under high greenhouse gas emissions by the end of the century (Bustos Usta et al., 2024; Cetina-Heredia et al., 2023; Wicquart et al., 2025).

To assess the occurrence of the most extreme warm events around the islands, marine heatwaves are here defined as periods of at least five consecutive days during which sea surface temperature exceeds the 99th

percentile of the 1982–2016 climatology. This threshold is more stringent than commonly used definitions and was selected to focus specifically on the most extreme warm events. To evaluate the quality of the sea surface temperature (SST) data, annual mean SSTs derived from ERA5 were compared with NOAA Optimum Interpolation (NOAA-OI) observations. Figure 3.12 shows the annual mean SST near each island for the period 1990–2024. Overall, ERA5 reproduces both the magnitude and interannual variability in NOAA-OI well, with correlation coefficients ranging from 0.92 to 0.94 and RMSE values between 0.14 and 0.31 °C. A small cold bias is present for Aruba and Curaçao (−0.31 °C and −0.13 °C, respectively), whereas virtually no systematic bias is found for Sint Maarten (+0.02 °C). Additional comparisons with buoy observations at St. Croix, the Eastern Caribbean Sea and Caribbean Valley show good agreement between buoy measurements, NOAA-OI and ERA5 (Figure 3.13), providing confidence that ERA5 adequately represents SST variability in the region.

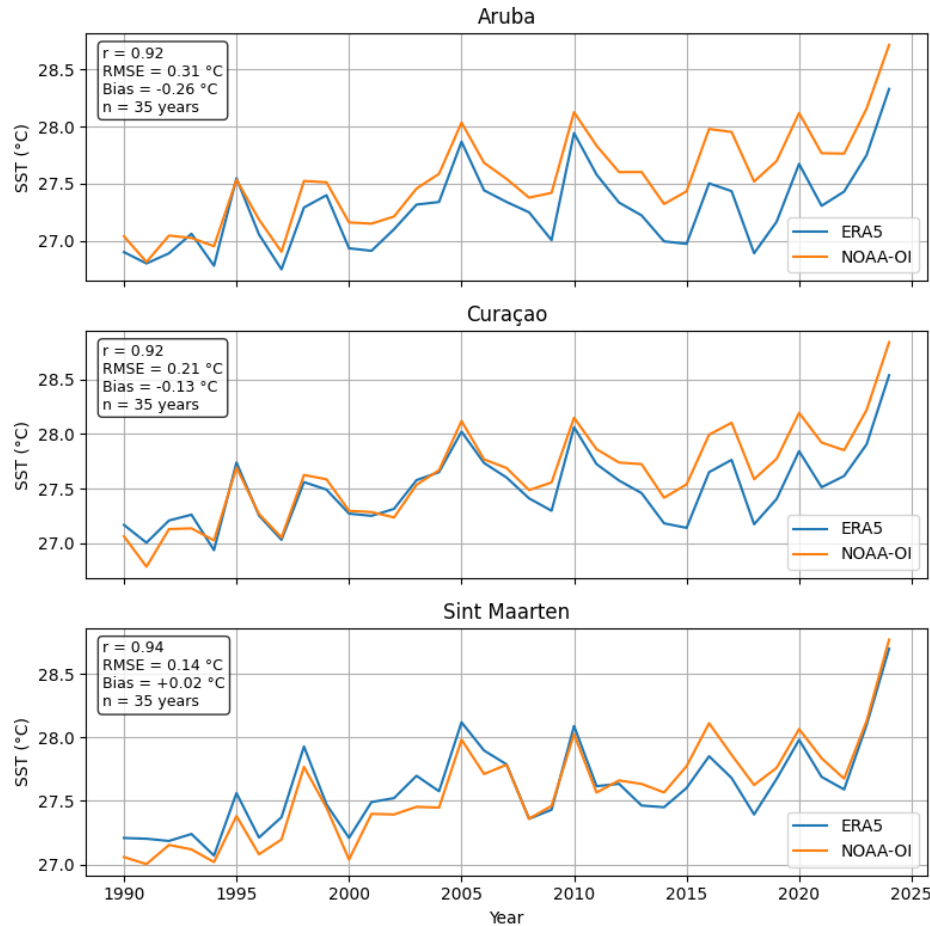


Figure 3.12: Comparison of ERA5 and NOAA-OI annual mean sea surface temperatures near each island for the period 1990–2024.

Based on these comparisons, ERA5 was used to analyse long-term SST changes around the islands. Figure 3.14 shows that Aruba exhibits the lowest mean SST, likely because of coastal upwelling along the Venezuelan coast (Jury, 2018). Sint Maarten generally experiences the highest SSTs and also shows the strongest warming trend, amounting to approximately 0.16 °C per decade. For all islands, 2024 was exceptionally warm, with annual mean SSTs approaching 28.5 °C.

Daily mean sea surface temperatures were extracted from the ERA5 grid point nearest to each island. Data from one grid point is used due to the small size of the islands relative to the ERA5 grid spacing. For each island separately, the 99th percentile was calculated from all daily SST values during the 1991–2020 reference period. Marine heatwaves were defined as periods of at least five consecutive days with daily SST exceeding this fixed threshold. Figure 3.15 shows that the number of marine heatwaves has increased over recent decades around all three islands.

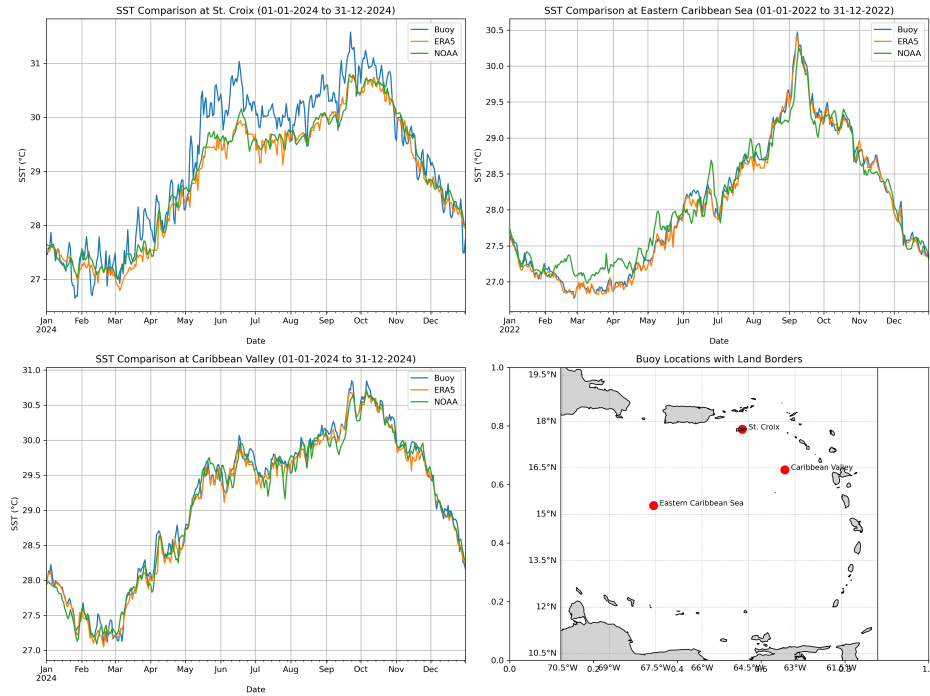


Figure 3.13: Comparison of buoy observations, NOAA-OI and ERA5 sea surface temperatures at three Caribbean locations.

A positive relationship is found between annual mean SST and the number of marine heatwave events in the observational record. For the period analysed here, an increase of 0.1 °C in annual mean SST is associated with approximately 0.12 additional marine heatwave events per year for Aruba and Sint Maarten and approximately 0.14 events per year for Curaçao. These values should be interpreted as empirical relationships based on the historical record rather than as quantitative future projections. The empirical relationship illustrates the sensitivity of extreme-event occurrence to relatively small changes in mean SST.

No dedicated future SST projections were available for this project. However, an indicative estimate of future ocean warming was obtained using CMIP6 surface temperature projections for the Caribbean region (8–22°N, 285–305°E) under the high emissions scenario. Figure 3.16 shows that the historical CMIP6 simulations compare reasonably well with ERA5 observations.

Based on these projections, mean ocean temperatures in the Caribbean region could increase by approximately 1.4 °C by 2050 and by approximately 3.7 °C by 2100 under the high emissions scenario. Consistent with previous CMIP6-based studies for the Caribbean, continued ocean warming would be expected to substantially increase the frequency and duration of marine heatwaves (Bustos Usta et al., 2024). These estimates should be interpreted with caution. Local ocean processes, including coastal upwelling and circulation changes, are not explicitly represented in this analysis. In particular, the slight increase in wind speed found in Section 2 may enhance coastal upwelling near Aruba and Curaçao and partly moderate local SST increases (Rueda-Roa et al., 2013).

Overall, the observational analysis indicates that marine heatwaves have become more frequent around Aruba, Curaçao and Sint Maarten during recent decades. This finding is consistent with recent observational studies for the wider Caribbean Sea, which also report increasing marine heatwave frequency and duration (Bustos Usta et al., 2024; Cetina-Heredia et al., 2023). Although exploratory, the analysis consistently indicates that marine heatwaves are likely to become an increasingly important climate hazard for the islands as ocean temperatures continue to rise. Because dedicated island-scale SST projections were beyond the scope of this project, the future estimates presented here should be interpreted with caution. They are based on regional CMIP6 surface temperature projections and do not explicitly account for local oceanographic processes, such as coastal upwelling and circulation changes, which may locally modify SST trends. Consequently, the results should be regarded as an exploratory assessment rather than quantitative projections.

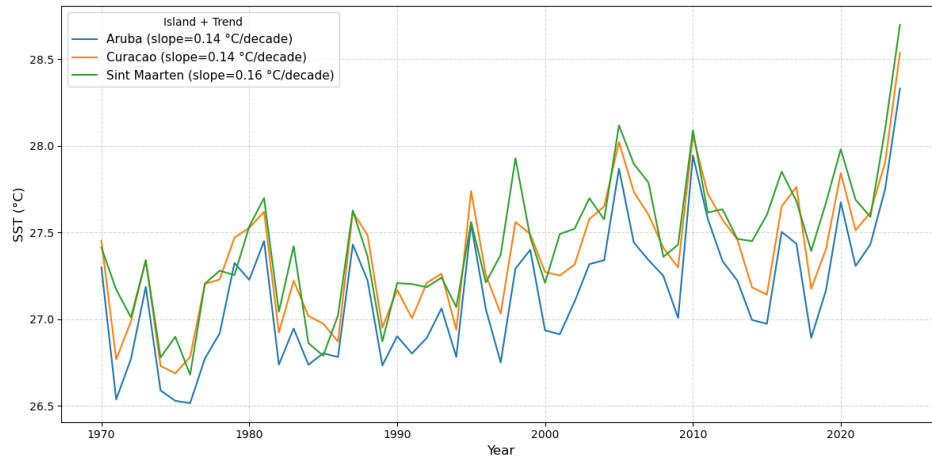


Figure 3.14: Observed annual mean sea surface temperatures derived from ERA5, including linear trends for the period 1970–2024.

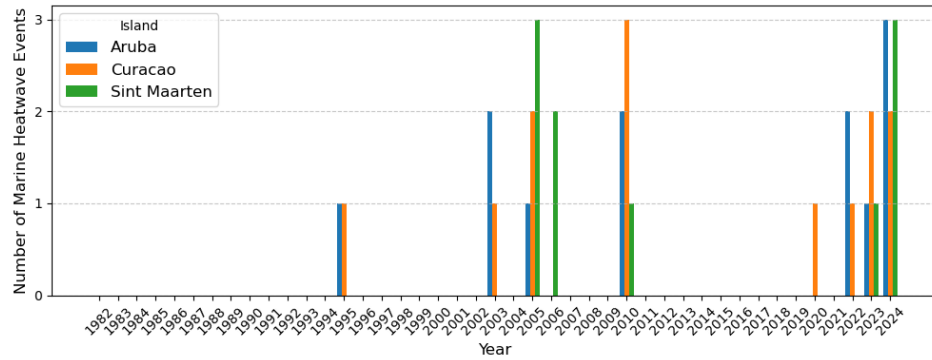


Figure 3.15: Number of marine heatwave events near each island derived from ERA5 using the extreme-event definition applied in this study.

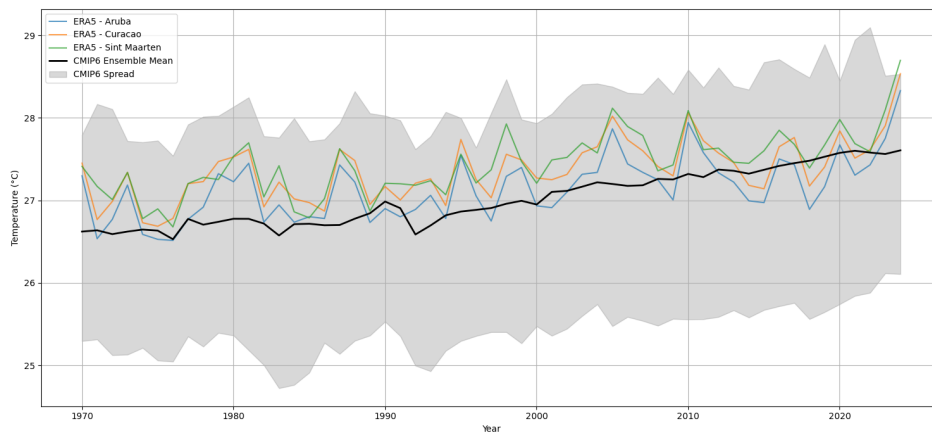


Figure 3.16: Comparison between the CMIP6 ensemble mean surface temperature and ERA5 sea surface temperatures for the period 1970–2024. The CMIP6 data represent a larger Caribbean region (8–22°N, 285–305°E), whereas ERA5 values correspond to the ocean grid cells nearest to each island.

Chapter 4

Main findings and discussion

This chapter summarizes the main findings of the climate scenarios for Aruba, Curaçao and Sint Maarten and places them in the context of current understanding of the Caribbean climate system. The physical mechanisms underlying the projected changes are discussed, followed by an assessment of uncertainties and methodological limitations. Finally, implications for climate adaptation and priorities for future research are addressed.

4.1 Main findings

The climate scenarios developed in this study consistently indicate continued warming, rising sea levels and increasing climate-related risks for Aruba, Curaçao and Sint Maarten. All scenarios show higher temperatures throughout the twenty-first century, whereas precipitation generally decreases, although substantial uncertainty remains regarding the magnitude of this drying.

Among all climate variables considered, precipitation exhibits the largest uncertainty. Depending on the drying and emissions scenario, future precipitation changes range from modest increases to substantial decreases. Projected changes in wind speed are relatively small compared to changes in temperature and precipitation. Nevertheless, changes in the trade winds may influence several components of the regional climate system, including precipitation, sea surface temperatures and coastal upwelling.

Sea level is projected to continue rising under all emissions scenarios. Differences between scenarios remain limited until around mid-century but become increasingly pronounced after 2050. By 2100, projected sea-level rise ranges from approximately 0.5 m under low emissions scenario to around 0.8 m under high emissions scenario. On longer timescales, multi-metre sea-level rise becomes possible, especially under high emissions scenarios. The exploratory analysis of marine heatwaves indicates that sea surface temperatures have increased during recent decades and that extreme warm events in the marine environment have become more frequent.

4.2 Physical interpretation

The projected changes presented in this study can be interpreted in terms of several large-scale physical processes governing the Caribbean climate system. In particular, changes in ENSO behaviour, ocean circulation and regional ocean-atmosphere interactions provide explanations for many of the projected changes in precipitation, wind speed, sea level and marine heatwaves.

4.2.1 ENSO and Caribbean precipitation

The El Niño–Southern Oscillation (ENSO) has a major influence on the climate of the Caribbean (Giannini et al., 2000). During El Niño conditions, enhanced advection over anomalously warm SSTs in the central

Figure 4.1: Illustration of the El Niño-like spatial response simulated by the CMIP6 ensemble under the high emissions scenario in 2100. Figures show projected changes for precipitation (left column) and temperature (right column) for the dry and mild drying scenarios as well as the dry and wet season as defined for Aruba and Curaçao. The wetter and warmer eastern Pacific and drier Caribbean resemble an El Niño-like pattern.

and eastern equatorial Pacific weakens and shifts the Walker circulation eastward, resulting in enhanced subsidence and moisture divergence over the Caribbean (Fig. 1.2). These processes generally favour drier conditions, whereas La Niña conditions tend to promote increased precipitation (Giannini et al., 2001).

The precipitation projections obtained from the CMIP6 ensemble exhibit characteristics resembling an El Niño-like response. For the high emissions scenario, wetter conditions develop over the eastern tropical Pacific and western South America, while the Caribbean becomes progressively drier (Figures 4.1 and 4.2). Similar behaviour has been identified by Marta Brotons et al., 2024. This El Niño-like tendency provides a physical explanation for the projected drying in most scenarios and may also contribute to the modest strengthening of the trade winds found in this study. The strongest drying occurs in the high emissions scenarios, whereas the lower-emissions scenarios generally show weaker reductions in precipitation.

4.2.2 Sea-level processes

Projected sea-level rise around Aruba, Curaçao and Sint Maarten is primarily driven by global thermosteric expansion. Thermal expansion constitutes the largest contribution to sea-level rise in all scenarios and becomes increasingly important under stronger greenhouse gas forcing. Towards the end of the century, contributions from glaciers and the Greenland and Antarctic Ice Sheets become increasingly important. In particular, the Antarctic Ice Sheet represents one of the largest sources of uncertainty in the projections because future Antarctic mass loss remains difficult to constrain.

Figure 4.2: Illustration of the El Niño-like spatial response simulated by the CMIP6 ensemble under the high emissions scenario in 2100. Figures show projected changes for precipitation (left column) and temperature (right column) for the dry and mild drying scenarios as well as the dry and wet season as defined for Sint Maarten. The wetter and warmer eastern Pacific and drier Caribbean resemble an El Niño-like pattern.

Regional differences in projected sea-level rise between the islands are mainly caused by ocean dynamic sea level (ODSL). Aruba and Curaçao generally experience slightly larger sea-level rise than Sint Maarten because of differences in the simulated ocean dynamic response. The spatial patterns identified in this study are consistent with previous work (Van Westen et al., 2020) and may reflect changes in large-scale ocean circulation. Although the underlying mechanisms were not explicitly investigated in this study, changes in the Atlantic Meridional Overturning Circulation (AMOC) may contribute to regional differences in sea level within the Caribbean (Maitland et al., 2024).

4.2.3 Marine heatwaves and ocean processes

The increase in marine heatwaves identified in this study is closely related to the observed increase in sea surface temperature. Regional differences between the islands are partly explained by local oceanographic processes. Aruba generally exhibits lower sea surface temperatures than the other islands because of coastal upwelling occurring near the Venezuelan coast (Jury, 2018). Wind speed also influences ocean mixing and upwelling. Consequently, projected changes in the trade winds may indirectly affect future sea surface temperatures and marine ecosystems. The slight increase in wind speed found in this study could enhance coastal upwelling near Aruba and Curaçao and partly moderate local warming of the ocean (Rueda-Roa et al., 2013). These interactions illustrate that the atmosphere and ocean are strongly coupled in the Caribbean climate system and that changes in one component can influence several others simultaneously.

4.3 Uncertainties and limitations

Although the climate scenarios presented in this study are based on established methodologies and state-of-the-art climate model projections, several sources of uncertainty remain. These uncertainties originate both from incomplete knowledge of the climate system and from methodological choices that were necessary to construct the scenarios. Understanding these limitations is essential for the interpretation and application of the results.

4.3.1 Uncertainty in ENSO and precipitation projections

One of the largest uncertainties in the climate scenarios concerns future changes in precipitation, as reflected by the large spread between the mild and strong drying scenarios for all islands. Previous studies have shown that much of this spread originates from differences among CMIP6 models in their simulated response of the tropical Pacific and the associated Walker circulation under global warming (Marta Brotons et al., 2024). Because Caribbean precipitation is strongly influenced by the El Niño–Southern Oscillation (ENSO), relatively small differences in the simulated ENSO response can lead to substantial differences in projected regional precipitation (Giannini et al., 2000; Giannini et al., 2001).

The simulated ENSO response remains uncertain. In addition to the large spread among CMIP6 models, many models project a tendency towards a more El Niño-like mean state under global warming, whereas observations over recent decades instead suggest a more La Niña-like tendency (Seager, Henderson, et al., 2022). This discrepancy has been identified in several studies and reduces confidence in the strongest drying projections simulated by CMIP6 (Bayr et al., 2014; Plesca et al., 2018; Seager, Cane, et al., 2019; Seager, Henderson, et al., 2022; Zhao et al., 2019; Chung et al., 2019). To account for the uncertainty arising from the spread in projected ENSO responses across CMIP6 models, the climate scenarios presented in this study explicitly distinguish between mild and strong drying scenarios. At the same time, the discrepancy between the observed and simulated ENSO response reduces confidence in the strong drying scenario.

4.3.2 Methodological choices compared to KNMI’23 BES

Several methodological changes were introduced compared to the KNMI’23 scenarios developed for Bonaire, Sint Eustatius and Saba (Dorland et al., 2024; Wiel et al., 2024). First, different seasons were adopted based on the operational definitions used by the meteorological services of the islands. In addition, the geographical regions used for model selection were refined to better represent the local climate characteristics

of Aruba, Curaçao and Sint Maarten. Correlation analyses showed that smaller regions surrounding the islands provide a more physically consistent basis for selecting the drying scenarios (Figure 2.3; Table 4.1). Although these methodological improvements lead to slightly different model selections, their influence on the resulting climate scenarios is limited. Most of the models selected for the KNMI'23 BES scenarios are retained, implying that the resulting changes in the scenario outcomes are relatively small.

Table 4.1: Model selection based on different regions. Red are the selected strong drying models and blue the selected mild drying models.

	Aruba and Curacao Season			Sint Maarten Season		
Modelname	Caribbean region	Curacao & Aruba region	New region: Curaçao & Aruba (small)	Caribbean region	St. Maarten region	New region: St. Maarten (small)
ACCESS-CM2						
ACCESS-ESM1-5						
AWI-CM-1-1-MR						
BCC-CSM2-MR						
CanESM5						
CESM2						
CESM2-WACCM						
CMCC-CM2-SR5						
CNRM-CM6-1						
CNRM-CM6-1-HR						
CNRM-ESM2-1						
EC-Earth3						
EC-Earth3-Veg						
FGOALS-g3						
GFDL-ESM4						
HadGEM3-GC31-LL						
INM-CM4-8						
INM-CM5-0						
IPSL-CM6A-LR						
KACE-1-0-G						
MIROC6						
MIROC-ES2L						
MPI-ESM1-2-HR						
MPI-ESM1-2-LR						
MRI-ESM2-0						
NESM3						
NorESM2-LM						
NorESM2-MM						
UKESM1-0-LL						

A second methodological difference concerns the use of NOAA GSOD observations. Because long-term station records were unavailable for Aruba and Curaçao, NOAA GSOD data were used to derive the observational climatology. Comparisons with available station observations on Sint Maarten and Aruba indicate that NOAA GSOD reproduces temperature and precipitation characteristics well and does not substantially affect the resulting climate scenarios (Table 4.2). These comparisons provide confidence in the application of NOAA GSOD data for islands with limited observational records.

4.3.3 Sea-level limitations

The sea-level methodology applied in this study follows the framework used in KNMI'23 and is ultimately based on the IPCC AR6 sea-level assessment (Fox-Kemper et al., 2021; Le Bars et al., 2025). Although this approach provides physically consistent projections, several limitations remain. The selection of CMIP6 models used for ocean dynamic sea level and thermosteric expansion was originally optimized for the Netherlands rather than for the Caribbean Sea. Consequently, the model selection may not fully capture regional

Table 4.2: Resulting climate scenarios for Sint Maarten based on the station data (column 2-4) and NOAA GSOD data (column 5-7)

Scenario	Station T (°C)	Station P (%) / mm	Station W (m/s / %)	NOAA T (°C)	NOAA P (%) / mm	NOAA W (m/s / %)
Observations 1991–2020	27.11	1112.44 mm	4.54	27.39	1130.13 mm	4.58
2050 Low emissions – Strong drying	+0.78	-5.53 %	-0.30 %	+0.78	-5.45 %	-0.30 %
2050 Low emissions – Mild drying	+0.78	+2.66 %	-0.17 %	+0.78	+2.66 %	-0.18 %
2050 High emissions – Strong drying	+1.25	-11.64 %	-0.16 %	+1.25	-11.53 %	-0.17 %
2050 High emissions – Mild drying	+1.25	+2.44 %	-0.20 %	+1.28	+2.40 %	-0.21 %
2100 Low emissions – Strong drying	+0.70	-4.67 %	-0.30 %	+0.70	-4.60 %	-0.30 %
2100 Low emissions – Mild drying	+0.69	+2.56 %	-0.16 %	+0.70	+2.56 %	-0.16 %
2100 High emissions – Strong drying	+3.06	-44.57 %	+1.38 %	+3.07	-44.40 %	+1.38 %
2100 High emissions – Mild drying	+3.30	-5.32 %	+0.13 %	+3.31	-5.61 %	+0.11 %

oceanographic processes that influence sea level around Aruba, Curaçao and Sint Maarten.

Furthermore, no dedicated observational sea-level budget currently exists for the islands. Improved understanding of Caribbean ocean dynamics and the development of a location-specific sea-level budget could help reduce uncertainties in future projections. Additional uncertainty is associated with low-likelihood high-impact scenarios. These scenarios are dominated by processes related to future Antarctic ice-sheet behaviour, which remain poorly constrained. Consequently, the probability of these extreme outcomes cannot presently be quantified robustly.

4.3.4 Limitations of the marine heatwave analysis

Marine heatwaves and sea surface temperatures were not included in the original scope of the KNMI'23 Caribbean scenarios, and no dedicated sea surface temperature scenarios were developed for this study. The analysis presented here should therefore be regarded as exploratory rather than as a formal scenario product.

Future sea surface temperatures were estimated using regional CMIP6 surface temperature data rather than dedicated ocean projections. In addition, local processes such as coastal upwelling and ocean circulation are only represented indirectly.

The choice to define marine heatwaves using the 99th percentile of the 1982–2016 climatology is also somewhat arbitrary and intentionally focuses on the most extreme events. Alternative threshold definitions would result in different frequencies and trends of marine heatwaves. Consequently, the results should primarily be interpreted as an indication of ongoing changes in the marine environment rather than as quantitative projections.

4.4 Implications for adaptation and future research

The scenarios presented in this study provide information on future changes in mean climate conditions and sea level for Aruba, Curaçao and Sint Maarten. Nevertheless, several topics require further investigation to improve understanding of climate change impacts and to support climate adaptation on the islands. The priorities discussed below are ordered from broader societal relevance to more specific research needs.

4.4.1 Coastal adaptation and sea-level rise

Sea-level rise represents one of the most important long-term climate risks for Aruba, Curaçao and Sint Maarten. Even under low emissions scenarios, sea level is projected to continue rising for centuries. Consequently, adaptation strategies need to account not only for twenty-first century projections but also for the long-term commitment associated with greenhouse gas emissions.

Although the methodology used in this study follows the KNMI'23 approach developed for the Netherlands and Caribbean Netherlands, further work is required to improve understanding of Caribbean-specific sea-level processes. In particular, a dedicated sea-level budget for the islands and a region-specific evaluation of CMIP6 ocean models would help reduce uncertainties in ocean dynamic sea level (ODSL) and improve future projections (Le Bars et al., 2025). A better understanding of regional ocean circulation could also provide more insight into the possible influence of changes in the Atlantic Meridional Overturning Circulation (AMOC) on Caribbean sea level (Maitland et al., 2024).

4.4.2 Extreme water levels and hurricanes

Extreme events associated with tropical cyclones represent an important source of climate risk for the Caribbean islands. In particular, Sint Maarten is highly exposed to hurricanes, although Aruba and Curaçao may also experience impacts from passing storms through elevated waves, storm surge and heavy precipitation (International Panel on Deltas and Coastal Areas (IPDC), 2024).

Recent studies indicate that future changes in storm surge and wave climate may contribute substantially to coastal flood risk and should therefore not be regarded as negligible compared to projected mean sea-level rise

(Dullaart et al., 2024). Improved understanding of future extreme water levels would therefore complement the mean sea-level scenarios presented in this study.

ENSO strongly influences Atlantic hurricane activity (Klotzbach, 2011; Tartaglione et al., 2003). Because uncertainties in future ENSO behaviour remain large, improved understanding of ENSO may also contribute to better assessments of future hurricane risk in the Caribbean.

4.4.3 Climate extremes

The methodology employed in this study provides scenarios for changes in annual, seasonal and monthly mean climate conditions. In addition, changes in hot days and marine heatwaves were explored. However, climate change also affects the frequency and intensity of extreme events, which were not investigated in detail. Further research into heatwaves, heavy precipitation, dry spells, droughts and wind gusts is required to better understand the societal impacts of climate change on Aruba, Curaçao and Sint Maarten.

4.4.4 Marine heatwaves and sea surface temperatures

Section 3.3.8 showed that marine heatwaves have become more frequent during recent decades and that sea surface temperatures are increasing around all three islands. Because coral reefs and marine ecosystems are highly sensitive to ocean temperature extremes, dedicated sea surface temperature scenarios would be valuable additions to future Caribbean climate scenario studies. Due to limited observational and modeling resources, such scenarios were beyond the scope of the present study. Further work focusing on ocean temperatures and marine heatwaves could provide valuable information for coral reef management and ecosystem conservation.

4.4.5 Minimum and maximum temperatures

This study focused on changes in daily mean temperature. Future research could be extended by explicitly considering daily minimum and maximum temperatures. Such information would provide a more detailed understanding of the impacts of climate change on public health, energy demand and human comfort. In particular, increasing nighttime temperatures may increase cooling demand and negatively affect human health (Cheng et al., 2014).

4.4.6 Trade winds and coastal upwelling

Projected changes in wind speed are relatively small compared to projected changes in temperature and precipitation. Nevertheless, wind plays an important role in regulating rainfall, evaporation, sea surface temperatures and coastal upwelling. The strengthening of the trade winds found in several scenarios may be linked to the El Niño-like tendency simulated by CMIP6 (Marta Brotons et al., 2024). Because the realism of this response remains uncertain, further research into future changes in the trade winds is required. Improved understanding of wind changes could also provide more insight into their influence on coastal upwelling near Aruba and Curaçao and on interactions between the atmosphere and the marine environment.

Overall, the largest uncertainties in the climate scenarios presented in this study are associated with future precipitation changes and long-term sea-level rise. These uncertainties mainly originate from unresolved changes in ENSO behaviour, ocean circulation and ice-sheet dynamics rather than from the statistical methods used to construct the scenarios. Despite these uncertainties, all scenarios consistently indicate continued warming, rising sea levels and increasing climate-related risks for Aruba, Curaçao and Sint Maarten.

Bibliography

- Bayr, Tobias et al. (2014). “The eastward shift of the Walker Circulation in response to global warming and its relationship to ENSO variability”. In: *Climate dynamics* 43.9, pp. 2747–2763.
- Brotons, Marta et al. (2024). “Drivers of Caribbean precipitation change due to global warming: analyses and emergent constraint of CMIP6 simulations”. In: *Climate Dynamics* 62.5, pp. 3395–3415.
- Bustos Usta, David Francisco et al. (2024). “Observation and Projection of Marine Heatwaves in the Caribbean Sea from CMIP6 Models”. In: *Remote Sensing* 16.13, p. 2357. DOI: 10.3390/rs16132357.
- Campbell, Jayaka D et al. (2011). “Future climate of the Caribbean from a regional climate model”. In: *International Journal of Climatology* 31.12, pp. 1866–1878.
- Cannon, Alex J, Stephen R Sobie, and Trevor Q Murdock (2015). “Bias correction of GCM precipitation by quantile mapping: how well do methods preserve changes in quantiles and extremes?” In: *Journal of climate* 28.17, pp. 6938–6959.
- Centella-Artola, Abel et al. (2020). “Evaluation of sixteen gridded precipitation datasets over the Caribbean region using gauge observations”. In: *Atmosphere* 11.12, p. 1334.
- Cetina-Heredia, P. and M. E. Allende-Arandía (2023). “Caribbean Marine Heatwaves, Marine Cold Spells, and Co-Occurrence of Bleaching Events”. In: *Journal of Geophysical Research: Oceans* 128, e2023JC020147. DOI: 10.1029/2023JC020147.
- Cheng, Jian et al. (2014). “Impact of diurnal temperature range on human health: a systematic review”. In: *International journal of biometeorology* 58.9, pp. 2011–2024.
- Chung, Eui-Seok et al. (2019). “Reconciling opposing Walker circulation trends in observations and model projections”. In: *Nature Climate Change* 9.5, pp. 405–412.
- Copernicus Climate Change Service (C3S) (2024). *2024: First year to exceed 1.5°C above pre-industrial level*. URL: <https://climate.copernicus.eu/copernicus-2024-first-year-exceed-15degc-above-pre-industrial-level> (visited on 02/19/2025).
- Cruz, Mayra et al. (2025). “Where heat does not come in waves: a framework for understanding and managing chronic heat”. In: *Environmental Research: Climate* 4.2, p. 023002.
- DeConto, Robert M and David Pollard (2016). “Contribution of Antarctica to past and future sea-level rise”. In: *Nature* 531.7596, pp. 591–597.
- DeConto, Robert M, David Pollard, et al. (2021). “The Paris Climate Agreement and future sea-level rise from Antarctica”. In: *Nature* 593.7857, pp. 83–89.
- Dorland, R. van et al. (2024). *KNMI National Climate Scenarios 2023 for the Netherlands*. Scientific Report WR-23-02. Royal Netherlands Meteorological Office (KNMI).
- Dullaart, Job CM et al. (2024). “Improving our understanding of future tropical cyclone intensities in the Caribbean using a high-resolution regional climate model”. In: *Scientific Reports* 14.1, p. 6108.
- Fox-Kemper, B. et al. (2021). “Ocean, Cryosphere and Sea Level Change”. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by V. Masson-Delmotte et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, pp. 1211–1362. DOI: 10.1017/9781009157896.011.
- Giannini, A., Y. Kushnir, and M. A. Cane (2000). “Interannual variability of Caribbean rainfall, ENSO, and the Atlantic Ocean”. In: *Journal of Climate* 13.2, pp. 297–311. DOI: 10.1175/1520-0442(2000)013<0297:IVOCRE>2.0.CO;2.
- (2001). “Seasonality in the impact of ENSO and the North Atlantic High on Caribbean rainfall”. In: *Physics and Chemistry of the Earth Part B* 26.2, pp. 143–147. DOI: 10.1016/s1464-1909(00)00231-8.
- Hausfather, Z. et al. (2022). “Climate simulations: recognize the ‘hot model’ problem”. In: *Nature* 605.7908, pp. 26–29. DOI: 10.1038/d41586-022-01192-2.

- Hawkins, Ed and Rowan Sutton (2009). “The potential to narrow uncertainty in regional climate predictions”. In: *Bulletin of the American Meteorological Society* 90.8, pp. 1095–1108.
- Idier, Déborah et al. (2019). “Interactions between mean sea level, tide, surge, waves and flooding: mechanisms and contributions to sea level variations at the coast”. In: *Surveys in Geophysics* 40.6, pp. 1603–1630.
- International Panel on Deltas and Coastal Areas (IPDC) (2024). *Climate Adaptation in Deltas, Coasts, and Islands: Introducing the IPDC Guidance Framework*. Printed by Deltares, Delft. International Panel on Deltas and Coastal Areas (IPDC).
- IPCC (2021a). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report*. Intergovernmental Panel on Climate Change (IPCC). URL: <https://www.ipcc.ch/report/ar6/wg1/> (visited on 11/19/2025).
- (2021b). *Regional Fact Sheet: Small Islands*. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Accessed 6 December 2025. URL: <https://www.ipcc.ch/report/ar6/wg1/resources/fact-sheets/>.
- (2022). *Fact Sheet – Small Islands*. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Accessed 6 December 2025. URL: https://www.ipcc.ch/report/ar6/wg2/downloads/outreach/IPCC_AR6_WGII_FactSheet_SmallIslands.pdf.
- James, Rachel et al. (2017). “Characterizing half-a-degree difference: a review of methods for identifying regional climate responses to global warming targets”. In: *Wiley Interdisciplinary Reviews: Climate Change* 8.2, e457.
- Jury, Mark R (2018). “Eastern Venezuela coastal upwelling in context of regional weather and climate variability”. In: *Regional Studies in Marine Science* 18, pp. 219–228.
- Klotzbach, Philip J (2011). “The influence of El Niño–Southern Oscillation and the Atlantic multidecadal oscillation on Caribbean tropical cyclone activity”. In: *Journal of Climate* 24.3, pp. 721–731.
- Knutson, Thomas et al. (2020). “Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming”. In: *Bulletin of the American Meteorological Society* 101.3, E303–E322.
- Koole, E. C., N. Bloemendaal, M. Brotons, et al. (2024). *KNMI climate scenarios for Suriname*. Scientific Report WR24-01. Royal Netherlands Meteorological Office (KNMI).
- Le Bars, D. (2022). *Past and Future Sea Level around the BES Islands*. Tech. rep. TR-397. De Bilt, The Netherlands: Royal Netherlands Meteorological Office (KNMI). URL: <https://cdn.knmi.nl/knmi/pdf/bibliotheek/knmipubTR/TR397.pdf>.
- Le Bars, D., I. Keizer, and S. Drijfhout (2025). “Constraining local ocean dynamic sea-level projections using observations”. In: *Ocean Science* 21, pp. 1303–1314. DOI: 10.5194/os-21-1303-2025.
- Maitland, Deron O et al. (2024). “Determining sea-level rise in the Caribbean: A shift from temperature to mass control”. In: *Scientific Reports* 14.1, p. 10387.
- Martyr-Koller, Rosanne et al. (2021). “Loss and damage implications of sea-level rise on Small Island Developing States”. In: *Current Opinion in Environmental Sustainability* 50, pp. 245–259.
- Meesters, EH et al. (2025). “Conservation state of coral reefs and communities of the Caribbean Netherlands”. In: Meteorological Department Curaçao (2024). *De gevolgen van klimaatverandering 2025*. Accessed 6 December 2025. Willemstad, Curaçao: Meteorological Department Curaçao (MDC). URL: https://www.meteo.cw/Data_www/pdf/pub/klimaatverandering_scenario_finalv6.pdf.
- Mona, Climate Studies Group (2020). *The State of the Caribbean Climate*. Tech. rep. Accessed 6 December 2025. Barbados: Caribbean Development Bank. URL: <https://www.caribank.org/sites/default/files/publication-resources/The%20State%20of%20the%20Caribbean%20Climate%20Report.pdf>.
- Mora, Camilo, Bénédicte Dousset, et al. (2017). “Global risk of deadly heat”. In: *Nature climate change* 7.7, pp. 501–506.
- Mora, Camilo, Abby G Frazier, et al. (2013). “The projected timing of climate departure from recent variability”. In: *Nature* 502.7470, pp. 183–187.
- Muis, Sanne et al. (2020). “A high-resolution global dataset of extreme sea levels, tides, and storm surges, including future projections”. In: *Frontiers in Marine Science* 7, p. 263.
- Mycoo, Michelle et al. (2022). “Small islands”. In: *IPCC WGII sixth assessment report*.
- National Hurricane Center (Mar. 2018). *Tropical Cyclone Report: Hurricane Irma (AL112017)*. Technical report AL112017. PDF. National Oceanic and Atmospheric Administration (NOAA). URL: https://www.nhc.noaa.gov/data/tcr/AL112017_Irma.pdf.

- NOAA Climate Prediction Center (2025). *Oceanic Niño Index (ONI): Cold and Warm Episodes (1950–Present)*. Accessed 2025-12-06. URL: https://psl.noaa.gov/enso/past_events.html.
- NOAA National Hurricane Center (2006). *2005 Atlantic Hurricane Season*. Accessed 14 July 2025. URL: <https://www.nhc.noaa.gov/data/tcr/index.php?season=2005&basin=atl>.
- (2011). *2010 Atlantic Hurricane Season*. Accessed 14 July 2025. URL: <https://www.nhc.noaa.gov/data/tcr/index.php?season=2010&basin=atl>.
- O’Neill, Brian C et al. (2016). “The scenario model intercomparison project (ScenarioMIP) for CMIP6”. In: *Geoscientific Model Development* 9.9, pp. 3461–3482.
- Oliver, Eric CJ, Jessica A Benthuyssen, et al. (2021). “Marine heatwaves”. In: *Annual review of marine science* 13.1, pp. 313–342.
- Oliver, Eric CJ, Markus G Donat, et al. (2018). “Longer and more frequent marine heatwaves over the past century”. In: *Nature communications* 9.1, p. 1324.
- Pardaens, A. K. et al. (2011). “Sea-level rise and impacts projections under a future scenario with large greenhouse gas emission reductions”. In: *Geophysical Research Letters* 38.12. DOI: 10.1029/2011gl047678.
- Plesca, Elina, Verena Grützun, and Stefan A Buehler (2018). “How robust is the weakening of the Pacific Walker circulation in CMIP5 idealized transient climate simulations?” In: *Journal of Climate* 31.1, pp. 81–97.
- Rueda-Roa, Digna T and Frank E Muller-Karger (2013). “The southern Caribbean upwelling system: Sea surface temperature, wind forcing and chlorophyll concentration patterns”. In: *Deep Sea Research Part I: Oceanographic Research Papers* 78, pp. 102–114.
- Schneider, Udo et al. (2022). *GPCC Full Data Monthly Product Version 2022 (0.25°): Monthly Land-Surface Precipitation from Rain-Gauges*. https://opendata.dwd.de/climate_environment/GPCC/html/fulldata-monthly_v2022_download.html. Dataset accessed via GPCC / DWD. DOI: 10.5676/DWD_GPCC/FD_M_V2022_025.
- Seager, Richard, Mark Cane, et al. (2019). “Strengthening tropical Pacific zonal sea surface temperature gradient consistent with rising greenhouse gases”. In: *Nature Climate Change* 9.7, pp. 517–522.
- Seager, Richard, Naomi Henderson, and Mark Cane (2022). “Persistent discrepancies between observed and modeled trends in the tropical Pacific Ocean”. In: *Journal of Climate* 35.14, pp. 4571–4584.
- Selten, F. and B. Verheggen (2025). *What do the new emissions scenarios mean for the KNMI climate scenarios?* URL: <https://www.knmi.nl/over-het-knmi/nieuws/wat-betekenen-de-nieuwe-emissiescenario-s-voor-de-knmi-klimaatscenario-s>.
- Shepherd, Theodore G and Adam H Sobel (2020). “Localness in climate change”. In: *Comparative Studies of South Asia, Africa and the Middle East* 40.1, pp. 7–16.
- Tartaglione, Carissa A, Shawn R Smith, and James J O’Brien (2003). “ENSO impact on hurricane landfall probabilities for the Caribbean”. In: *Journal of Climate* 16.17, pp. 2925–2931.
- Taylor, Michael A et al. (2013). “The precis Caribbean story: lessons and legacies”. In: *Bulletin of the American Meteorological Society* 94.7, pp. 1065–1073.
- Taylor, Michael A. et al. (2018). “Future Caribbean Climates in a World of Rising Temperatures: The 1.5 vs 2.0 Dilemma”. In: *Journal of Climate* 31.7, pp. 2907–2926. DOI: 10.1175/JCLI-D-17-0074.1. URL: <https://doi.org/10.1175/JCLI-D-17-0074.1>.
- Teunisse, Anneloes M F (2024). “When the East Wind No Longer Prevails: Exploring the (Synoptic) Characteristics and Drivers of Wind Reversals on Bonaire”. Department of Earth Sciences. Master’s thesis. Amsterdam, The Netherlands: Vrije Universiteit Amsterdam.
- Van Meerbeeck, Cédric J. (2020). *OECS Climate Trends and Projections 2020*. Tech. rep. Accessed 6 December 2025. Organisation of Eastern Caribbean States / Caribbean Institute for Meteorology & Hydrology. URL: <https://rcc.cimh.edu.bb/files/2021/08/OECS-Climate-Report.pdf>.
- Van Vuuren, D. P., B. C. O’Neill, C. Tebaldi, et al. (2026). “The Scenario Model Intercomparison Project for CMIP7 (ScenarioMIP-CMIP7)”. In: *Geoscientific Model Development* 19, pp. 2627–2656. DOI: 10.5194/gmd-19-2627-2026.
- Van Westen, R. M., H. A. Dijkstra, C. G. Van Der Boog, et al. (2020). “Ocean model resolution dependence of Caribbean sea-level projections”. In: *Scientific Reports* 10.1. DOI: 10.1038/s41598-020-71563-0.
- Wal, Roderik SW van de et al. (2022). “A high-end estimate of sea level rise for practitioners”. In: *Earth’s future* 10.11, e2022EF002751.
- Wang, Chunzai (2007). “Variability of the Caribbean Low-Level Jet and its relations to climate”. In: *Climate Dynamics* 29, pp. 411–422.

- Status and Trends of Caribbean Coral Reefs: 1970–2024* (2025). Global Coral Reef Monitoring Network (GCRMN) and International Coral Reef Initiative (ICRI). DOI: 10.59387/BDHF9180. URL: <https://doi.org/10.59387/BDHF9180>.
- Wiel, Karin van der et al. (2024). “KNMI’23 climate scenarios for the Netherlands: storyline scenarios of regional climate change”. In: *Earth’s Future* 12.2, e2023EF003983.
- Yu, Mei et al. (2019). “Landscape-level consequences of rising sea-level on coastal wetlands: saltwater intrusion drives displacement and mortality in the twenty-first century”. In: *Wetlands* 39.6, pp. 1343–1355.
- Zhao, Xueying and Robert J Allen (2019). “Strengthening of the Walker Circulation in recent decades and the role of natural sea surface temperature variability”. In: *Environmental Research Communications* 1.2, p. 021003.

Appendix A

Evaluation of observational datasets

A.1 Datasets

Observational datasets are required for the bias adjustment of the CMIP6 simulations used in the climate scenarios. For each island, meteorological departments were asked to provide daily observations. However, only one station record was available per island, and no station observations were available for Curaçao. To assess the suitability of these datasets, the station records were compared with independent sources, namely ERA5-Land and NOAA GSOD. For precipitation, GPCC data were also considered.

Because Aruba and Curaçao are geographically close and experience similar climate conditions, the evaluation for Aruba was used to guide the selection of observational datasets for Curaçao. Using consistent reference datasets for both islands helps to avoid artificial differences between their climate scenarios.

A.1.1 Station data

The Departamento Meteorological Aruba provided different datasets for different time periods and time scales. For the period 1991-2004, no daily digitalized datasets were available. For the period 2005-2020, there is hourly data and summarized daily data. The latter is used in the data analysis. For the period 1991-2004, the monthly reports are used to compare the data to the NOAA GSOD data. From 2018, FMC8 was used to measure the weather, which had a sampling rate of 5 seconds. From 2018 onwards, the meteorological department switched to Vaisala, which has different sample rates per variable (Table A.1). The station is located 12.50139 N, 70.01528 W, 18 meters above sea level

Table A.1: Overview of received data from the meteorological department of Aruba

Parameters measured	Units	Frequency	% missing data (2005 – 2020)
Wind speed	m/s	Every second	0.07 %
Air temperature	Degrees Celsius	Every second	0.09 %
Maximum temperature	Degrees Celsius	Every second	0.07 %
Minimum temperature	Degrees Celsius	Every second	0.09 %
Average atmospheric pressure	Decapascals (daPa) ?		0.9 %
Relative Humidity	Percentage		0.09 %
Precipitation	Millimeters	Every minute	0.09 %
Average dew point temperature	Degrees Celsius	Every second	0.09 %
Vapor pressure ? (eee avg)	Hectopascals ?		0.09 %
Wind direction	Vector	Every second	36.0 %
Cloud cover	Percentage		9.6 %
Thunderdays	Count		40.28 %
Hours with precipitation	Count		42.43 %

From the Meteorological Department of Sint Maarten, we received a dataset measured at Princess Juliana

International Airport (PJIA) with daily data (Table A.2). The dataset starts in 1982 and contains data up to 31-12-2024. In the period that is needed for the climate scenarios (1991–2020) the dataset is relatively complete, except for the wind data, with 12.89 % of the days with no data. The largest gaps are 1993-01-01, 2005-09-01, 2008-03-01, 2008-10-01, 2010-08-01 with more than 100 consecutive missing days. No noticeable events happened during these periods. The NaN values are noted as empty cells in the dataset.

Table A.2: Overview of received data from the Meteorological Department of Sint Maarten

Parameters measured	Units	Frequency	Location	Sensor	Exposure	% missing data (1991 – 2020)
Wind speed	Knots	Hourly	18.03852 N 63.11917 W	Sutron AWS	Airside 10m high	12.89
Air temperature	Degrees Celsius	Hourly	18.03852 N 63.11917 W	Sutron AWS	Airside 10m high	1.96
Maximum temperature	Degrees Celsius	Hourly	18.03852 N 63.11917 W	Sutron AWS	Airside 10m high	1.98
Minimum temperature	Degrees Celsius	Hourly	18.03852 N 63.11917 W	Sutron AWS	Airside 10m high	2.06
Barometric Pressure (QNH)	Millibars	Hourly	18.03852 N 63.11917 W	Sutron AWS	Airside 10m high	2.96
Relative Humidity	Percentage	Hourly	18.03852 N 63.11917 W	Sutron AWS	Airside 10m high	1.99
Precipitation	Millimeters	6-hourly	18.04357 N 63.11632 W	Snowdon Rain gauge (manual)	Near office (elevation 12.5m/41ft)	0.24

A.1.2 NOAA GSOD

The NOAA Global Surface Summary of the Day (GSOD) is derived from the Integrated Surface Database (ISD) maintained by the National Centers for Environmental Information (NCEI). Global station data is gathered and undergoes an automatic quality control, but does not include a quality attribute in the resulting datasets. For all three islands, there is an extensive time series available for at least the study period of 1991–2020. This enables us to compare the observation data we received with the NOAA data.

A.1.3 ERA5-Land

The observation data is also compared to hourly ERA5-land data. This dataset has a horizontal resolution of $0.1^\circ \times 0.1^\circ$ and only contains data above land-dominated grid cells. For Sint Maarten, no ERA5-Land grid cell is centred over the island. Therefore, the nearest land grid cell located over Saint Kitts (17.4°N , 62.8°W), approximately 70 km south-southeast of Sint Maarten, was used. This can influence the applicability of this dataset for Sint Maarten. ERA5 is expected to underestimate the precipitation in the Caribbean region (Centella-Artola et al., 2020).

A.1.4 Global Precipitation Climatology Centre (GPCC)

The GPCC dataset is a product of the Deutscher Wetterdienst. It is a gridded dataset with daily precipitation data and a grid of $1.0^\circ \times 1.0^\circ$. The dataset is formed using up to 40,000 stations per month. This data is then interpolated to cover the global extent. For the Caribbean, there are minimal measuring stations . For

the three islands, only one or two stations per grid cell over or near the island are used for the interpolation of the precipitation (Schneider et al., 2022).

A.2 Comparison

A.2.1 Aruba

The mean temperature of Aruba is around 28.5 °C according to NOAA and the station data. The ERA5-land dataset is substantially lower, with a mean temperature of 27.0 °C. However, all three datasets show the same daily and yearly variation. What stands out is that the temperature trend according to NOAA is negative, with 0.23 °C cooling in 2005-2020, where ERA5 and the station data show an increasing temperature trend. This can be explained by decadal cycles that are now not properly captured due to the short overlapping time series of 15 years. In precipitation, there are relatively large differences in the daily mean. Also, the

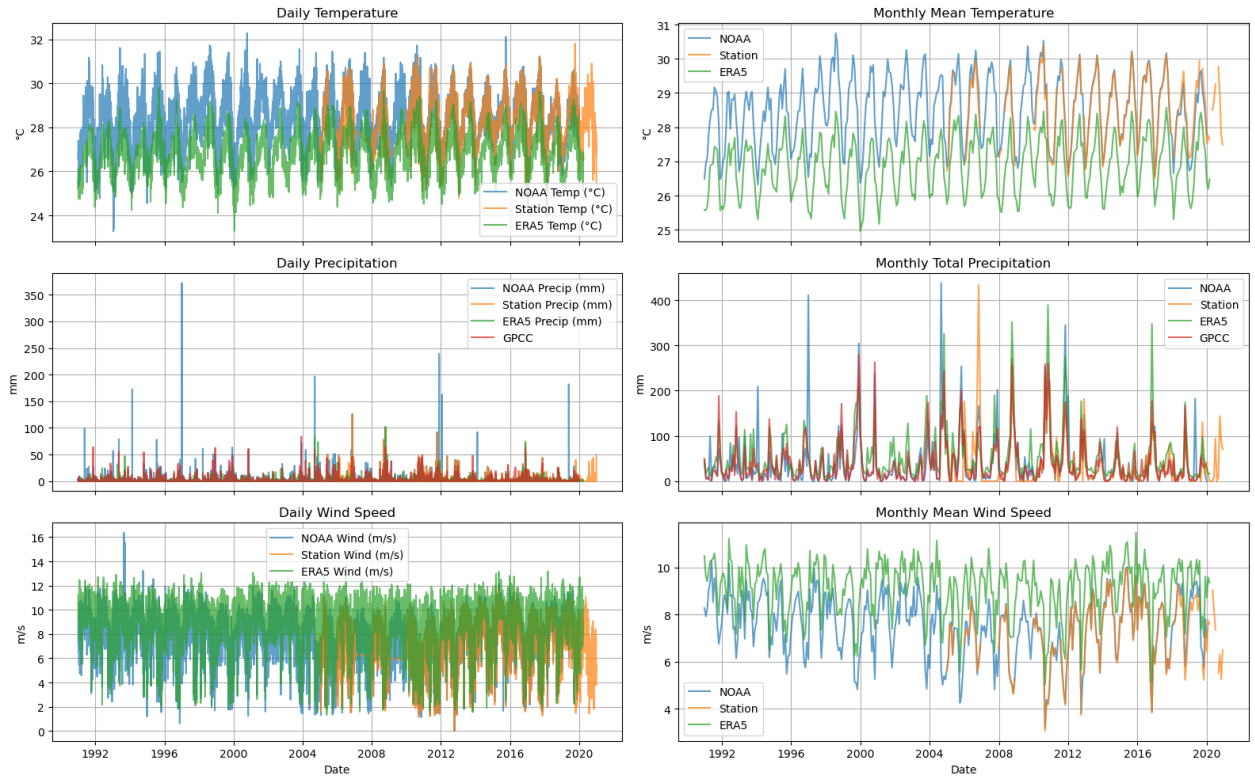


Figure A.1: time series from 1991–2020 with daily (left column) and month mean (right column) data for Aruba comparing ERA5, NOAA and Station data for temperature (top), precipitation (middle) and wind speed (bottom). For precipitation, the GPCC dataset is also included.

NOAA dataset shows some very large peaks in the precipitation that the other time series do not show in the same magnitude (Figure A.1). The peak on 01/01/1994 has no clear explanation. The peak around 10/09/2004 can be explained by Hurricane Ivan, which passed by and left large amounts of precipitation. The peak around 23/11/2011 also does not have a clear explanation, but the other time series also show a peak around this date, though to a lesser extent (Figure A.1). For wind speed, the NOAA and Station data are very similar, with similar median, standard deviation, and cycles (Figures A.1 & A.2). Here, ERA5-land is off with higher wind speed than observed. However, the monthly cycles do correspond. The GPCC data show lower precipitation values than the station data, comparable with the median of ERA5 (Figure A.2). The peaks within the time series are less represented in the GPCC data than in the other datasets (Figure A.1). This can be explained because the GPCC data averages over a larger area than the island (Centella-Artola et al., 2020). Overall, the station observations and NOAA GSOD show very similar characteristics and the highest correlations among the evaluated datasets. ERA5-Land reproduces the temporal variability but

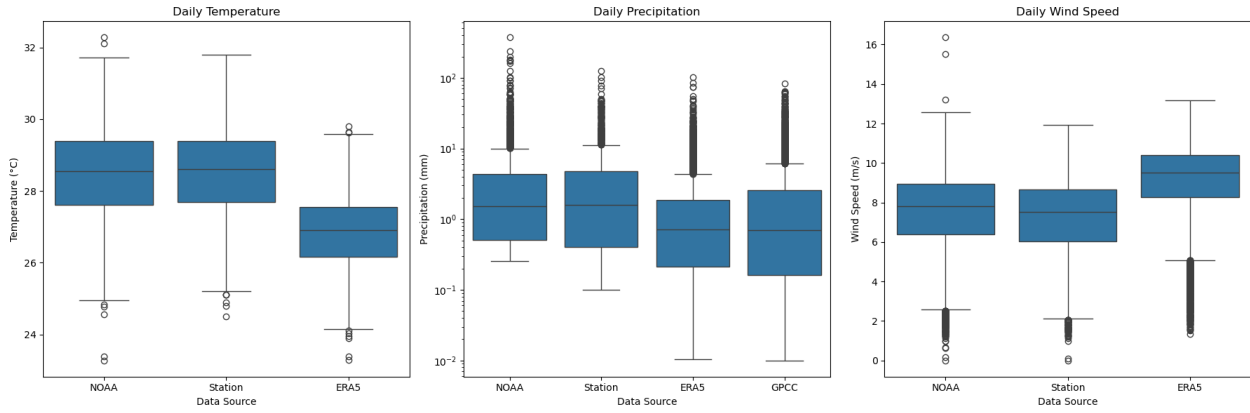


Figure A.2: Box plots showing the daily weather variables of Aruba (temperature, precipitation and wind speed). Boxes show median (line), interquartile range (box), and $1.5 \times \text{IQR}$ whiskers of daily values from NOAA, Station, ERA5, and GPCC datasets. Outliers are plotted as points.

exhibits systematic biases, particularly for temperature and wind speed. Therefore, the station observations were selected as the reference dataset for Aruba (Figure A.3). The trend over the period 2005–2020 differs for the different datasets but this can be caused by the short time series that does not capture decadal cycles. ERA5 does tend to overestimate the wind and underestimate the temperature and precipitation (Figure A.2).

A.2.2 Sint Maarten

According to NOAA and the station data, the mean temperature on Sint Maarten in 1991–2020 was approximately 27.4 °C. Here, in correspondence with the results from Aruba, the ERA5 data seems to underestimate the temperature and gives a mean temperature of 26 °C. The trend in temperature is negative according to NOAA and the station data, but positive in the ERA5 dataset. The three datasets show a comparable daily and monthly cycle (Figure A.4). For precipitation, the datasets do not agree. The NOAA and station datasets show peaks where none of the other time series do, and ERA5 underestimates precipitation over the whole period (A.5). The large NOAA peaks in 2017 can be explained by Hurricane Irma which passed over Sint Maarten. The station was not functional during this event, thus not capturing these peaks. The station data has large gaps in the wind time series, but does compare very well to the NOAA data, which is complete. The ERA5 data also shows similar cycles and trends, but has an offset in wind speed of 2.5–3 m/s. In conclusion, the station data does cover the whole time series needed for the climate scenarios, and the data compares well with the NOAA data, which is also represented in the correlation graphs (Figure A.6). The daily and monthly cycles in the data are also represented in the ERA5-land data, but with offsets. This can be explained by the fact that the ERA5 data has no grid cell on Sint Maarten but 70 km away on Saint Kitts. Using NOAA GSOD instead of station observations results in only minor differences in the projected changes. This confirms that NOAA GSOD provides a suitable alternative observational reference dataset.

A.2.3 Curaçao

Based on the correlation between the station data of Aruba and Sint Maarten and the NOAA data, the NOAA data is used for Curaçao. No station observations were available for Curaçao, preventing a direct evaluation. Based on the consistency between NOAA GSOD and station observations for Aruba and Sint Maarten, NOAA GSOD was selected as the reference dataset for Curaçao.

Just like the ERA5 data of Sint Maarten and Aruba, the data shows lower temperatures than the NOAA data does. Also, the wind speed has a difference of almost 3m/s (Figure A.7). However, the correlation for temperature and wind speed between ERA5 and NOAA is relatively high (Figure A.9), showing that the patterns in these variables are comparable for these islands. Precipitation in the ERA5 and GPCC data is again lower than the NOAA data, mainly missing the peaks that are present in the NOAA data (Figure A.7

& A.8).

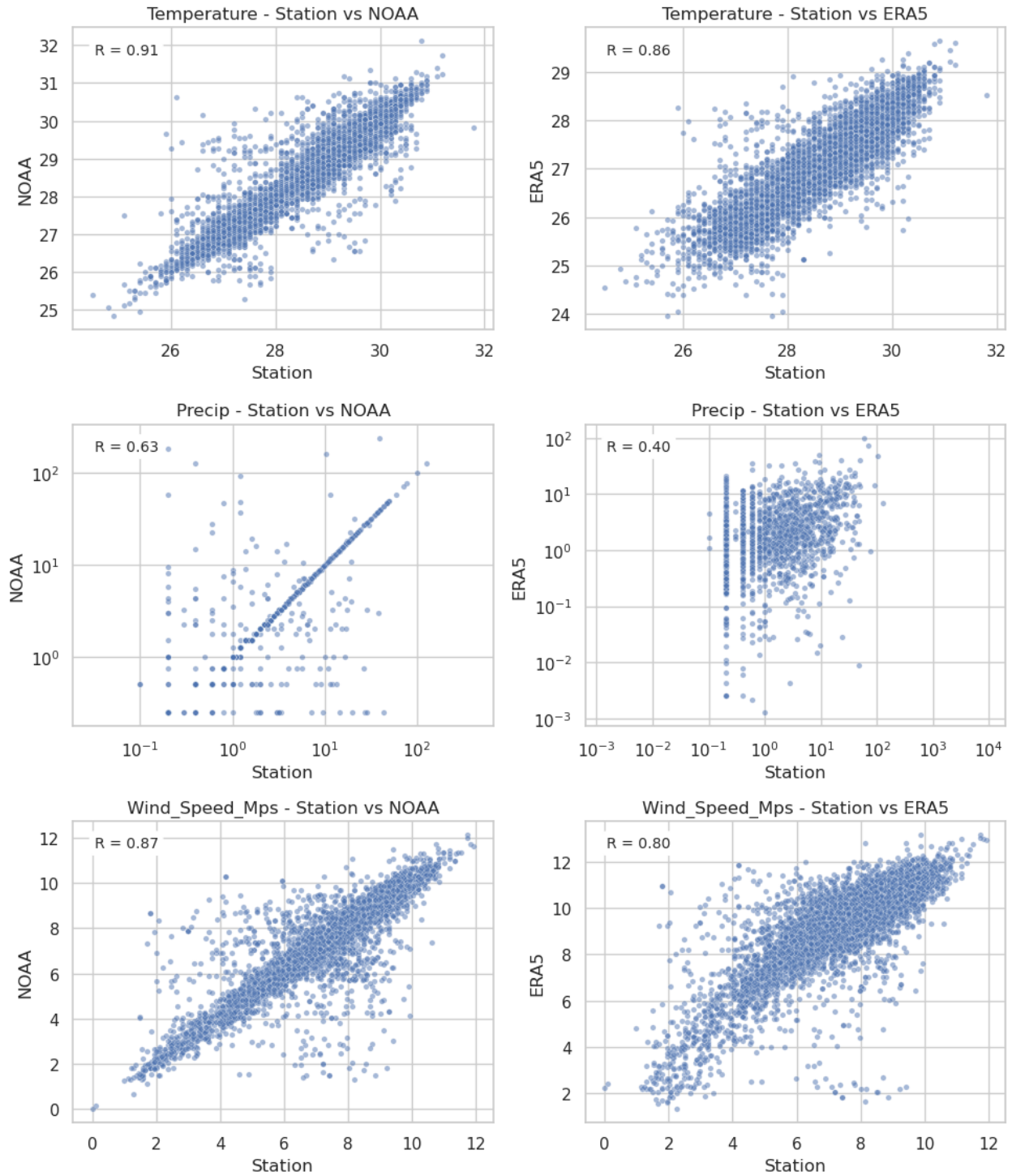


Figure A.3: Comparison of daily station observations with NOAA GSOD and ERA5-Land for Aruba (1991–2020). Numbers indicate Pearson correlation coefficients (R). Precipitation values are shown on a $\log_{1+x}$ scale.



Figure A.4: Time series from 1991-2024 with daily (left column) and month mean (right column) data for Sint Maarten comparing ERA5, NOAA and Station data for temperature (top), precipitation (middle) and wind speed (bottom). For precipitation, the GPCC dataset is also included.

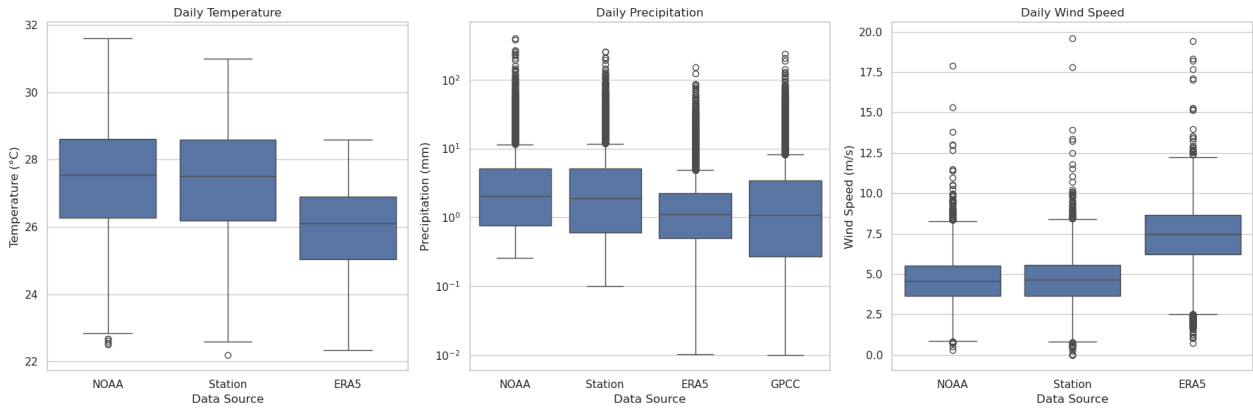


Figure A.5: Box plots showing the daily weather variables of Sint Maarten (temperature, precipitation and wind speed). Boxes show median (line), inter-quartile range (box), and $1.5 \times \text{IQR}$ whiskers of daily values from NOAA, Station, ERA5, and GPCC datasets. Outliers are plotted as points

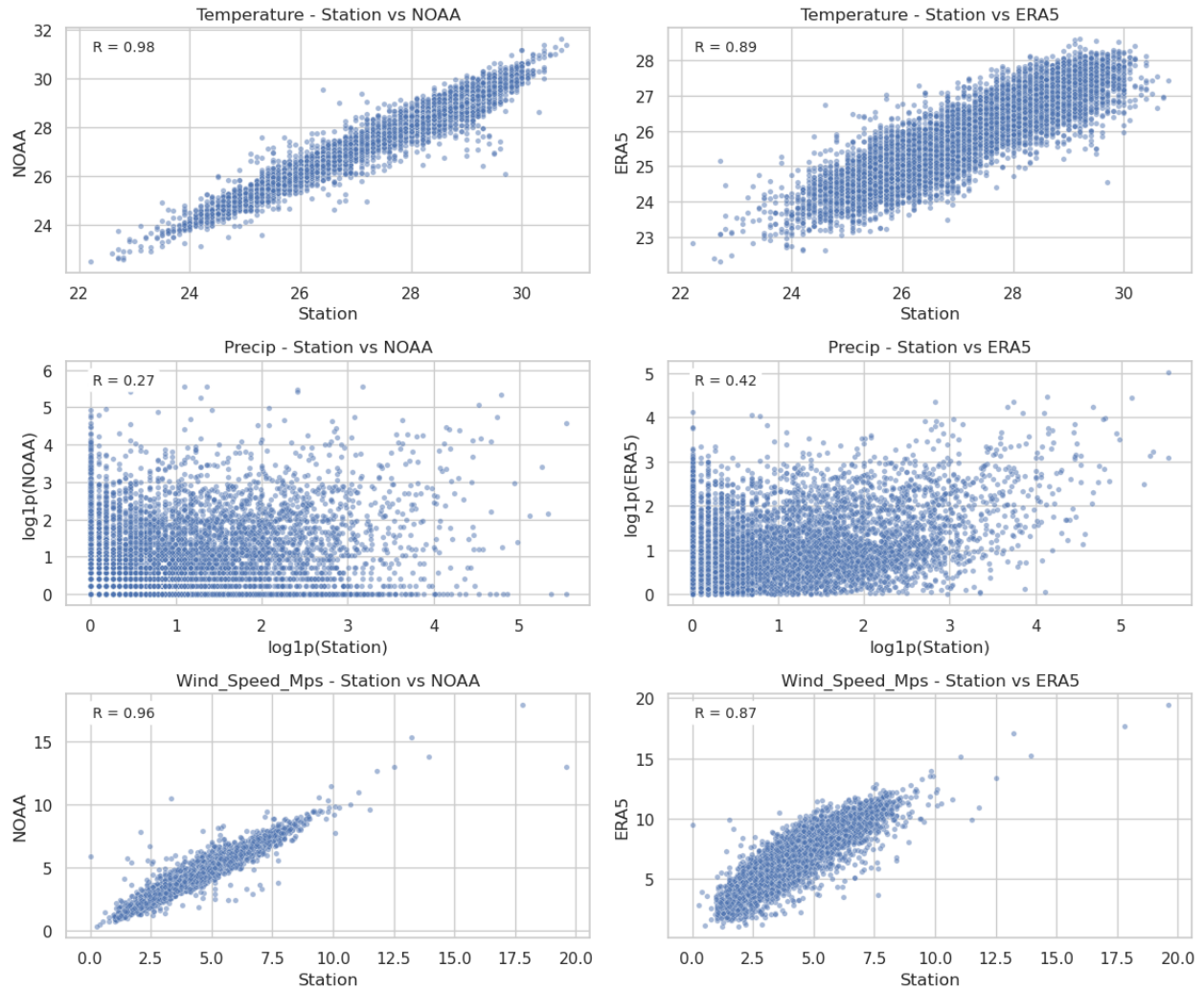


Figure A.6: Scatter plots compare daily station observations with NOAA and ERA5 datasets for temperature, precipitation, and wind speed on Sint Maarten (1991–2020). For precipitation, values are log-transformed using $\log_{1+x}$ to reduce skew from extreme events. Each plot shows the Pearson correlation coefficient (R) between the two datasets. Points represent individual days

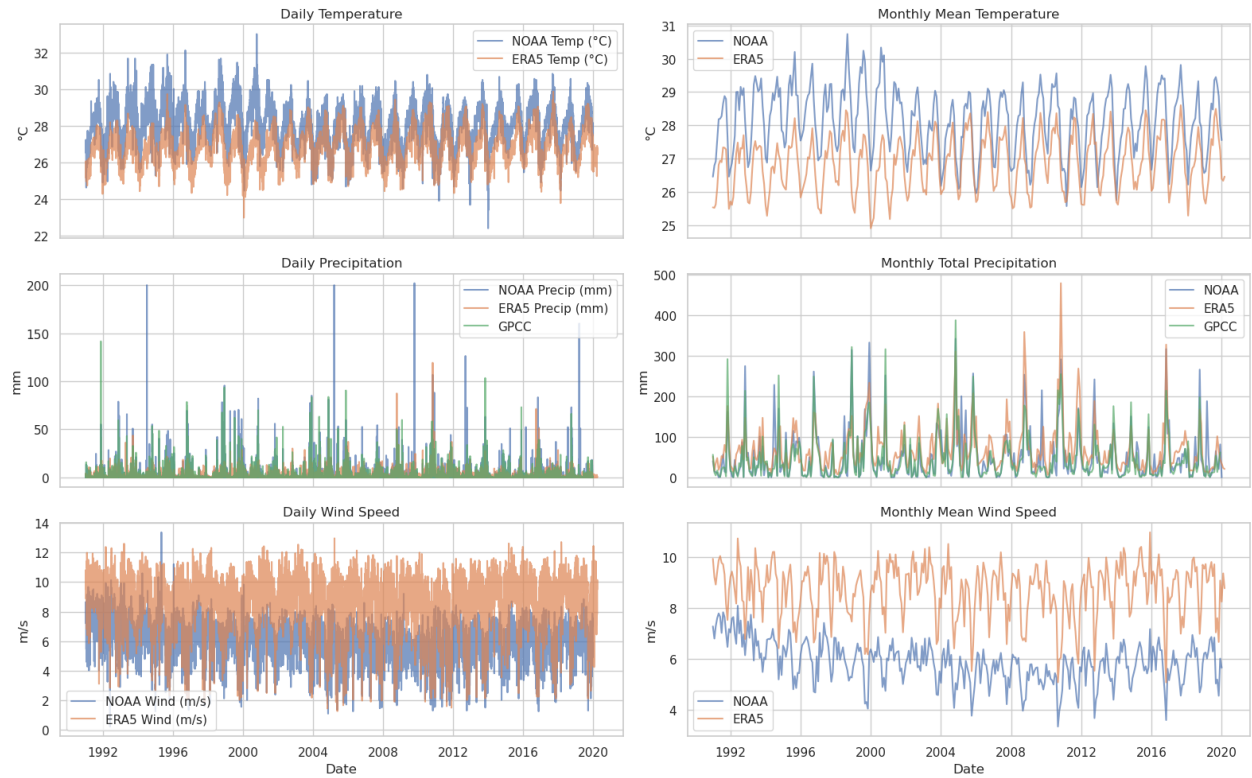


Figure A.7: time series from 1991–2020 with daily (left column) and monthly mean (right column) data for Curaçao comparing ERA5 and NOAA data for temperature (top), precipitation (middle), and wind speed (bottom). For precipitation, the GPCP dataset is also included.

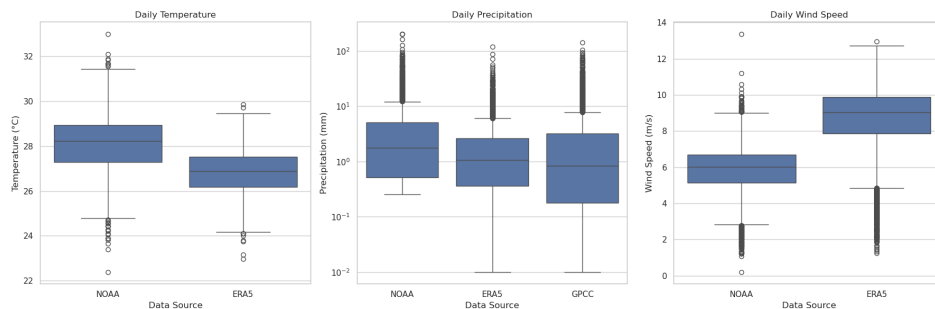


Figure A.8: Box plots showing the daily weather variables of Curaçao (temperature, precipitation and wind speed). Boxes show median (line), inter-quartile range (box), and $1.5 \times \text{IQR}$ whiskers of daily values from NOAA, ERA5, and GPCP datasets. Outliers are plotted as points

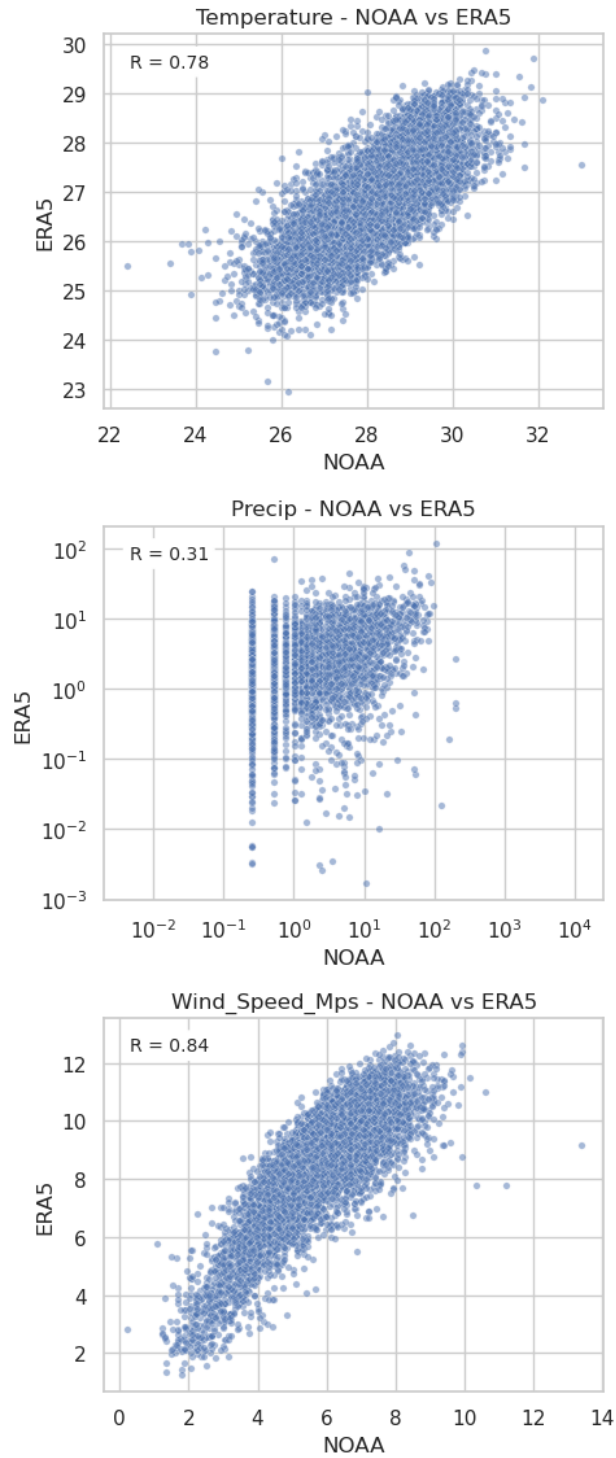


Figure A.9: Comparison of daily station observations with NOAA GSOD and ERA5-Land for Aruba (1991–2020). Numbers indicate Pearson correlation coefficients (R). Precipitation values are shown on a $\log_{1+x}$ scale.

Appendix B

Supplementary climatology figures

B.1 Climatology 2050

These graphs are an addition to Chapter 2. For each island, the monthly mean temperature and precipitation are shown for the mid-century climate (2035–2065) and for the low, moderate and high emissions scenario.



Figure B.1: Climatology of Aruba according to the observations (A, D, G) and in a mid-century climate (B,C,E,F,H,I), with a distinction between the mild drying scenario (B,E,H) and strong drying scenario (C,F,I) based on the low, moderate and high emissions scenarios.

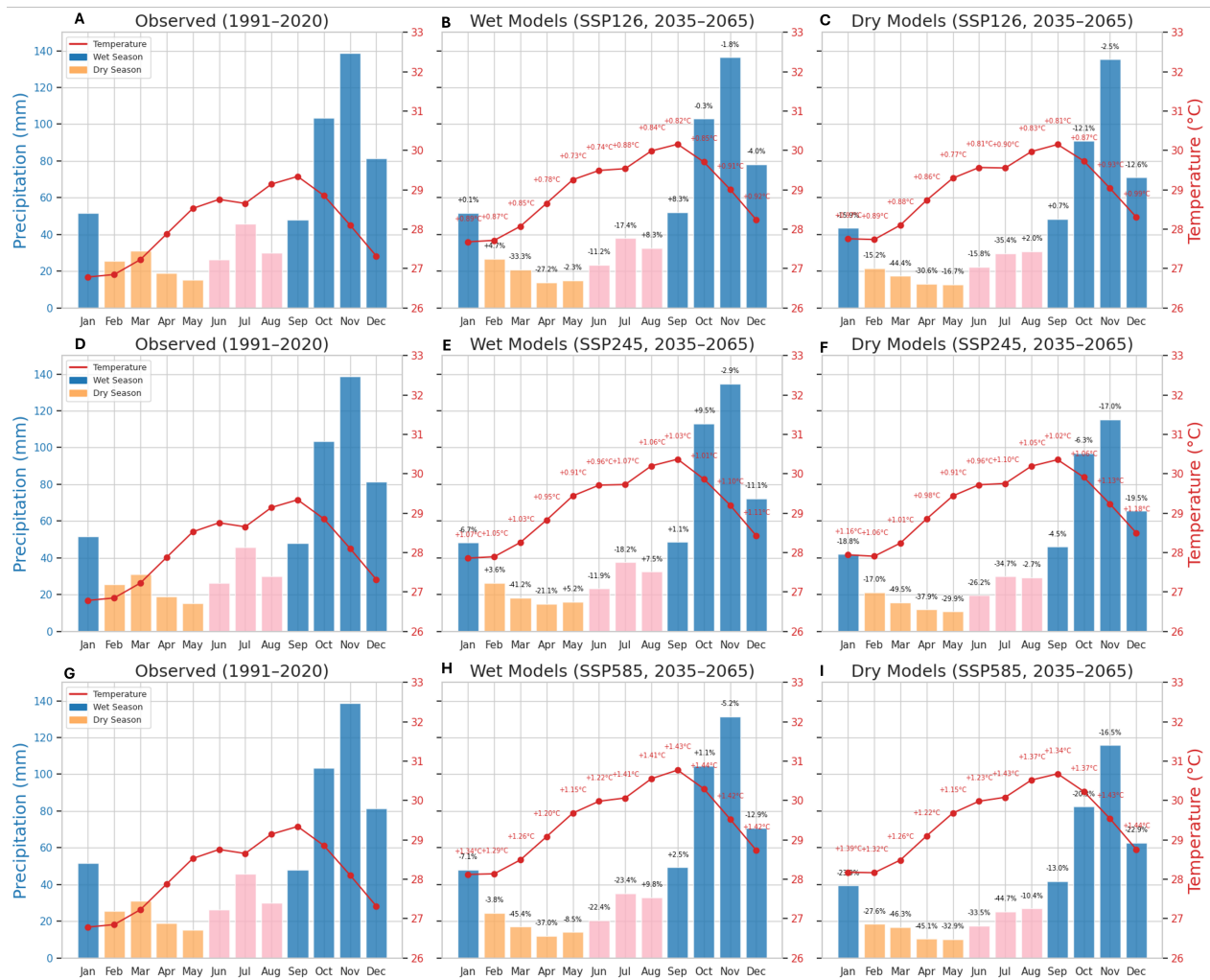


Figure B.2: Climatology of Curaçao according to the observations (A, D, G) and in a mid-century climate (B,C,E,F,H,I), with a distinction between the mild drying scenario (B,E,H) and strong drying scenario (C,F,I) based on the low, moderate and high emissions scenarios.

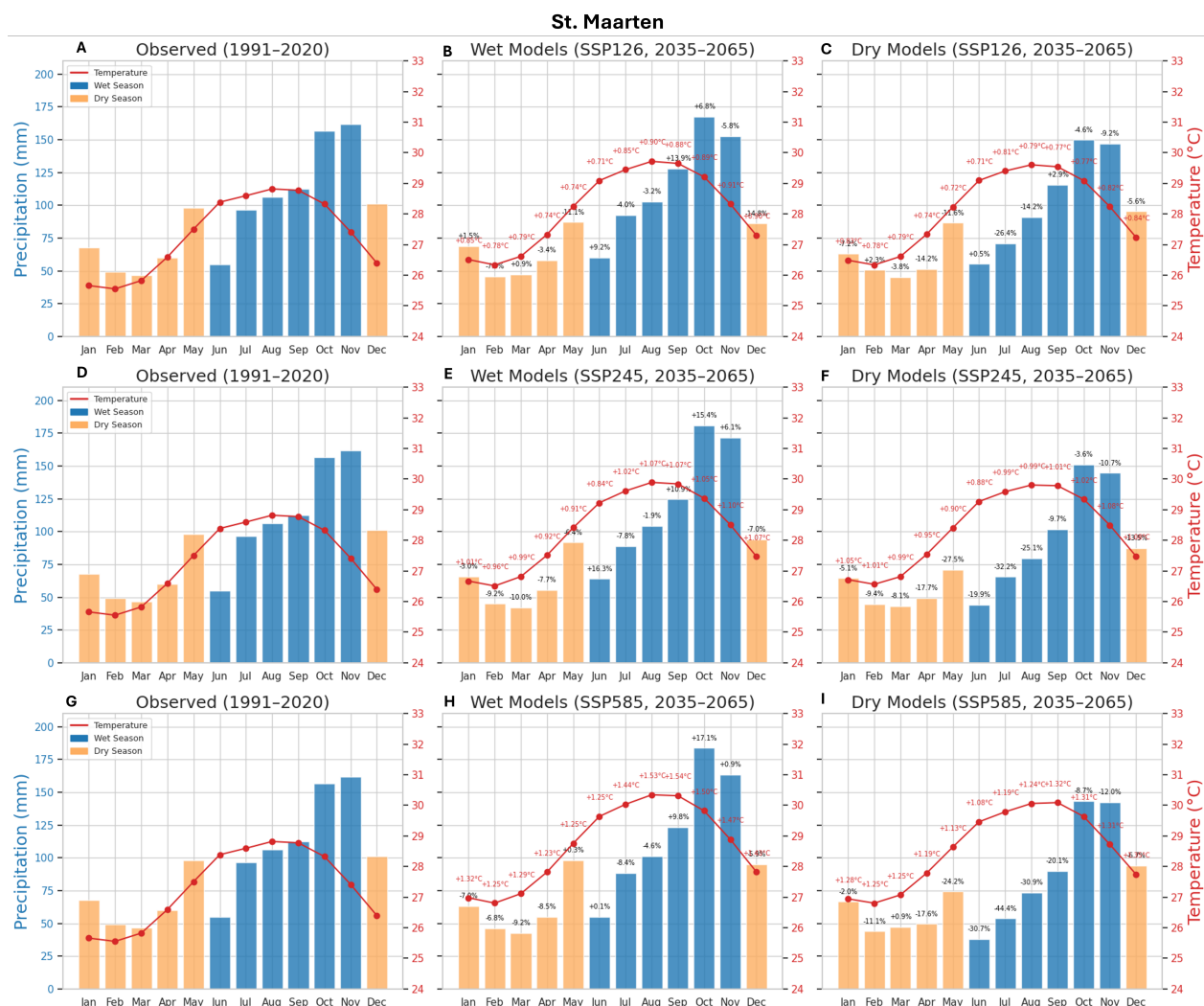


Figure B.3: Climatology of Sint Maarten according to the observations (A, D, G) and in a mid-century climate (B,C,E,F,H,I), with a distinction between the mild drying scenario (B,E,H) and strong drying scenario (C,F,I) based on the low, moderate and high emissions scenarios.

B.2 Climatology 2100

These graphs are an addition to Chapter 2. For each island, the monthly mean temperature and precipitation are shown for the end-of-century climate (2085–2115) and for the low, moderate and high emissions scenario.

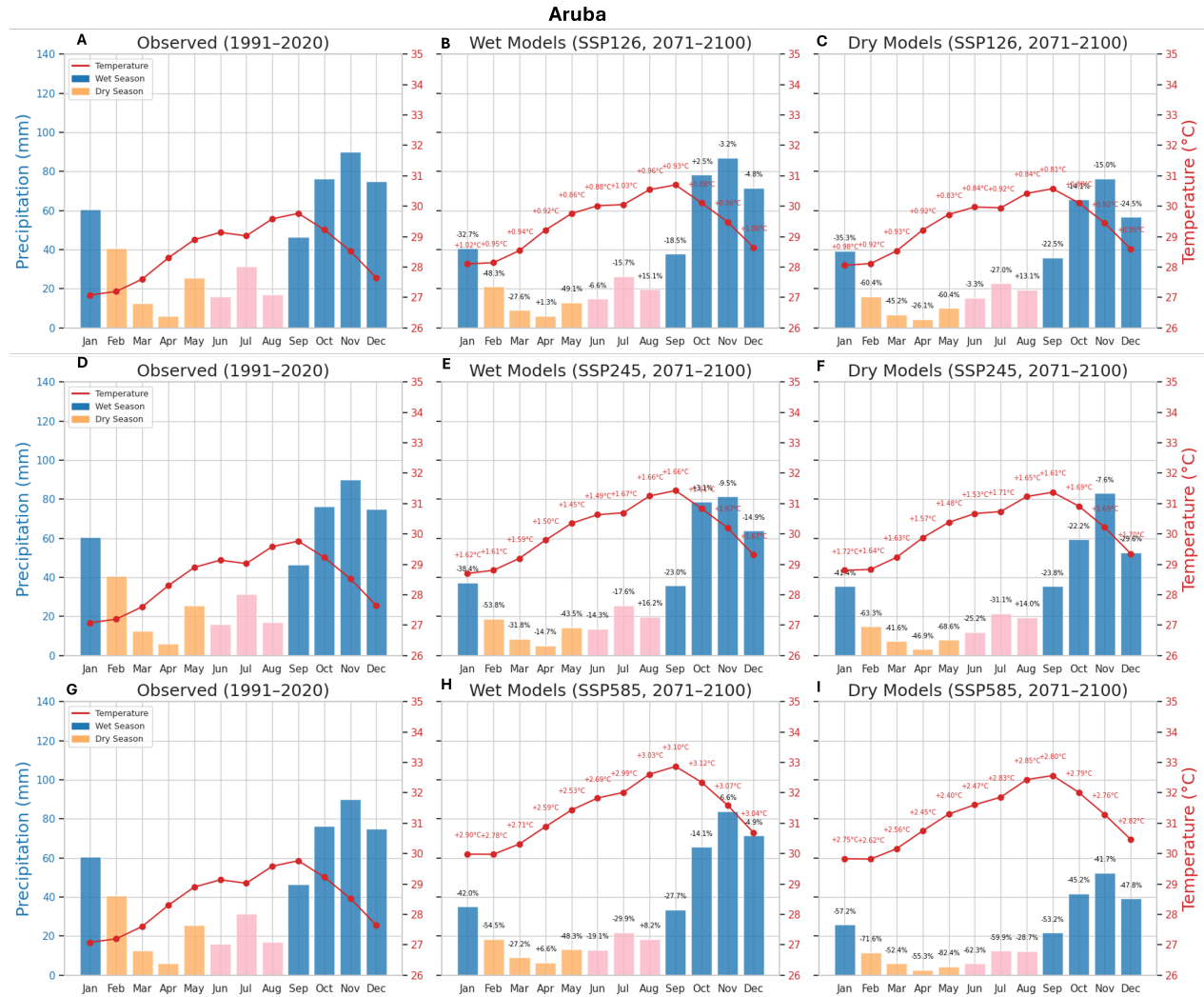


Figure B.4: Climatology of Aruba according to the observations (A, D, G) and in a end-of-century climate (B,C,E,F,H,I), with a distinction between the mild drying scenario (B,E,H) and strong drying scenario (C,F,I) based on the low, moderate and high emissions scenarios.

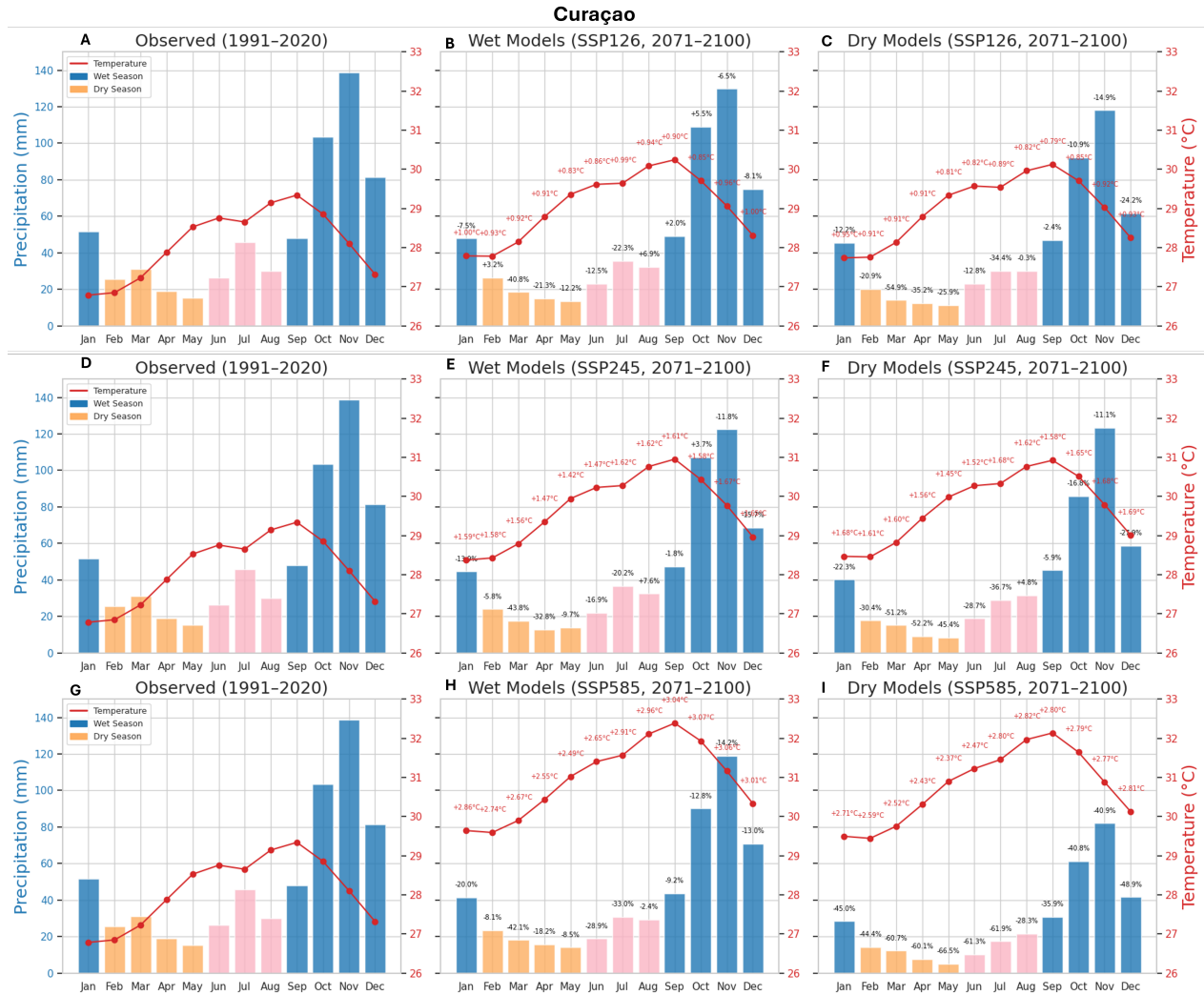


Figure B.5: Climatology of Curaçao according to the observations (A, D, G) and in a end-of-century climate (B,C,E,F,H,I), with a distinction between the mild drying scenario (B,E,H) and strong drying scenario (C,F,I) based on the low, moderate and high emissions scenarios.

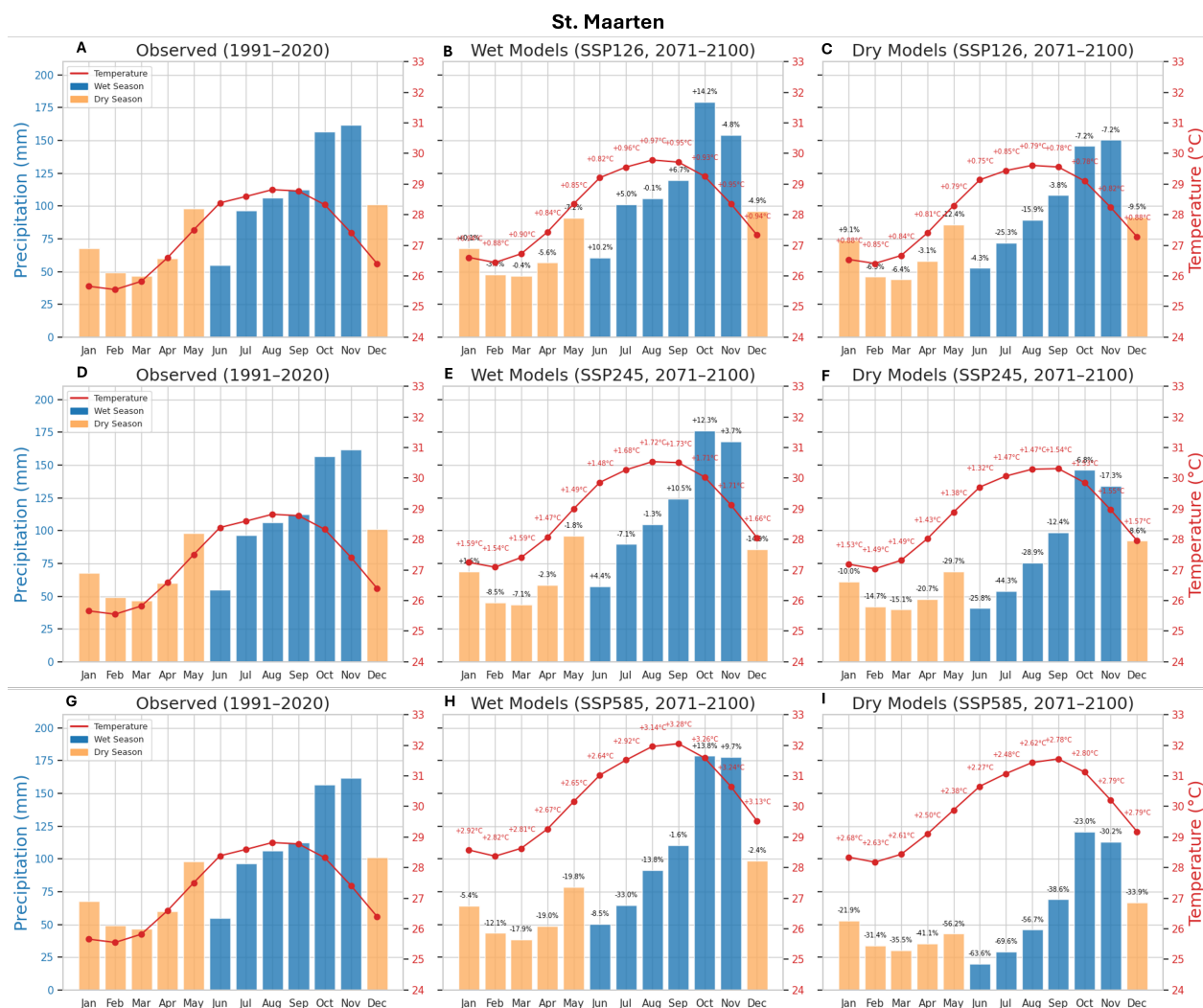


Figure B.6: Climatology of Sint Maarten according to the observations (A, D, G) and in a end-of-century climate (B,C,E,F,H,I), with a distinction between the mild drying scenario (B,E,H) and strong drying scenario (C,F,I) based on the low, moderate and high emissions scenarios.



Royal Netherlands Meteorological Institute

PO Box 201 | NL-3730 AE De Bilt
Netherlands | www.knmi.nl