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Sea-Level Rise and Climate Adaptation in Aruba

Emanuele Massetti

SIP/2025/157

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Sea-Level Rise and Climate Adaptation in Aruba
Prepared by Emanuele Massetti*

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ABSTRACT: Sea-level rise presents long-term risks in Aruba that can lead to sizable permanent costs with potentially large macroeconomic and fiscal consequences. Aruba cannot control global sea-level, but it can manage how it affects the country by adapting. Using the state-of-the-art model CIAM, IMF Staff estimates finds that planned coastline protection—in the form of dykes, revetment, floodgates, costal dunes, etc.—can reduce losses by approximately 40 percent by avoiding permanent inundation of land and relocation of population. Estimates of protection costs in Aruba are around 0.4 percent of annual GDP with a moderate emission scenario and do not grow. This will likely require an increase in public spending as coastal protections are public infrastructure.

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SELECTED ISSUES PAPERS

Sea-Level Rise and Climate Adaptation in Aruba

Kingdom of the Netherlands—Aruba

Prepared by Emanuele Massetti

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SEA-LEVEL RISE AND CLIMATE ADAPTION IN ARUBA[1]

Sea-level rise presents long-term risks in Aruba that can lead to sizable permanent costs with potentially large macroeconomic and fiscal consequences. Aruba cannot control global sea-level, but it can manage how it affects the country by adapting. Using the state-of-the-art model CIAM, IMF Staff estimates finds that planned coastline protection—in the form of dykes, revetment, floodgates, costal dunes, etc.—can reduce losses by approximately 40 percent by avoiding permanent inundation of land and relocation of population. Estimates of protection costs in Aruba are around 0.4 percent of annual GDP with a moderate emission scenario and do not grow. This will likely require an increase in public spending as coastal protections are public infrastructure.

I. Introduction

1. **Aruba faces growing climate change risks that adversely affect its macroeconomic outlook**. Higher temperatures are associated with reduced outdoor labor productivity, increased electricity consumption for cooling, and higher morbidity and mortality rates. Aruba's rapidly aging population is particularly vulnerable to heat-related risks (Peterson, 2024). Projections of declining and more erratic precipitations indicate additional stress on the island's limited water resources and increased flood-related costs. Tourism is especially vulnerable to climate change, and even modest negative impacts can have significant balance of payments implications, as tourism is the main driver of Aruba's economic growth (Centrale Bank van Aruba, 2021). Rising sea temperatures and ocean acidification cause bleaching and diebacks of coral reefs, which may reduce Aruba's attractiveness as a tourism destination (Centrale Bank van Aruba, 2021). Considering multiple stressors, some studies project that climate change could lead to a substantial decline in tourism income (ECLAC, 2011; Centrale Bank van Aruba, 2021).

2. **Sea level rise (SLR) poses significant long-term challenges to Aruba's economy and population**. Sea level will continue to rise slowly but steadily for thousands of years, even with strong global mitigation efforts (Box 1). Without adaptation, rising seas will gradually threaten most of the country's infrastructure, capital, and population, which are all concentrated along an environmentally fragile coastline. Because SLR presents macro-critical risks to Aruba, it is the focus of this analysis.

3. **Climate change impacts can be contained with the right mix of policies and long-term planning**. Aruba has already successfully adapted to a dry climate through investments in desalination. Over the years, its coastline has been modified to support tourism and accommodate critical infrastructure. However, this adaptation to historical conditions must be gradually updated to address new environmental conditions. Strategic long-term planning and targeted investments can significantly reduce present vulnerabilities,[2] mitigate future damages, and minimize macroeconomic risks. The following section presents climate trends and projections in Aruba to identify key areas of concern. After this review, the analysis shifts to preliminary

[1] Prepared by Emanuele Massetti (FAD).

[2] While successful in developing a vibrant tourism economy, coastal development also caused environmental problems that challenge its long-term viability, even without additional stress from SLR (Centrale Bank van Aruba, 2020).

estimates of SLR costs under different adaptation strategies, a blueprint for more advanced studies. The final section outlines key principles for effective and efficient public adaptation policy.

II. Climate Trends and Projections

4. **Aruba has a tropical semi-arid climate that is hotter, drier, and warming faster than most countries.** Located at the southern end of the Caribbean Sea, at 12 degrees north of latitude, Aruba shares a hot and relatively dry climate with neighboring Curaçao and Bonaire. The average annual mean temperature is equal to 29.4 °C, and the average total annual precipitation is equal to 426 mm.[3] This climate is considerably hotter and dryer than most countries globally, as well as compared to most of Aruba's regional (Latin America) and development (Upper Middle Income) peers (Figure 1). Due to a clear warming trend (Figure 2), the average mean annual temperature has increased by 1.6 °C with respect to pre-industrial levels.[4] Temperatures have increased uniformly across seasons. While total annual rainfall exhibits considerable interannual variability, historical data shows no changes in either the average total annual rainfall or its seasonality (Figure 2).[5]

5. **High-resolution and high-frequency data do not reveal significant historical trends in drought and in extreme precipitation events, but conditions could deteriorate rapidly.** Analysis of national averages and gridded data in the larger region surrounding Aruba does not show significant shifts in the average annual occurrence of precipitation extremes or the duration of dry periods (Figure 3).[6] Maps indicate very different trends in areas north of the 13th parallel, with significant increases in the duration of dry spells and in rainfall intensity. The southward shift of this sharp demarcation line, predicted by many models for the future, could substantially alter the climate outlook for Aruba.

6. **Climate models project increasing climate risks: continued warming, a reduction in total annual precipitation, and longer dry periods.** Median projections of warming across all climate model simulations indicate that temperature will increase by additional 0.6 to 0.9 °C in 2050 and by between 0.8 and 1.9 °C in 2085, relative to present levels, depending on the emission scenario (Figure 4).[7] Accounting for 1.6 °C of present warming above pre-industrial level implies that warming will exceed 2 °C and potentially approach 4 °C by the end of the century (Massetti and Tagklis, 2024; Harris et al. 2020; Copernicus Climate Change Service,

[3] Average annual mean temperature in 2021 is predicted by estimating a linear temperature trend using data from the previous 30 years. Observed temperature in 2021 could be higher/lower due to random weather fluctuations.

[4] Estimated temperature in 2021 minus average temperature in the 30-year climatological period 1901-1930, which can be used as a proxy for pre-industrial temperature levels.

[5] Average annual total precipitations range between 200 and 600 mm/year, and average monthly precipitations range between 90 mm/month in January and 12 mm/month in March. Averages calculate using estimated values in 2021.

[6] The maximum number of consecutive dry days in a year (CDD) is used as a proxy for meteorological drought conditions. Total precipitations during the 1-day (RX1Day) and 5-day (RX5Day) periods with the largest precipitation amount in a year are used as an indicator for intense precipitation events. Days with maximum daily temperature above 35 °C – a standard threshold used to identify "hot" days – are never observed in ERA5 data used for this analysis.

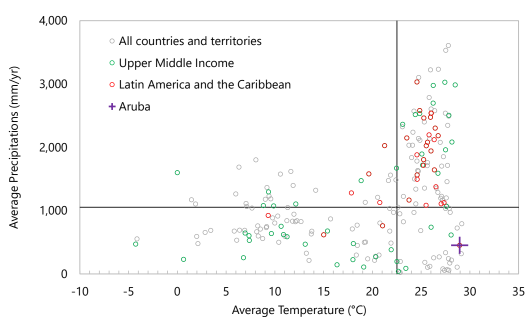
[7] We consider three emission scenarios. The SSP1-2.6 scenario is in line with the Paris goal to keep global mean temperature increase below 2 ºC with respect to pre-industrial times. SSP2-4.5 represents continuation of present trends. SSP3-7.0 is a high emission scenario. Changes in climate variables are calculated by comparing average values in 2036-2065 and 1985-2014 for each model/scenario combination, following IPCC standards. Projected changes are then rescaled using as a reference the estimated value of climate variables in 2021, to provide a more up-to-date assessment. For a discussion of IPCC scenarios, see Bellon and Massetti (2022a) and Massetti and Tagklis (2025).

Climate Data Store, 2021).[8] As a result of a strong regional drying dynamic (Appendix, Figure A.1), precipitation is projected to decline by between 6 and 12 percent in 2050 and by between 9 and 29 percent by the end of the century. The projected percentage reduction in precipitation is among the largest in the world, and more severe outcomes cannot be excluded (Figure 4). Models indicate potential additional risks from longer dry periods and episodes with extreme heat especially with high emissions scenarios, but uncertainty is large (Appendix, Figure A.2).

7. **Sea level is rising and will continue to do so for thousands of years, a risk that can be managed, but cannot be avoided.** With a moderate emission scenario, sea level is projected to increase by 0.71 m relative to its level in 2000 (Figure 5). Strong global emission cuts aligned with the Paris Agreement goal of limiting the global mean temperature rise to below 2 °C (RCP 2.6) will have a modest effect until 2050 but could limit SLR to 0.60 m by 2100 (Figure 5). Faster SLR caused by higher emissions and/or accelerated melting of the Greenland and Antarctic Ice Sheets could lead to a rise of 1 m or more by the end of the century. Due to the strong inertia in land ice melting, sea-levels will continue to rise for thousands of years even if global mean temperature stabilizes during this century (Box 1).

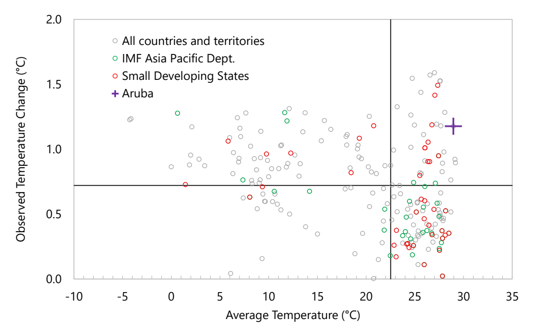
Figure 1. Climate Characteristics

Cross-Country Comparison of Climates (1984-2014)



Sources: FADCP Climate Dataset (Massetti and Tagklis, 2024), using CRU data (Harris et al., 2020).
Notes: Average annual temperature and precipitation during the period 1985-2014 from CRU. Solid lines display sample medians.

Observed Temperature Change (1985-2014 wrt 1901-30)

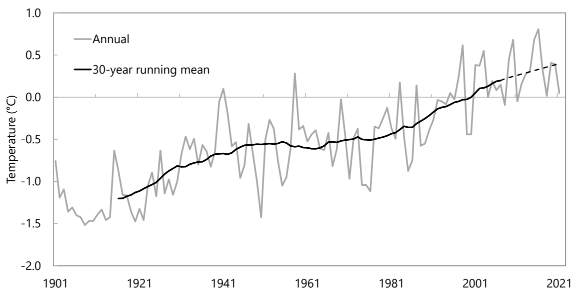


Sources: FADCP Climate Dataset (Massetti and Tagklis, 2024), using CRU data (Harris et al., 2020).
Notes: The observed temperature change 1985-2014 (2000) with respect to 1901-1930 (1915) can be used as a proxy of warming relative to the pre-industrial period..

[8] The 90th percentile of the SSP3-7.0 ensemble can be used to provide a high-emission, fast-warming, pessimistic case, with an increase of temperature equal to 2.4 °C at the end of the century relative to present levels, or 4 °C higher than its pre-industrial level.

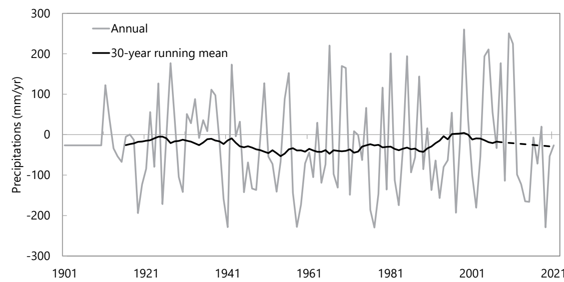
Figure 2. Historical Temperature and Precipitations

Annual Mean Temperature Anomaly (ºC)



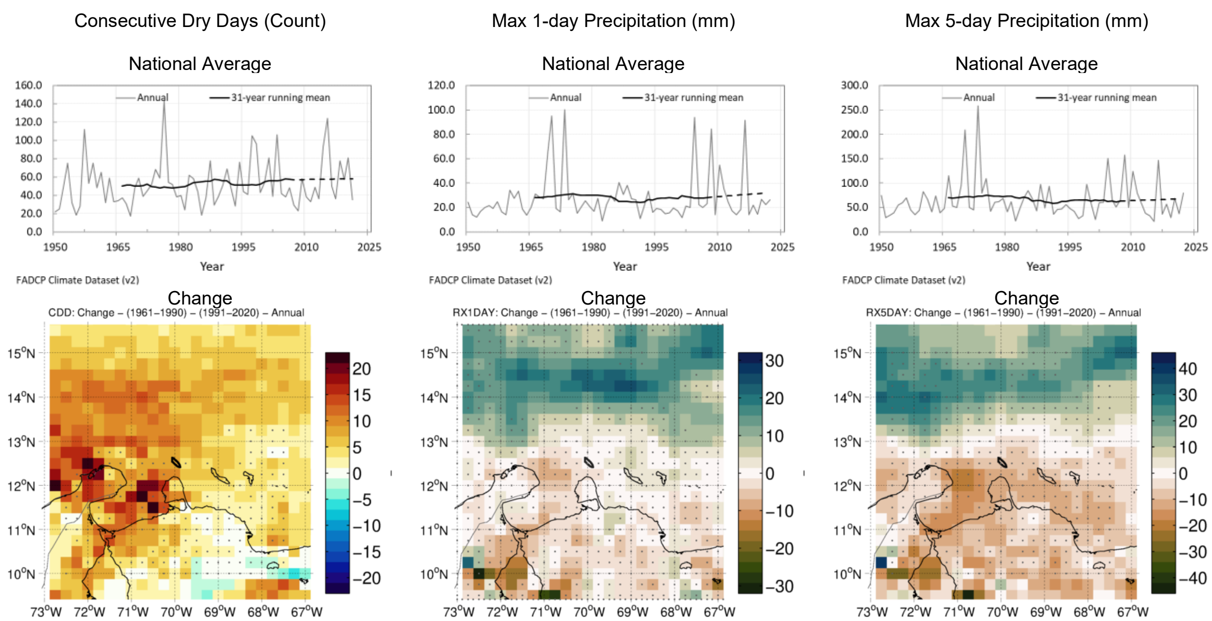
Sources: FADCP Climate Dataset (Massetti and Tagklis, 2024), using CRU data (Harris et al., 2020).
Notes: The solid gray line displays anomalies of annual mean temperature relative to the 1985-2014 average. The solid black line displays the 30-year moving average of these anomalies and is equal to zero in 2000. The first complete 15 years of the moving average are not shown because incomplete. The last 14 years show a linear trend estimated using the last 30 years of annual data (dashed).

Total Annual Precipitations Anomaly (mm/year)



Sources: FADCP Climate Dataset (Massetti and Tagklis, 2024), using CRU data (Harris et al., 2020).
Notes: The solid gray line displays anomalies of total annual precipitations relative to their 1985-2014 average. The solid black line displays the 30-year moving average of these anomalies centered around each year and is equal to zero in 1999. The first complete 15 years of the moving average are not shown because incomplete. The last 14 year show a linear trend estimated using the last 30 years of annual data (dashed).

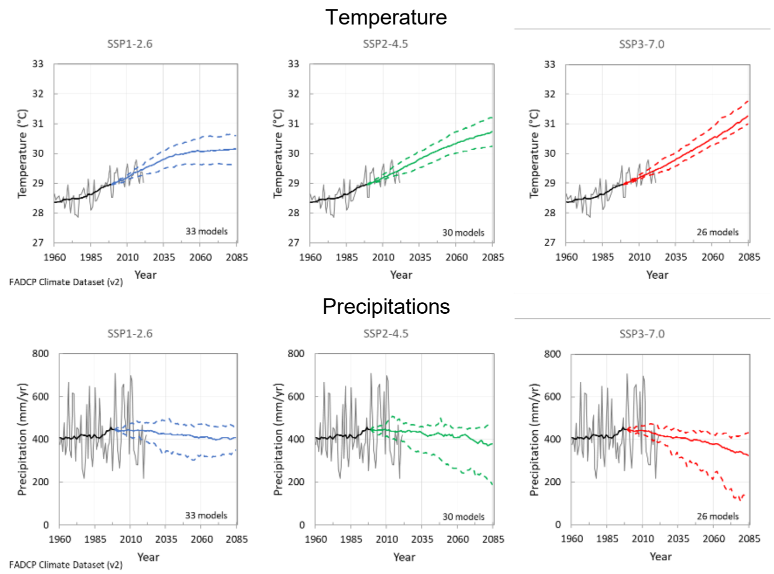
Figure 3. Historical Time Series of Selected Indicators of Extreme Weather



Source: FADCP Climate Dataset (Massetti and Tagklis, 2023), using ERA5 data [ref].

Notes: The solid line displays the 30-year average centered around each 30-year period. Edge effects near the beginning and end of the time series may affect the accuracy of the mean in those regions (dashed). Change: 1991-2020 relative to 1961-1990. Dots indicate grid cells with non significant change.

Figure 4. Historical and Simulated Annual Average Temperature and Total Annual Precipitations



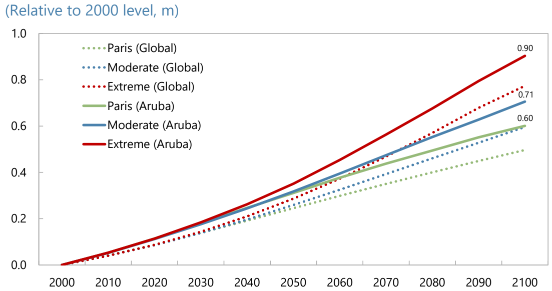
Source: FADCP Climate Dataset (Massetti and Tagklis, 2024), using CRU data (Harris et al., 2020), and CMIP6 data (Copernicus Climate Change Service, Climate Data Store, 2021: CMIP6 climate projections).

Notes: The gray line describes historical average annual temperature and total annual precipitation based on observations (CRU). The black line describes the 30-year moving average of historical data centered around each 30-year period. Colored lines represent the median and the 80 percent range of CMIP6 ensemble temperature anomalies (10th and 90th percentiles) added to the CRU value (thick black line in the year 2000). SSP1-2.6 scenario is in line with the Paris goal to keep global mean temperature increase below 2ºC with respect to pre-industrial times. SSP2-4.5 represents continuation of present trends. SSP3-7.0 is a high emission scenario.

Figure 5. Scenarios of Sea-Level Rise

Sea-Level rise, Aruba and Global

(Relative to 2000 level, m)

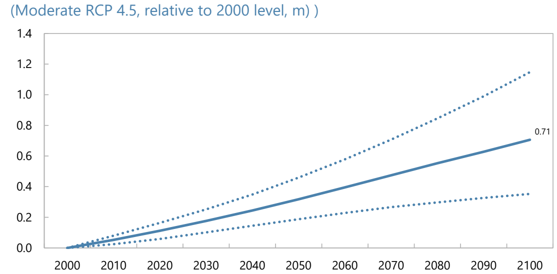


Sources: Sea-level rise projections from the CIAM model database (Diaz, 2016) based on data from Kopp et al. (2014).

Notes: (left) Local (solid) and Global (dotted) Sea-Level Rise (SLR) probabilistic projections until 2100 under three emission scenarios (Paris - RCP 2.6; Moderate - RCP 4.5; Extreme - RCP 8.5). Median SLR for each emission scenario.

Sea-Level Rise in Aruba

(Moderate RCP 4.5, relative to 2000 level, m))



Sources: Sea-level rise projections from the CIAM model database (Diaz, 2016) based on data from Kopp et al. (2014).

Local Sea-Level Rise (SLR) probabilistic projections until 2100 using the Moderate (RCP 4.5) emission scenario. Solid lines depict median SLR, dotted lines depict the 5th and 95th percentiles of the distribution to account for uncertainty in the speed of sea-level rise and tipping points in Greenland and Antarctica Ice Sheets melting.

Box 1. Sea-Level Rise: Drivers and Projections

The primary sources of global mean sea level rise (SLR) are thermal expansion directly caused by global warming and melting of land-based ice mass, most of which is in Greenland and Antarctica (Kopp et al., 2014). A slow but persistent response of ice masses to higher temperature will cause sea level to increase for centuries after global mean temperature stabilizes. As a result, there is no doubt that sea level will continue to increase but uncertainty remains on SLR speed and final extent. Thermal expansion and melting of the Greenland Ice sheet are projected to be the main sources of SLR this century with high confidence. The contribution to SLR of Antarctic Ice Sheet melting is instead very uncertain, going from slightly negative (due to increased snow accumulation) to very large (due to fast melting of Western Antarctica) (Kopp et al., 2014). Projections of global mean-sea level are useful to monitor global trends but are not accurate to predict local impacts and support adaptation decisions (Kopp et al., 2014; Diaz, 2016). Local SLR can differ from global mean SLR due to multiple factors, including local vertical land movement (for example, due to tectonics) (Kopp et al., 2014). The analysis of the cost of sea-level rise in this Annex relies on probabilistic local SLR projections, which account for regional SLR, local vertical land movements, and uncertainty in the range of SLR (Kopp et al., 2014; Diaz, 2016).

More recent projections of SLR (Fox-Kemper et al., 2021) are in line with those used for this analysis in Aruba (data at latitude 12° north and longitude -70°, from Garner et al., 2021). In Fox-Kemper et al. (2021), the SSP2-4.5 scenario is comparable to the RCP4.5 scenario in Kopp et al. (2014) and projects 0.65 m of SLR in 2100 in Aruba, instead of 0.60 m. The SSP5-8.5 scenario is comparable to the RCP 8.5 scenario and projects 0.86 m of SLR in 2100, while Kopp et al. (2014) project 0.90 m. The 95th percentiles of the SSP2-4.5 and SSP5-8.5 used for this analysis are five centimeters higher than the most recent projections. The new projections also consider a new low confidence (limited empirical evidence) scenario, with extreme emissions and extremely fast Antarctica Ice Sheet melting, which could lead to higher SLR than in the worst-case scenario used for this analysis.

III. Sea-Level Rise Impacts and Adaptation

8. **Aruba alone cannot control global sea level, but it can manage how SLR affects its highly developed and densely populated coastline by adapting**. Reducing global greenhouse gases emissions is crucial for limiting the rate of SLR this century and its overall extent in future centuries, but this is a process over which Aruba has little control. Adaptation plays a crucial role in limiting the unavoidable impacts of SLR on Aruba's economy and population this century. Macroeconomic risks from inaction are potentially very large.

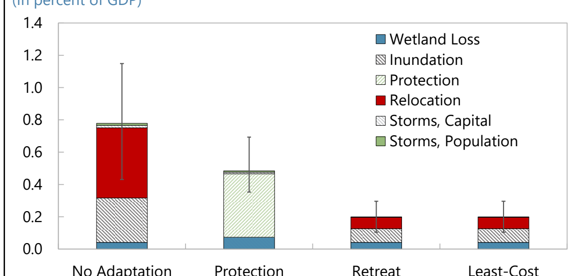
9. **SLR introduces new slow-moving risks and magnifies existing acute risks from floods and storm surges by impacting areas that house most economic activity and strategic assets**. A significant portion of Aruba's GDP is generated in a densely built and populated coastal area. Approximately 46 percent of all households live in coastal areas. Coastal population density is well over 1,000 residents per km^2, and coastal areas host at least 10,000 tourists per km^2.[9] Satellite data reveals an extremely high density of economic activities along a narrow coastal area with beachfront hotels and supporting services. The only airport on the island, all major industrial facilities, the major hospital, the only desalination plant are all located on the coastline, marginally above sea-level. As Aruba does not have redundant capacity to quickly replace these strategic assets, SLR can cause acute macroeconomic risks by exacerbating the impact of extreme rainfall and storm surges.[10] Lower fiscal revenues as a result of production losses, higher expenditure to replace damaged public assets, and lower capital inflows from reduced tourism can create risks related to balance of payments and long-term debt sustainability.[11]

10. **This calls for a long-term adaptation plan for SLR that is both effective in reducing risks and efficient in using Aruba's resources.** An exercise using the state-of-the-art CIAM model for SLR costs and adaptation (Diaz, 2016) illustrates potential costs of inaction, adaptation options, and costs. All details on the model and scenarios are provided in Box 2. This preliminary, highly stylized exercise can provide a blueprint for a more accurate assessment of risks and adaptation costs using hyper-resolution data and more precise cost estimates.

11. **The annual average cost of SLR without adaptation is estimated at approximately 0.8 percent of GDP from 2020 to 2099.** This central case assumes moderate emissions and median sea-level projections, but uncertainty regarding future emissions and the response of SLR to a warming planet is large. Using the full range of scenarios available, costs range between 0.4 to 1.4 percent of GDP annually, based on the lowest projection for the lowest emission scenario and the largest projection for the highest emission scenario, respectively. Most of the cost is attributed to permanent inundation and abrupt relocation costs. These costs represent welfare losses and are the appropriate metric for

Cost of Sea-Level Rise

(In percent of GDP)



Sources: IMF Staff calculations using the CIAM model (Diaz, 2016).
Note: Average annual cost 2020-2099. Whiskers on top of each bar indicate the range of total cost using the 5th and 95th percentile of the probabilistic distribution of sea-level rise. Due to the highly non-linear nature of coastal impacts, adaptation costs, and effectiveness of adaptation measures, ranges are not always symmetric around total costs.

[9] All data on coastal population density from Centrale Bank van Aruba (2020, p. 41).

[10] SLR complicates efforts to drain water in low-lying coastal areas and magnifies the impact of storm surge by bringing sea level dangerously close to existing protection levels under normal conditions.

[11] Centrale Bank van Aruba (2020, p. 39) estimates that net foreign assets decline by between 7 and 10 percent for at least four months after major flooding events. Persistent risks from SLR can cause a persistent decline of foreign assets.

estimating the full economic impact of SLR. However, they cannot be translated into GDP losses or other fiscal impacts without additional models or assumptions.[12] These losses do not include potentially large reductions in tourism revenues in the event of extensive coastal flooding. They also do not account for the incremental cost of pluvial floods potentially caused by SLR. As a comparison, Centrale Bank van Aruba (2020, p. 39) estimates that damages from major floods amount to between 1.5 and 2.1 percent of GDP per event. The central estimate of SLR costs implies damages equal to a major flood event every other year. These large costs can be substantially mitigated by adapting to SLR.

Coastal protection is estimated to reduce average annual costs of SLR from 0.8 to 0.5 percent of GDP from 2020 to 2099. These large costs can be substantially mitigated by adapting to SLR the model CIAM estimates that coastal protection needed to prevent inundation from sea-level and to minimize storm surge costs requires an annual investment of approximately 0.4 percent of GDP, annually, throughout the century. Coastal protections may exacerbate damages from pluvial floods by slowing the drainage of flooded areas, which could lead to higher investment needs than those estimated in this preliminary analysis. Coastal protection in the model consists of a mix of hard barriers (e.g., seawall, revetment, groyne, or breakwater)[13] and soft solutions, like beach nourishment. The economic value of wetland areas lost as a result of coastal protection is equal to 0.1 percent of GDP annually. The combined investment needs for coastal protection and the negative externality associated with wetland loss amount to 0.5 percent of GDP annually, representing the cost of SLR in this adaptation scenario. Adaptation reduces costs by approximately 40 percent compared to inaction.[14]

12. Planned retreat from the coastline can further lower the average annual cost of SLR to 0.2 percent of GDP from 2020 to 2099. Planned retreat relies on a proactive relocation of the population and a long-term strategy that lets assets exposed to permanent inundation to depreciate over time, followed by rebuilding in areas not exposed to coastal inundation. Thanks to this gradual process, capital losses and disruptions to the population can be contained. The long-term cost of this strategy is equal to the opportunity cost of land to which the population and assets move, plus any disutility from relocation and residual storm surge impacts.[15] CIAM estimates that the cost of planned retreat averages 0.2 percent of GDP between 2020 and 2099, which is less than half the cost of protection and 80 percent less than the cost of inaction.[16] This

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[12] The literature uses general equilibrium models to translate loss of capital and land into long-term macroeconomic impacts, including global trade effects (e.g., Bosello et al. 2012). Alternatively, it is possible to derive first-order approximations of the fiscal costs of SLR by assuming how much of the social cost of SLR is either directly borne by the public sector or compensated with public finances. Direct losses may derive from reconstruction costs of public assets and purchase of new land for public use. Losses of private capital and private land may have an impact on public finances if they affect tax revenues, or if the government compensates private losses. Increased spending on social programs aimed at easing disutility costs of relocation from inundated area can lead to higher expenses.

[13] Seawalls (vertical or near vertical) and revetment (sloped or gently angled) are structures made of concrete or stone to protect the coastline. A groyne is a structure made of rocks, cement or other hard materials built perpendicularly from an ocean shore to modify the water flow and capture sand or limit sand movement. A breakwater is a structure built offshore, designed to protect a harbor, coastline, or marina from the effects of waves and erosion.

[14] Non-market impacts are very uncertain, but they should be part of cost-benefit assessments to provide a full assessment of societal welfare impacts. Nature-based protection, for example coastal buffer zones with mangroves, can be cost-effective and have positive environmental externalities but it is not considered by CIAM because more granular data is needed to assess the viability and effectiveness of this strategy.

[15] CIAM follows Yohe (1990) and uses the value of interior agricultural or marginal land in the country to estimate the cost of inundated land.

[16] SLR is predicted to cause less damage in Aruba than in other Caribbean countries and territories. The median country suffers losses equal to 1.13 percent of GDP without adaptation, and equal to 0.3 percent of GDP with the least-cost adaptation strategy according to CIAM.

strategy can be implemented by rebuilding future generations of beachfront hotels in Aruba slightly farther away from the coastline, leaving space for beaches to slowly migrate inland. Areas immediately behind beachfront properties would need to be redeveloped. Long-term plans and coordination are key to the success of this strategy. In coastal areas not yet developed, planned retreat not allowing the construction of long-lived capital in areas exposed to SLR could be the least cost strategy. A coastal buffer with light infrastructure can create a safety perimeter for continued use of beachfront areas while incurring minimal opportunity costs.

13. **The fiscal implications of SLR depend on the role of the government in compensating losses and building protection.** In cases of inaction and of planned retreat, there are no direct costs for the government. If the government assumes full responsibility for all losses, including the adverse effects of relocation, the estimated losses in this analysis can be interpreted as an upper bound to government financing needs, ranging from 0.2 percent of GDP annually for of planned retreat to 0.8 percent annually for inaction. In the case of coastal protection, if the government is fully responsible for protection costs, public spending must increase by 0.4 percent of GDP annually, on average, between 2020 and 2099. In all these scenarios, if revenue and non-climate expenditure as a share of GDP remain constant, additional spending for adaptation leads to deficit and increasing debt

14. **The distributional impacts of SLR depend on exposure to SLR and policy choices.** The CIAM model does not provide information on the distribution of capital losses between the private and the public sectors. In cases of inaction or planned retreat, a substantial fraction of total costs will be suffered by the owners of coastal properties, manifested in accelerated capital depreciation, business disruption, disutility, and land depreciation. The private sector can effectively protect coastal properties in many cases, but private adaptation will likely be inefficient, as coastal property owners do not coordinate their actions and consider only private costs and benefits. This may result in negative externalities and cost diseconomies. For example, by investing in protections that increase coastal erosion in neighboring areas. Overall, there is a strong case for effective public coordination, as exemplified by the key role played by the government of the Netherlands in managing coastal defenses in a country that is in large part below sea-level.

15. **More granular data is necessary to precisely determine costs, protection needs, and retreat potential.** However, this preliminary analysis establishes a useful roadmap. CIAM has information on the average coastal slope for the entire island, but it does not capture coastal characteristics that will eventually determine if specific areas will be inundated or not, and whether retreat or protection are the optimal strategies. Hyper-resolution maps of elevation, currents, tides, infrastructure, and population must be developed as the basis for a more accurate assessment. The optimal adaptation strategy will consist of protection in some areas and retreat in other areas. Finally, while the model considers baseline erosion and vertical land movement, it does not capture the interaction of SLR with the ongoing coastal erosion processes in Aruba. Efforts to map climate risks with high resolution in the recently published Aruba Climate Impact Atlas are welcome as they allow for more accurate estimates of physical impacts and macroeconomic costs of climate change in Aruba.

16. **The cost-benefit analysis (CBA) framework used in this analysis can be empirically and methodologically challenging yet remains useful for identifying trade-offs and the most attractive policy options using a transparent and systematic approach.** Best practices can be drawn from coastal protection analysis and policies in the Netherlands, where there is a long-standing tradition of using CBA and cost-effectiveness analysis for flood risk management and water governance. This tradition started in 1954 with the pioneering CBA of the Delta Works by Tinbergen (1954) and continues to this day (Bos and Zwaneveld,

2017). The strong ties between Aruba and the Kingdom of the Netherlands can be leveraged to help the country find the most suitable engineering solutions and the most cost-effective adaptation strategies.

Box 2. Estimating the Cost of Sea-Level Rise and Adaptation

The analysis of sea-level rise impacts, and adaptation options is done using complex models that rely on necessary simplifications but provide important insights. While there is uncertainty on the exact extent and cost of damages from SLR and on the cost of protection measures, there is consensus in this literature that long-term planning of adaptation can be highly effective at containing physical impacts and costs of SLR. For example, the large EU-funded research project PESETA IV finds that coastal protection can reduce SLR damages in the EU by approximately 90 percent (Vousdoukas et al. 2020, Table 6). Model simulations fully agree that adaptation can be highly effective but may differ on the optimal mix of adaptation measures – e.g., hard protection, nature-based solutions, planned retreat – because they use different data, use different climate scenarios, or work under different normative criteria. There is also consensus that the transformations needed to adapt to SLR, while technologically feasible and economically sound, are complex and require strong governance (Hinkel et al., 2018).

IMF staff uses the state-of-the-art Coastal Impact and Adaptation Model (CIAM) to estimate the cost of sea-level rise under alternative adaptation strategies. CIAM is a global model used to estimate the economic cost and benefits of adaptation to sea-level rise (Diaz, 2016). The global coastline is divided into more than 12,000 segments of different length grouped by country. Aruba's coastline is only approximately 70 Km long and is considered as a single coastal segment in CIAM. The coastline is further divided into areas of different elevation. The model has data on capital, population, and wetland coverage at different elevations for the entire coastal segment. By using projections of local sea-level rise from Kopp et al. (2014), it is possible to estimate the areas that will be inundated and the amount of capital and population at risk. Storms cause periodic inundations on top of sea-level rise. The model does not consider increased risks from river floods.

The model calculates the cost of SLR—protection costs plus residual losses—under alternative adaptation options:

The ***no-adaptation*** scenario assumes that population does not move until the sea inundates the area where they live and then relocates to areas with higher elevation. Society keeps building and maintaining capital until inundation causes irreversible losses and capital is abandoned. The cost of sea-level rise is calculated as the sum of the residual value of capital that is abandoned, demolition costs, and the value of land that is inundated. The model uses the rental value of agricultural land in proximity to the coastline, following Yohe et al. (1990), because as SLR progresses, coastal proximity rents will shift from land that is inundated to adjacent land. Population density and development opportunity costs are assumed to be capitalized in agricultural land values. The disutility cost of reactive migration is monetized.

At the opposite, a ***protection*** scenario assumes that society invests in cost-effective seawalls and other barriers along the entire coastline to avoid inundation from sea-level rise, but storms can still periodically inundate protected areas if protection is not sufficiently high. Capital and land are not lost, the population does not move, but storms periodically cause capital and human losses. The cost of SLR is equal to the cost of protection plus the expected value of the cost of storms.

Another adaptation option relies on ***planned retreat*** from areas that will be subject to inundation. The goal of retreat is to keep using coastal areas without building new capital and by letting the existing capital depreciate. For example, a coastal road is used until it needs major retrofitting investment. Then, a new coastal road is built inland on higher grounds. This strategy accepts that land and some residual value of capital will be lost, but it avoids coastal protection costs. The population gradually moves to higher grounds before areas are inundated. This usually does not require migration to distant places, but rather relocation within the same coastal area. The cost of SLR is equal to the sum of the residual cost of capital, the value of inundated land, and the disutility cost of relocation.

Box 2. Estimating the Cost of Sea-Level Rise and Adaptation (concluded)

The model considers variants of protection and retreat scenarios to deal with risks from storm surge floods. For example, the model calculates the height of the coastal protections to contain SLR and increasingly large storm surges (1/10, 1/100, 1/1,000 and 1/10,000 year events). In the base scenario (Retreat 1), the retreat perimeter is calculated to only deal with permanent inundation of land, but the retreat perimeter can be pushed to also avoid storm surges (from 1/10 to 1/10,000 year events).

For each coastal segment, the model calculates the net present value of SLR costs for each adaptation strategy. Loss of life is monetized using the Value of Statistical Life and loss of wetland due to either SLR or protection of barriers that impede the normal circulation of tidal waters is monetized using estimates of willingness to pay for biodiversity preservation.

The cost of building and maintaining seawalls, and other key parameters are from the literature. Storm surge costs are incremental with respect to a baseline scenario in which storms occur without SLR.

By comparing SLR costs across all scenarios it is possible to find the least-cost adaptation strategy for each coastal segment and to calculate the lowest possible cost of SLR for the country. Coastal protection is usually the least cost strategy in areas with large existing capital and high population density. Planned retreat is usually the least-cost strategy in areas with low capital and population density. The optimal height of coastal protection infrastructure and the optimal retreat perimeter vary on many factors, including projected incremental costs of protection, the opportunity cost of not using land that would normally not be flooded, capital and population at risk, sea-level rise scenarios.

Despite many uncertainties and some necessary simplifying assumptions, CIAM provides a useful framework to systematically study costs and benefits of alternative adaptation strategies to SLR. More granular coastal modeling and more accurate mapping of assets can provide a more precise assessment of costs and benefits, but the key insights developed with a baseline version provide a useful starting point to deal with a complex, multidecadal challenge.

IV. Lessons for Efficient Adaptation Spending

17. **Total adaptation investment needs in Aruba are difficult to predict due to many uncertainties in predicting climate change impacts and optimal responses across multiple sectors.** Estimated investment needs against SLR can serve as a lower-bound for total adaptation spending. Private and public expenditure in energy for cooling purposes is expected to increase and is a form of adaptation to higher temperatures. Investment needs to improve stormwater drainage are harder to assess. Increased desalination capacity may be needed to respond to both higher temperatures and decreased rainfall.

18. **While estimating with precision what should be done, and at what cost is difficult, it is possible to build a roadmap for efficient adaptation policies by starting from important general principles.** IMF Staff has developed guidance to help countries adapt by integrating adaptation to climate change in macro-fiscal planning (Gonguet et al. 2021; Bellon and Massetti, 2022a,b; Aligishiev, Bellon, and Massetti, 2022; Sakrak et al. 2022). These principles frame adaptation in terms familiar to economists and position it in the broader context of economic development. They may serve as a framework to inform the efforts of the newly established National Climate Resilience Council (NCRC) in formulating a comprehensive National Action Plan.

19. **Adaptation would be most effective if it is an integral part of sustainable development planning.** In the Paris Agreement (Article 7), adaptation is established as “the global goal of enhancing adaptive capacity,

strengthening resilience and reducing vulnerability to climate change, with a view to contributing to sustainable development." Investments in climate change adaptation are similar to other investments in development because their common goal is to maximize future welfare given the available resources (Bellon and Massetti, 2022a).

20. With many competing needs, the government of Aruba must carefully allocate resources across all possible uses, including adaptation to climate change, while considering the distributional effects of its programs. This requires: (i) concentrating government efforts and resources in key areas; and (ii) collecting information on how effective spending is across alternative programs and how spending affects distinct groups in society (Bellon and Massetti, 2022a).

21. The government can prioritize adaptation policies with positive externalities, as shown in the case of adaptation to SLR. Individuals and firms have strong incentives to adapt because many adaptation benefits tend to be local and private. However, there is a clear role for government intervention when adaptation has large externalities, as discussed in the case of coastal protection or for strengthening public infrastructure.

22. Despite limitations, cost-benefit analysis (CBA) can play an important role in helping decision makers to consistently collect, aggregate, and compare information on public adaptation projects. As exemplified by the analysis of SLR, adaptation investment and policy will typically have trade-offs that would be better assessed by comparing social costs and benefits using a systematic approach. What to do, when, how, and at what cost ultimately relies on ethical choices that should reflect the preferences of each society. However, cost-benefit analysis (CBA), complemented by analysis and correction of distributional impacts, can help decision makers maximize overall social welfare by avoiding wasting scarce resources. To achieve this goal, it is essential that CBA is applied to adaptation as well as to all other development programs in a consistent manner (Bellon and Massetti, 2022a).

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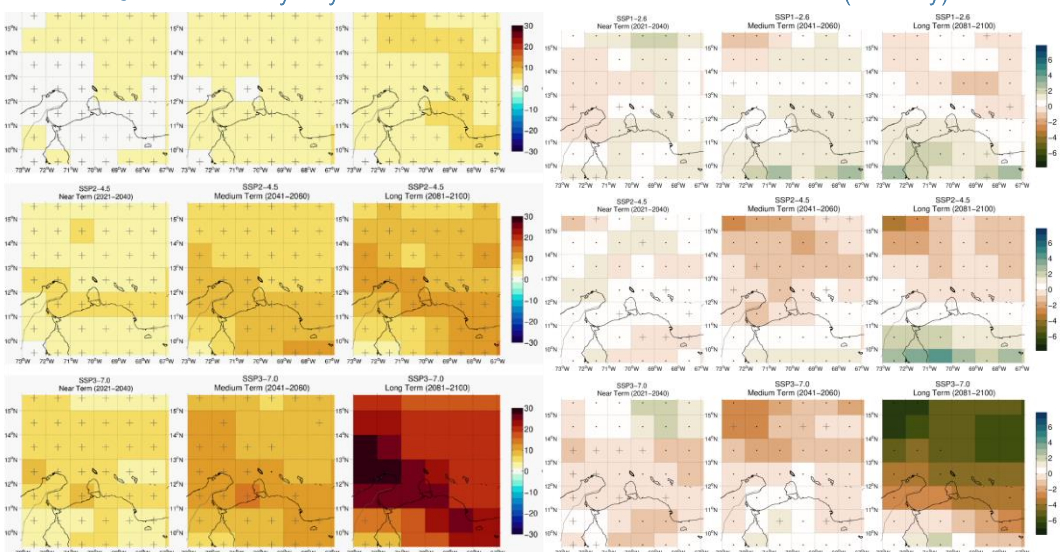
Annex I. Maps of Simulated Changes

Annex I. Figure A1. Maps of Simulated Changes for Indicators of Droughts and Intense Precipitations

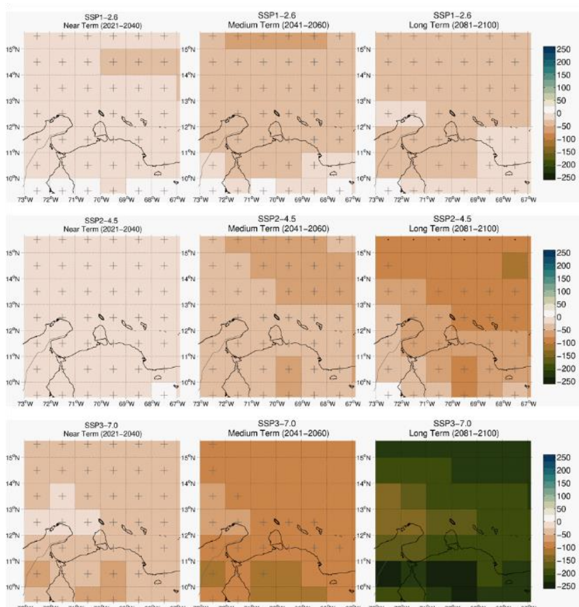
Consecutive Dry Days | Intense Rainfall (RX1Day)



Source: FADCP Climate Dataset (Massetti and Tagklis, 2024), using CMIP6 data (Copernicus Climate Change Service, Climate Data Store, 2021: CMIP6 climate projections).

Notes: Crosses indicate areas in which models disagreen on both the magnitude and sign of precipitation changes. Dots indicate areas in which most models agree on the direction of change, but it cannot be excluded with high confidence that no change or change of a different sign is possible.

Annex I. Figure A2. Maps of Simulated Changes for Total Annual Precipitation



Source: FADCP Climate Dataset (Massetti and Tagklis, 2024), using CMIP6 data (Copernicus Climate Change Service, Climate Data Store, 2021: CMIP6 climate projections).

Notes: Crosses indicate areas in which models disagree on both the magnitude and sign of precipitation changes. Dots indicate areas in which most models agree on the direction of change, but it cannot be excluded with high confidence that no change or change of a different sign is possible.

Annex I. Table A1. Aruba: Sea-Level Rise Projections Relative to 2000 level (meters)

	2030	2050	2070	2100
Global Mean				
Paris (RCP2.6)	0.14 [0.10 , 0.18]	0.25 [0.18 , 0.33]	0.35 [0.23 , 0.51]	0.50 [0.30 , 0.82]
Moderate (RCP4.5)	0.14 [0.10 , 0.18]	0.26 [0.18 , 0.35]	0.39 [0.26 , 0.56]	0.60 [0.35 , 0.94]
Extreme (RCP8.5)	0.14 [0.11 , 0.18]	0.29 [0.21 , 0.38]	0.47 [0.33 , 0.66]	0.77 [0.51 , 1.19]
Aruba				
Baseline	0.02 [-0.03 , 0.07]	0.04 [-0.04 , 0.12]	0.05 [-0.06 , 0.17]	0.08 [-0.09 , 0.24]
Paris (RCP2.6)	0.18 [0.10 , 0.26]	0.31 [0.19 , 0.45]	0.44 [0.24 , 0.67]	0.60 [0.31 , 1.01]
Moderate (RCP4.5)	0.18 [0.10 , 0.25]	0.32 [0.19 , 0.46]	0.47 [0.27 , 0.71]	0.71 [0.35 , 1.15]
Extreme (RCP8.5)	0.18 [0.11 , 0.26]	0.35 [0.21 , 0.50]	0.56 [0.34 , 0.83]	0.90 [0.53 , 1.40]

Source: Sea-level rise projections from Kopp et al. (2014) derived from the CIAM model database (Diaz, 2016).

Notes: Global and Local Sea-Level Rise (SLR) probabilistic projections until 2100 under three emission scenarios (Paris - RCP 2.6; Moderate - RCP 4.5; Extreme - RCP 8.5). The range in brackets represents the 5th and 95th percentiles of the distribution of SLR for each emission scenario. Local SLR projections include information on local climate change induced SLR rates and a baseline projections of local vertical land movement (subsidence or uplifting) not caused by climate change.