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Past and future sea level around the BES islands

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PAST AND FUTURE SEA LEVEL AROUND THE BES ISLANDS

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SUMMARY

In this short report I provide an overview of the recent evolution of sea level and the state of the art future projections for the BES islands. Since there are no long tide gauge records available for the BES islands I use data from satellite altimetry available since 1993 to analyse past sea level. I find important month-to-month and year-to-year variability and a linear trend of 3.3 mm/yr at Bonaire and 2.9 mm/yr at Sint Eustatius and Saba which is close to the global sea level of 3.4 mm/yr over the same period. The analysis of the longest tide gauge record of the region starting in 1955, located in Puerto Rico, shows important multi-decadal variability, faster sea level rise measured by the tide gauge than by the satellite altimetry and an acceleration of sea level rise over time. Sea level projections from the latest Intergovernmental Panel on Climate Change reports are between 30 cm and 120 cm in 2100 compared to the reference period 1986-2005. Sea level at the BES islands is expected to rise a little bit faster than globally averaged sea level. Sea level rise will continue after 2100 in all scenarios. However, the ability of global climate models to make reliable sea level projections in the Carribean Sea region has been questioned recently because ocean eddies might be important to set the regional pattern of sea level change. This argument is in line with the different sea level rise pattern observed by satellite altimetry and projected by climate models for the end of the century which is described in this report. I propose possible further research directions to improve the understanding of past sea level changes in the region and improve the reliability of projections.

CONTENTS

1 INTRODUCTION

Global sea level rise is accelerating because of global warming [1]. Sea level rise in the 20th century had an average speed of 1 to 2 $mm/year$ [2, 3]. It was the fastest in the last 3000 years [4]. Sea level rise continues to accelerate and reached 4.3 $mm/year$ on average over the last 10 $years$ [5]. The main drivers

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of sea level rise are: thermal expansion, melting of glaciers all around the world and more recently the melting of Greenland and Antarctica, the two large ice sheets.

Sea level rise is important because a large part of human activities worldwide take place along to the coast. This is especially the case in islands like Bonaire, Sint Eustatius and Saba. It was recently shown that 10 to 20% of the economic damages from hurricane Sandy in the US east coast were due to sea level rise [6]. This is an example illustrating the fact that sea level rise already has an impact now. As sea level continues to rise it will have a growing impact on human societies around the world and challenge their ability to adapt [7, 8]. This issue is now internationally recognised as the Intergovernmental Panel on Climate Change (IPCC) published the Special Report on the Ocean and the Cryopshere in a Changing Climate (SROCC) in 2019 [9].

Many physical processes lead to differences between local and global sea level change [10]. For example, because of changes in the gravity field of the earth, when land ice melts, sea level rise is larger far away from the melt area. This is often found counter-intuitive. Other factors like changes in the earth rotation and the deformation of the earth's crust also have an influence so this rule of thumb is not always valid. An application of this simple rule is that for the Netherlands the future of Antarctica is more important than the future of Greenland [11]. However, since the BES islands are relatively far away from ice sheets and glaciers they are not largely affected by the gravitational effect.

Sea level is observed using multiple complementary instruments: tide gauges, satellite altimetry and geological proxies. In this report I analyse data from satellite altimetry and from one tide gauge in Magueyes Island, Puerto Rico. That tide gauge record is the longest in the region, with only few interruptions, covering the period 1955 to 2020.

Sea level rise in the 21^{st} century will be larger than in the 20^{th} century. The uncertainty in sea level projections has increased recently because the mass loss from Antarctica and Greenland could be faster than previously estimated [12]. There are now three main uncertainties in sea level rise projections: the total emissions of greenhouse gases, the speed at which the ice sheets will melt in a warming climate and the way that the ocean circulation will reorganise. Here I present the latest sea level projections for the BES islands from the IPCC SROCC and AR6 reports [9, 13] and compare these projections with global sea level projections.

2 PAST SEA LEVEL RISE GLOBALLY AND AT THE BES ISLANDS

Over the last 3000 years global sea level rose at a slow rate of between 0 and $0.2\,mm/yr$ caused by the transition from the last glacial period to the present interglacial (Holocene) [14]. From the late 19th century or beginning 20^{th} century this relatively slow rate accelerated to a larger rate of over $1\,mm/yr$ [15, 1]. As a result, 20th century sea level rise was the fastest in the last 30 centuries [1, 4]. This is mostly due to anthropogenic greenhouse gas emissions warming the earth [16]. Different reconstructions of sea level based on tide gauge measurements show that sea level rise during the 20th century was between 1 and $2\,mm/yr$ [2, 3]. The global mean rate of sea level rise since global satellite altimetry measurements started in 1992 is around $3.1\,mm/yr$ [5] with a detectable acceleration during that period [17]. Over the satellite altimetry period (1992-present) the drivers of sea level rise are known with a good accuracy: thermal expansion ($1.3\,mm/yr$), glaciers ($0.7\,mm/yr$), Greenland ($0.5\,mm/yr$), Antarctica ($0.3\,mm/yr$) which gives a total trend of $2.7\,mm/yr$. The discrepancy between this sum of contributors and the observed rate is $0.4\,mm/yr$. It is probably due to terrestrial water storage that is not included in the budget because it is highly uncertain [5] but it could also be due to an underestimation of past Antarctic mass loss [18].

Sea level rise is not uniform over the globe. The linear sea level trend over the satellite altimetry period shows that most places have seen a sea level rise close to the global mean (see top panel in figure 1). However, large areas of the ocean are rising much faster or slower. In the South Atlantic ocean there is an area where sea level rose with more than $6\,mm/yr$ while in the North Atlantic an area south of Greenland didn't see much sea level rise. These differences are mostly due to a change of the ocean circulation associated with salinity and temperature changes. When water becomes warmer or fresher (e.g. less saline) it expands and locally sea level rises. In the tropical Atlantic, where the BES islands are located, the rise has been relatively uniform and close to the global mean. However, when we zoom in as in the bottom panel of figure 1 some spatial heterogeneities appear. There is a difference of up to 2 mm/yr between the north of the Caribbean Sea and the coast of Venezuela and Guyana. These differences might be due to natural variability of the ocean temperature and salinity.

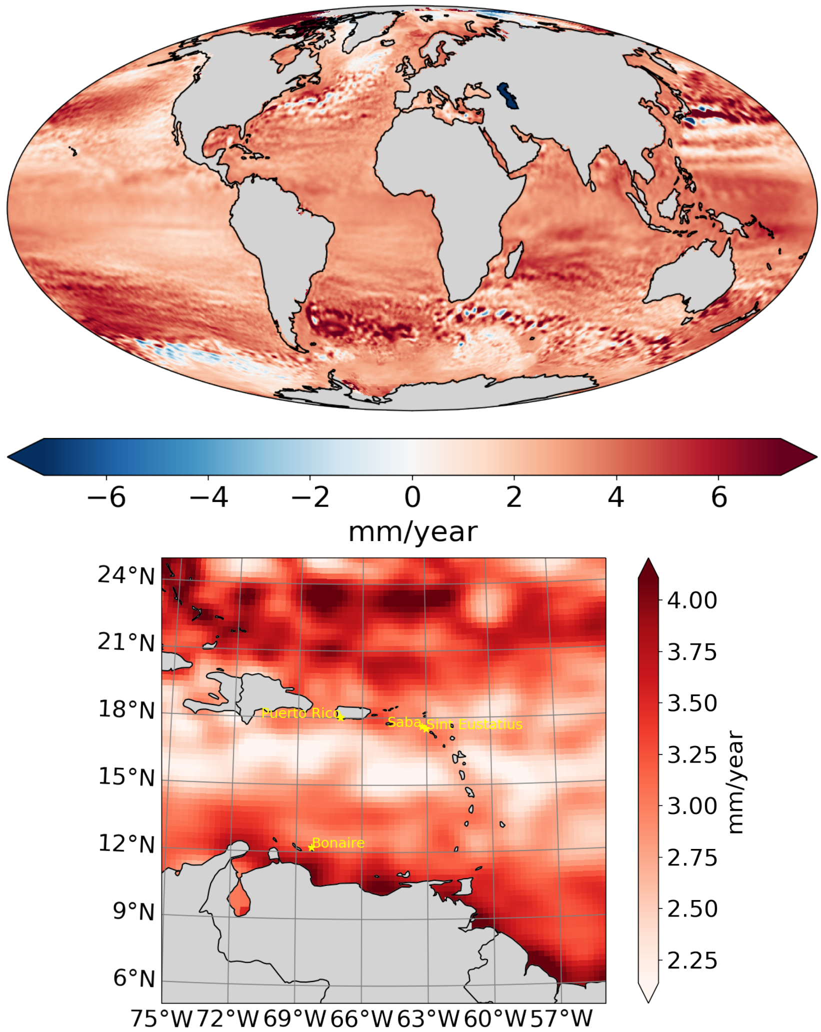

Figure 1: *Top panel*: Global linear sea level trend computed from satellite altimetry data from 1993 to 2019. *Bottom panel*: Zoom on the region of the Caribbean sea with the location of the the BES islands and the tide gauge at Puerto Rico.

There are no tide gauge data from the BES islands in the PSMSL database. However, there is a long, mostly uninterrupted, tide gauge record from Magueyes Island, Puerto Rico extending back to 1955 (see location in bottom panel of figure 1 and time series in 2). I use monthly averaged data downloaded from the PSMSL website (see section 6 for further information) to plot time series. The time series in the top panel of figure 2 show a large month-to-month variability with up to 15 cm variations from one month to the next. A long term sea level rise is also visible from the monthly data. On the bottom panel, where yearly averages are computed, the long term trend is even clearer. We see a fast sea level rise between 1955-1985 a plateau between 1985-2005 and continued rise after 2005. This could be due to natural climate variability in wind or local steric effects, but it could also be due to some missing data. There are 13 months of missing data between 1979 and 1982 out of a total of 36 missing months over the full time series. On the bottom panel of figure 2, I also compare tide gauge sea level observations to the satellite altimetry observations close to the tide gauge location. It is important to note that satellite altimetry and tide gauge do not measure exactly the same quantity. Tide gauges measure sea level relative to the ground where they are lying while satellite altimetry measures sea level compared to an ellipsoidal surface of reference that is fixed in time. Therefore if the ground where the tide gauge is located moves up or down this will influence the observations from tide gauges but not from satellite altimetry. Over the period 1993 to 2019, the overlapping period between satellite altimetry and tide gauge observation, there seem to be a reasonable agreement between the two measurements. However, the inter-annual variability of sea level seems to be smaller in the satellite measurements. This could be due to some very local wind effects at the coast that are only measured by the tide gauge. The trend over the overlapping period is also smaller in satellite altimetry measurement, with 2.8 ± 0.6 mm/yr than at the tide gauge, with 3.9 ± 0.6 mm/yr. More details about the uncertainties is given in section 7. This difference could be due to vertical land motion. Some local subsidence at the tide gauge location would increase the sea level trend measured there but would not have an effect on satellite measurements. The long term linear trend from 1955 to 2020 is 1.9 ± 0.2 mm/yr which indicates that sea level rise has accelerated in this region.

We now turn to the analysis of satellite altimetry measurements at the BES islands. Monthly and yearly time series are shown in figure 3. The distance between Saba and Sint Eustatius is small compared to the resolution of satellite altimetry measurements so sea level observations are almost the same along the coast of those two islands and we only show a monthly time series for Saba. At both Bonaire and Saba, there is a clear annual cycle of sea level with a peak-to-peak difference of around 10 cm. There is more variability in monthly sea level at Bonaire than at Saba. This could be due to a variability of the Caribbean current. The annual mea sea level for the three BES islands and global mean sea level is shown in the bottom panel of figure 3. Sea level can vary by up to 4 cm from one year to the next. The linear trend over the full period is 3.3 ± 0.4 mm/yr at Bonaire and 2.9 ± 0.5 at Sint Eustatius and Saba which is close to the global sea level rise of 3.4 ± 0.4 mm/yr.

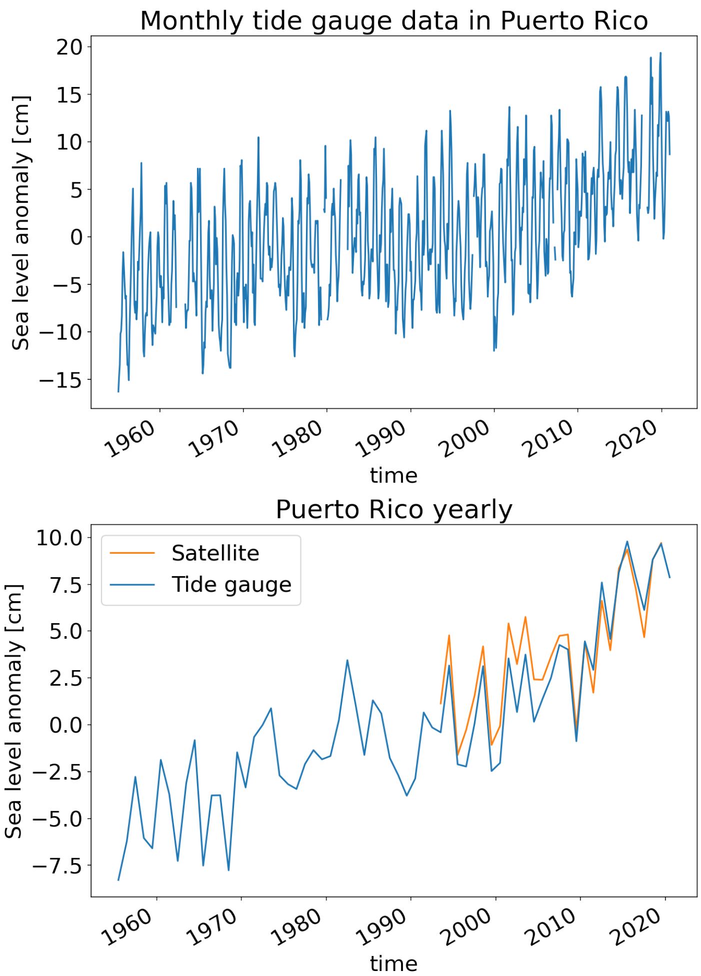

Figure 2: *Top panel*: Time series of monthly sea level anomalies at Magueyes Island, a tide gauge in Puerto Rico, with data extending back to 1955. Bottom panel: Yearly averaged sea level from tide gauge and satellite altimetry measurements at the same location. The vertical reference for both time series is arbitrary so only the time anomalies can be compared, not the absolute levels.

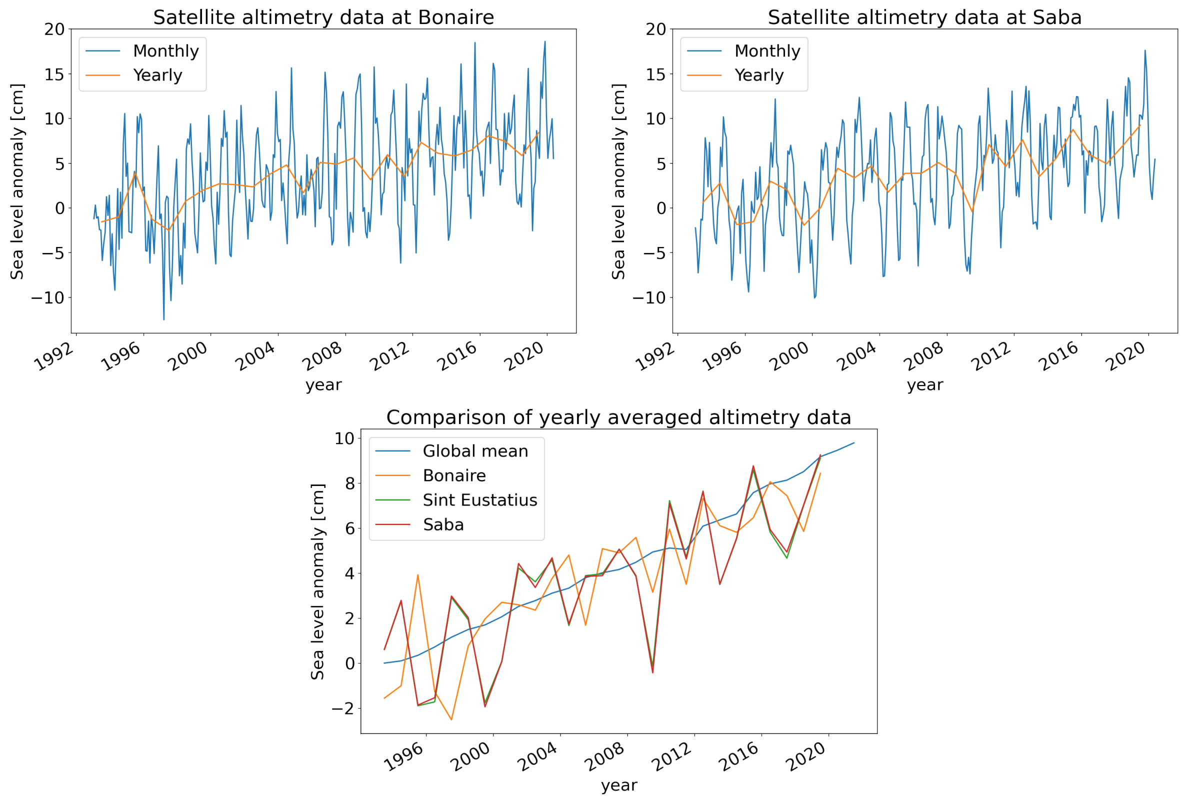

Figure 3: *Top panels*: Time series of monthly and yearly sea level anomalies in Bonaire (left) and Saba (right). *Bottom panel*: Comparison of yearly average sea level at the BES islands and for the global ocean.

3 SEA LEVEL PROJECTIONS GLOBALLY AND FOR THE BES ISLANDS

To know how much sea level we can expect in the future it helps to have an idea of the potential maximum contribution from the different sources of sea level: Antarctica $58\,m$ [19], Greenland $7.4\,m$ [20], glaciers and ice caps $0.4\,m$ [21]. Thermal expansion does not have a maximum but a reasonable order of magnitude is that over long time scales (millennia) an increase of the earth surface temperature by 1°C is associated with a sea level rise of $0.4\,m$. We note here that sea ice, the thin ($<5\,m$) layer of ice that forms at the surface of the ocean at the poles, does not contribute significantly to sea level rise when it melts because it is already floating.

Sea level projections for the 21^{st} century depend on three major unknowns: (1) the amount of greenhouse gases that will be emitted, (2) the speed at which the ice sheets will adapt to the warmer climate and (3) the reorganisation of ocean currents. This is why different scenarios are developed and used to help users of sea level information make the best decisions.

Global changes in sea level in 2100 are shown in the top panel of figure 4. This is under a medium climate change scenario (RCP4.5) which leads to a global averaged temperature increase of 2.4°C by the end of the century (2080-2100) compared to the pre-industrial period (1850-1900) [22]. In this case, sea level rise in most places is close to $50\,cm$. However, there are exceptions, for example close to the Greenland and Antarctic ice sheets sea level rise is slower [23]. From this global map we also see that the BES islands are expected to have a sea level rise similar to most places in the world. Zooming in on the Caribbean Sea in the lower panel of figure 4, we see that sea level rise in the region varies between around 55 and 60 cm in 2100 compared to the period 1986 to 2005.

I also present time series of sea level projections for Saba in figure 5. On the left panel, the SROCC projections [9] and on the right the AR6 projections [13]. The SROCC projections stop in 2100 while the AR6 ones go up to 2150. For both IPCC projections, the range of uncertainty in 2100 covers 30 cm up to 120 cm. With 30 cm being a very optimistic future in which the emission of greenhouse gases follow the Paris agreement and the climate and sea level are less sensitive than expected by current models.

On the other hand 120 cm would be for a future of continuous fast increase in greenhouse gas emissions and a climate and sea level that would be more sensitive to emissions than expected. The dashed lines in the left panel show the global mean sea level projections. We see that local sea level is expected to rise a little faster than global mean.

An important fact to keep in mind is that sea level will continue to rise after 2100, this is shown by the AR6 projections that stop in 2150. In 2050 the extreme upper bound of the projections is above 200 cm. Sea level will continue to rise for thousands of years even if the concentration of greenhouse gases in the atmosphere does not increase. Current estimates are that over millennial time scale sea level rises by 2 to 10 m per degree of global warming [24, 25]. This means that even if the world is successful in meeting the Paris agreement and limiting global warming to 1.5° to 2°C sea level will eventually rise by 3 to 20 m.

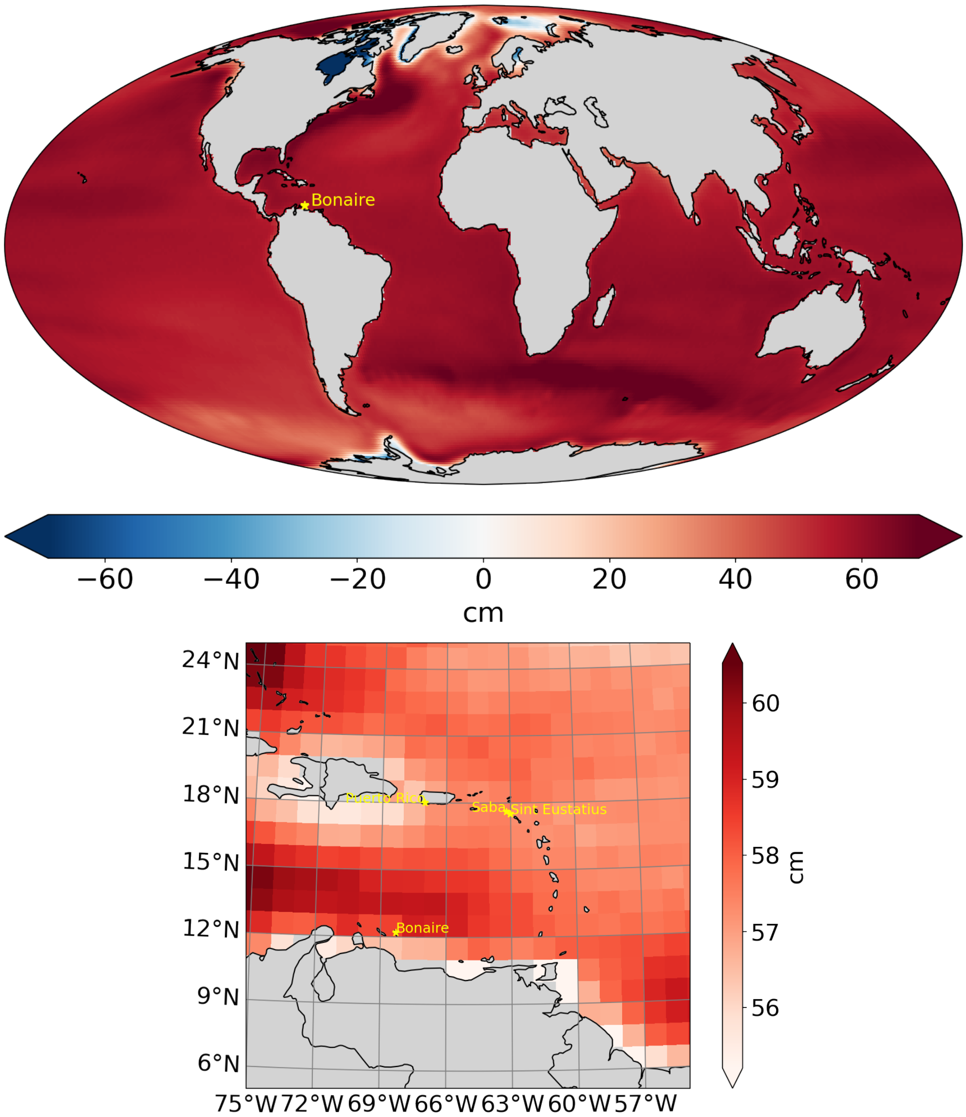

Figure 4: *Top panel:* Map of the median sea level projections from the IPCC SROCC report in 2100 compared to the reference period 1986-2005 under the RCP45 scenario. *Bottom panel:* Zoom on the BES islands region.

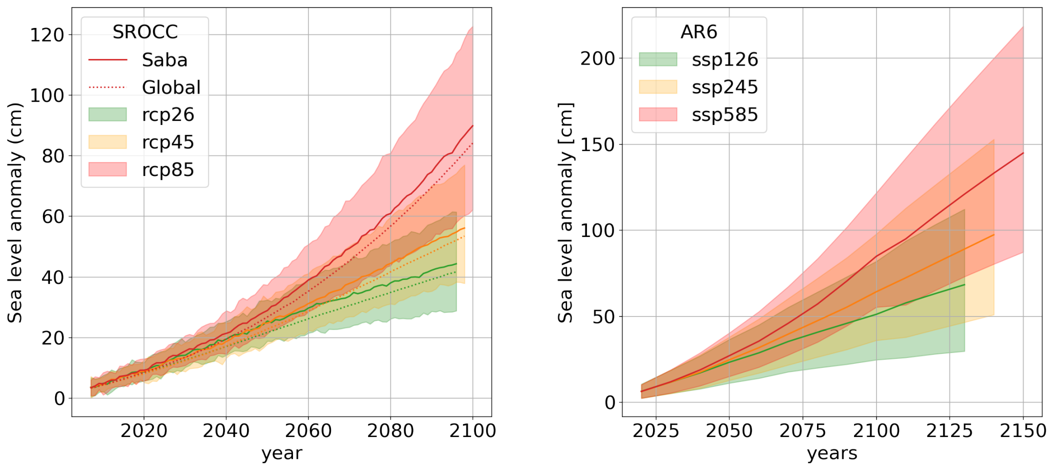

Figure 5: *Left panel:* time series of sea level for three RCP scenarios with reference period 1986-2005. Bold lines and uncertainty ranges are for Saba while dashed lines are for the global sea level. The bold and dashed lines show the medians while the uncertainty range is representing the likely range (17th to 83rd percentiles). *Right panel:* Same but for the AR6 sea level projections that extend up to 2150 and have a reference period of 1995-2014. The global mean is not shown in this panel.

4 CONCLUSION AND DISCUSSION

In this report I used tide gauge observations from Puerto Rico and satellite altimetry observations from the BES islands, the Carribean Sea and globally. I described that during the satellite altimetry period (1993-now) most of the Carribean Sea saw an average sea level rise close to the global mean of 3.4 mm/year but there are still some regional variations with linear trend between 2 and more than 4 mm/yr. For the BES islands the linear trend in sea level rise is 3.3 mm/yr at Bonaire and 2.9 mm/yr at Sint Eustatius and Saba.

Future projections from the SROCC and AR6 IPCC reports show that future sea level rise at the BES islands will be just a few centimetres higher than global mean sea level rise in 2100. There is a large range in future projections, between 30 cm and 120 cm in 2100 compared to the reference period 1986-2005. Sea level rise also continues after 2100 and AR6 projections have an upper bound of the uncertainty range above 200 cm in 2150.

The observed pattern of sea level rise during the altimetry period in the Carribean Sea (bottom panel figure 1) is noticeably different from the pattern seen in the projections (bottom panel figure 4). This could be due to the natural variability but it could also point to shortcomings in the climate models from CMIP5 to project realistic ocean dynamics. The importance of resolving ocean eddies in this region for realistic sea level projections was argued by [26]. In that case a resolution of 0.1^{o} would be necessary instead of the usual 1^{o} of ocean climate models. The uncertainty in the change of atmospheric circulation forcing the ocean has not been investigated yet but could also play an important role.

To write this report I only made used of general and easily available information and I did not consider the particular needs of decision makers in the BES islands. Nevertheless it is known that all decision makers do not need the same kind of information and that co-producing the information is often beneficial [27]. This approach was not used for this report because this is a long process that requires time investment from both the scientists and decision makers but this report could be a first step in that direction.

This report focuses on mean sea level exclusively, I did not cover the subject of extreme events while these are the moments when the impacts of sea level rise like floods, erosion and salt intrusion are felt. Highest sea levels at the coast are reached during storms, when wind set-up, inverse barometer effect, high tide and large waves combine.

5 POSSIBLE FUTURE RESEARCH

The work of this report is mostly descriptive. Understanding the past observations and gaining trust in the projections would require specific further investigations. Here is a list of possible directions for future work on sea level in the BES islands:

- Better understand the year-to-year and month-to-month variability. Is it coming from the wind or from steric sea level? What is its relation to large scale modes of variability like El-Niño Southern Oscillation, Pacific Decadal Oscillation and Atlantic Multi-decadal Variability. Answering this questions could open the way to a potential predictability of sea level which could help adjust high tide warnings for example. This could be achieved through a literature search and data analysis of the wind from ERA5 reanalysis and local ocean temperature and salinity observations or ocean reanalyses.
- Will year-to-year and month-to-month sea-level variability change in the future? This question could be answered using the CMIP5 and CMIP6 climate models if their representation of the current climate is deemed sufficient.
- The tide gauge with the longest and best data quality in the region is located in Puerto Rico and shows some multi-decadal changes in sea level trend. A sudden sea level rise acceleration or deceleration could have some impact on the BES islands but it is not known if it could also happen there. To better understand this variability we could first identify the physical mechanism at play at Puerto Rico using a complete sea level budget based on [3]. Then assess if these mechanisms are also important for the BES islands.
- The difference between the pattern of sea level rise in the Carribean Sea between satellite observations and climate models would deserve to be analysed in more depth. In the same way as it is now currently done for the North Sea in preparation for the KNMI'23 scenarios. The first step in this investigation would be to understand why such a pattern was observed and if some climate models are able to reproduce it. If, as argued by [26], a high resolution model is really necessary to make sea level projections in this region then the ROMS model could be also deployed in this region as we are now doing to improve future sea level at the western European shelves with the National Knowledge Program on sea level rise.
- Studying current and future extreme sea level events could also be a possible topic of further investigation. It could result in practical measures to decrease the social impacts of sea level rise. For example a "red-alert" tide calendar, as used in New-Zealand to inform everyone to be careful during times of larger tides than usual [28].

6 DATA AVAILABILITY

The tide gauge data was downloaded from the Permanent Service for Mean Sea Level (PSMSL), 2021, "Tide Gauge Data", Retrieved 14 Jun 2021 from `http://www.psmsl.org/data/obtaining/` [29]. The satellite altimetry product was downloaded from CMEMS `https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=SEALEVEL_GLO_PHY_L4_REP_OBSERVATIONS_008_047`. The AVISO product of global average sea level from satellite altimetry was downloaded from `https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level/data-acces.html`. The SROCC sea level projections were downloaded from `https://ipcc-temp.s3.eu-central-1.amazonaws.com/SROCC_Ch04-SM_DataFiles.zip`. The AR6 sea level data can be visualised and downloaded here: `https://sealevel.nasa.gov/data_tools/17`.

7 NOTE ON LINEAR TREND UNCERTAINTIES

The linear trends are computed with a linear least-squares regression. The uncertainty for all local computations are standard error of the estimated slope (gradient), under the assumption of residual normality. These uncertainties do not include measurement error which is assumed to be a small source of uncertainty compared to the random variability around the linear trend arising from wind and steric natural variability. For global sea level the uncertainty does include measurement errors, which are large compared to the random variability. More information about uncertainty in global sea level trend can be found on the AVISO website https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level/data-acces.html.

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