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Past and future sealevel in the Archipelago of Cabo Verde

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PAST AND FUTURE SEA LEVEL IN THE ARCHIPELAGO OF CABO VERDE

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SUMMARY

In this report I provide an overview of the recent evolution and the state of the art future projections of sea level in Cabo Verde. I use observational data from two tide gauges (Palmeira and Porto Grande) and from satellite altimetry and show that despite local time variability the sea level trend over the satellite altimetry period (1992-2019) in Cabo Verde is around $3\,mm/year$ which is similar to global sea level rise over the same period. However, a sea level drop is found in Porto Grande between 1991 and 1996 which would require further investigations to understand. Sea level projections from SROCC, the latest IPCC report, are used to show that sea level rise in the 21^{st} century in Capo Verde will be just a few centimetres higher than to global mean sea level rise in 2100. This holds for three very different climate scenarios. As a result, sea level in 2100 in Cabo Verde will be between $30\,cm$ and $120\,cm$ higher than during the period 1986-2005 depending on emissions and climate response uncertainties.

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

This is important because a large part of human activities worldwide take place close to the coast. This is especially the case in islands like Cabo Verde. 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

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(IPCC) published the Special Report on the Ocean and the Cryopshere in a Changing Climate (SROCC) in 2019 [9].

Many processes lead to differences between local and global sea level [10]. Because of changes in the gravity field of the earth a simple counter-intuitive rule is that when land ice melts sea level rise is larger far away from the melt area. However, 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 Cabo Verde is relatively far away from ice sheets and glaciers it is not protected 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 two tide gauges in Cabo Verde.

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 two main uncertainties in sea level rise projections: the total emissions of greenhouse gases and the speed at which the ice sheets adjust to a warming climate. Here I present the latest sea level projections for Capo Verde from the IPCC SROCC report [9] and compare these projections with global sea level projections.

2 PAST SEA LEVEL RISE GLOBALLY AND IN CABO VERDE

Over the last 3000 $years$ 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) [13]. From the late 19th century or beginning 20^{th} century this relatively slow rate accelerated to a larger rate of over 1 mm/yr [14, 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 [15]. Different reconstructions of sea level based on tide gauge measurements show that sea level during the 20th century was between 1 and 2 mm/yr [2, 3]. The 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 [16]. 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 [17].

This trend in sea level rise observation 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 Southern Atlantic ocean there is an area where sea level rose at more than 6 mm/yr while in the Northern Atlantic an area south of Greenland didn't see much sea level rise. These differences are due to a reorganisation of the ocean circulation that result in salinity and temperature changes. When water becomes warmer of fresher (e.g. less saline) it expands and locally sea level rises. In the tropical Atlantic, where Cabo Verde is 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 heterogeneities appear. There is a difference of up to 1 mm/yr between slow sea level rise 100 km off the coast of Senegal and Mauritania and faster sea level rise south of the island of Cabo Verde. These differences could be due to changes in ocean temperature and salinity, in that case I would not expect them to continue over the coming decades. They could also arise from ground water depletion in Senegal and Mauritania in which case the pattern could be sustained and even amplify in the future depending on future use of ground water in the region.

There are two tide gauges measuring sea level rise in Cabo Verde. They are located in Porto Grande and in Palmeira (see bottom panel of figure 1). I use monthly averaged data downloaded from the PSMSL website (see section 6 for further information) to plot time series (figure 2). At Porto Grande 45 months of data is available between 1991 and 1996 with some missing data in 1996. The tide gauge of Palmeira has 211 months of data between 2000 and 2019 with some missing data in 2001 and 2007. I

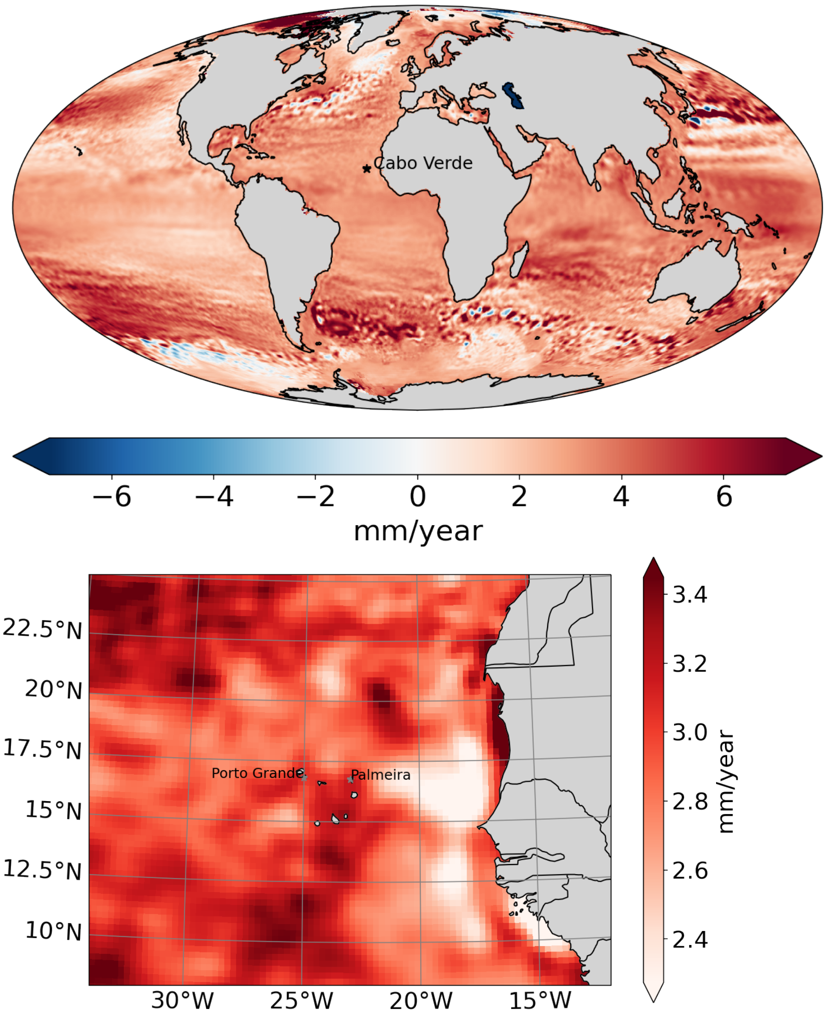

Figure 1: *Top panel*: Global linear sea level trend computed from satellite altimetry data from 1993 to 2019. *Bottom panel*: Zoom on the region of Cape Verde with the location of the two tide gauges at Porto Grande and Palmeira.

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 ellipsoide that is a reference 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. At Porto Grande, satellite and tide gauge measurements are consistent over the short overlapping period. However, there seem to be around $10\,cm$ drop in sea level between 1991 and 1996. This is not consistent with the long term trend from the altimetry. This apparent discrepancy could be due to two factors, either there was an effect of vertical land motion on the tide gauge measurement or it could be due to natural climate variability. Further investigations would be needed to resolve this intriguing discrepancy. The situation is simpler at Palmeira because the tide gauge measurements are longer and they completely overlap with the altimetry period. The monthly variability is consistent between the two time series. The multi-year signal is also consistent, with for instance phases of sea level drop between 2006 and 2010 and between 2012 and 2015 interspersed with sea level rise between 2003 and 2006 and between 2015 and 2018. The long term linear trend also agrees well between the two time series.

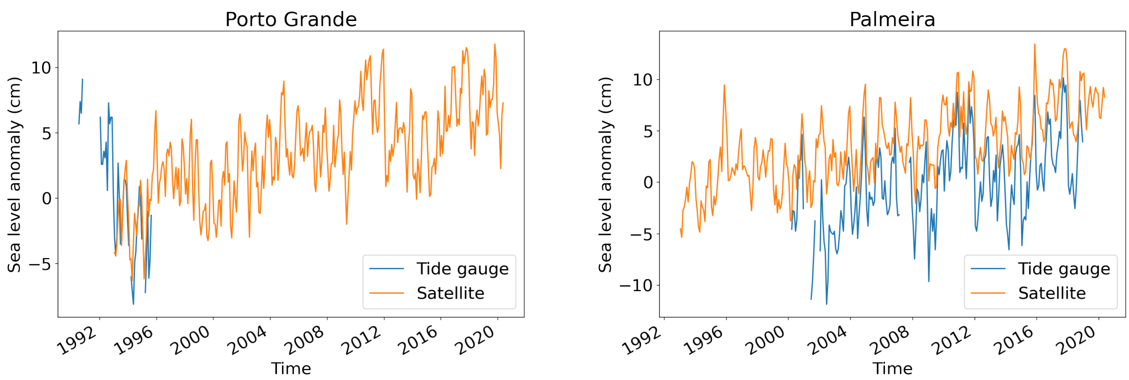

Figure 2: Time series of monthly sea level anomalies comparing tide gauge and satellite altimetry measurements at the same location. The vertical reference for both time series is arbitrary so only the time anomalies can be compared, not the absolute levels.

3 SEA LEVEL PROJECTIONS GLOBALLY AND IN CABO VERDE

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

Global changes in sea level in 2100 are shown in the top panel of figure 3. 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) [21]. In this case, sea level rise in most places is close to $50\,cm$. However, there are exceptions, for examples close to the Greenland and Antarctic ice sheets sea level rise is slower [22]. From this map we also see that Cabo Verde is expected to have a sea level rise similar to most places in the world. This is confirmed by the the time series in the bottom panel of figure 3. Three climate scenarios are compared here, additionally to the RCP4.5 scenario there is also a very extreme scenario (RCP8.5) leading to 4.3°C temperature rise at the end of the century and lower emission scenario (RCP2.6) that leads to a warming of 1.6°C by the end of the century, in accordance with the ambitions of the Paris agreement [21]. For all scenarios we see that sea level in Cabo Verde is expected to be a few centimetres higher than global averaged sea level. Overal the range of uncertainty is large, with a best case of around $30\,cm$ for the lower bound projection under a low emission scenario and up to $120\,cm$ for the upper bound of a high emission scenario.

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 $58\,m$ [18], Greenland $7.4\,m$ [19], glaciers and ice caps $0.4\,m$ [20]. 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.

An important fact to keep in mind is that sea level will continue to rise for thousands of years even if the concentration of greenhouse gazes 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 [23, 24]. 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 $20\,m$.

4 DISCUSSION

The large sea level drop observed in Porto Grande between 1991 and 1996 would need further investigation. Three paths could be followed. First look for other tide gauges in the region that have data over the same time period. That could help to confirm that it was indeed a sea level signal and not due to

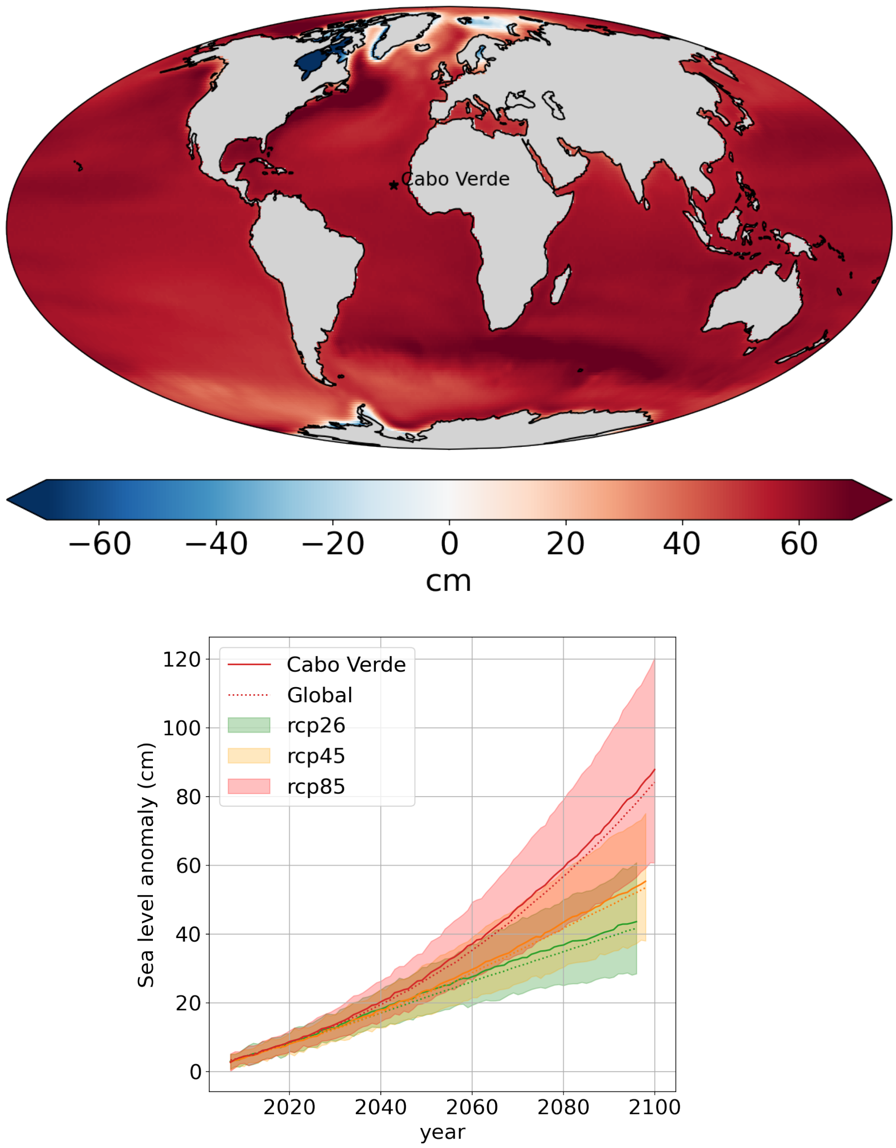

Figure 3: Sea level projections from the IPCC SROCC report using 1986-2005 as reference period. *Top panel:* Map of sea level in 2100 (median) under the RCP45 scenario compared to the reference period. *Bottom panel:* time series of sea level for three RCP scenarios. Bold lines and uncertainty ranges are for Cabo Verde 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).

vertical land motion. Second, a sea level budget could be build for this location. That would allow the identification of individual sea level contributors that could have played a role in this sea level drop. The most probable drivers of sea level at this time scale is changes in temperature and salinity in the deep ocean around Cabo Verde. Third, one could also search information about the land in which the tide gauge is located and if there could have been reasons why the land would have moved upward over this period.

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 Cabo Verde. 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 [26]. 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.

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. This could be a possible topic of further investigation that 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 [25].

5 CONCLUSION

In this report I used tide gauge observations and satellite altimetry observations globally and in Cabo Verde. I showed that the short term variability and long term trend in Palmeira is similar in both observational data. However, in Porto Grande a large sea level drop is observed between 1991 and 1996 which cannot be confirmed by the altimetry because the altimetry observations are only available from the end of 1992 (figure 2). The satellite altimetry data allows to compare the situation of Cabo Verde with the whole world. I showed that the sea level trend over the period 1992-2019 is close to the global mean sea level trend (around $3\,mm/year$, figure 1).

Future projections from SROCC show that as a first approximation it is reasonable to assume that future sea level rise in Cabo Verde will be close to global mean sea level rise. For three climate scenarios, sea level rise in Cabo Verde is expected to be a few centimetres more than global mean sea level in 2100 (figure 3). So in general over long time scales, longer than 30 years, global sea level seems to be a good indicator for sea level in Cabo Verde.

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/ [27]. 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 SROCC sea level projections were downloaded from https://ipcc-temp.s3.eu-central-1.amazonaws.com/SROCC_Ch04-SM_DataFiles.zip

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