MAY 2020

EFFECTS OF CLIMATE CHANGE ON COASTAL EROSION AND FLOODING

in Benin, Côte d'Ivoire, Mauritania, Senegal, and Togo

Technical Report

acciona Ingeniería
NDF Nordic Development Fund
WACA West Africa Coastal Areas Management Program
WORLD BANK GROUP

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This Technical Report was commissioned by the West Africa Coastal Areas Program (WACA) under the World Bank's Environment, Natural Resources and Blue Economy Global Practice. The report was prepared by Angel Luis de Luque Söllheim (Remote Sensing/Climate Change Specialist) and Jacopo Scafura (Climate Change Specialist) of Acciona Ingeniería. The work is based on published reports and scientific articles on climate change in West Africa. The World Bank Climate Change Portal was the primary source for climate change data used for the study.

The preparation of the report was guided by a World Bank team led by Junu Shrestha (Senior Environmental Specialist), under the supervision of Peter Kristensen (Lead Environmental Specialist) and benefitted from technical comments from Ana Bucher (Senior Climate Change Specialist), Nicolas Desramaut (Senior Environmental Engineer), and Yunziyi Lang (Analyst). Support on finalization was provided by Lelia Croitoru (Environmental Economist), Madjiguene Seck (Communications Officer) and Zubair Qamar (Editor). The team gratefully acknowledges the overall guidance of Maria Sarraf (Practice Manager).

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EXECUTIVE SUMMARY

West Africa, with countries spanning from Mauritania in the North to Nigeria in the South, is a hotspot of climate change according to the Fifth IPCC Assessment Report, expected to be strongly impacted by climate change in the 21st century and after. By 2020, between 75 and 250 million people are estimated to be particularly exposed to the impacts of climate change in Africa (MERF 2009). Climate change projections show that temperature may rise by 0.5°C per decade in West Africa, accompanied by increased rainfall variability and intensity, and accelerated sea level rise (SLR) of around 1 meter per century (IPCC 2014).

Despite these threats, the potential physical and economic impacts of climate change on the coastal zones of West Africa have not yet been adequately assessed at the country level. To address this gap, the World Bank undertook this study focusing on five countries in the region: **Benin, Côte d'Ivoire, Mauritania, Senegal, and Togo**. The study explores how climate change will affect the coastal zones and specifically identifies the exposed and vulnerable areas of the five countries. This executive summary presents key findings of the study.

The study presents coastal conditions and climate change at a regional scale, followed by an overview of each country's coastline - the geomorphological structure of the area and climate characteristics, including temperature, precipitation, winds, and tides.

Historical trends of three key climate parameters (**temperature, precipitation, and sea level rise**) were analyzed to assess how climate has been changing in recent decades. Updated time series data from 1950 to 2016 on temperature and precipitation were collected from meteorological stations in each country and the monthly SLR series were obtained from the World Bank Climate Change Knowledge Portal (CCKP). ERA-interim reanalysis data series were used to discern anomalies and variabilities in the key climate parameters in the last 10 years.

Future projections of the three parameters were modeled for three time-horizons (2030, 2050, and 2100)[1] and compared to the baseline period 1986-2005.[2] Two Representative Concentration Pathways (RCPs) scenarios (RCP 4.5 and RCP 8.5) were considered for each parameter and time horizon to illustrate the degree of change between the most commonly referenced pathways. The Coupled Model Intercomparison Project 5 (CMIP5) data from World Bank Climate Change Knowledge Portal (CCKP) were used to estimate potential changes in the three main parameters under the two major RCPs.

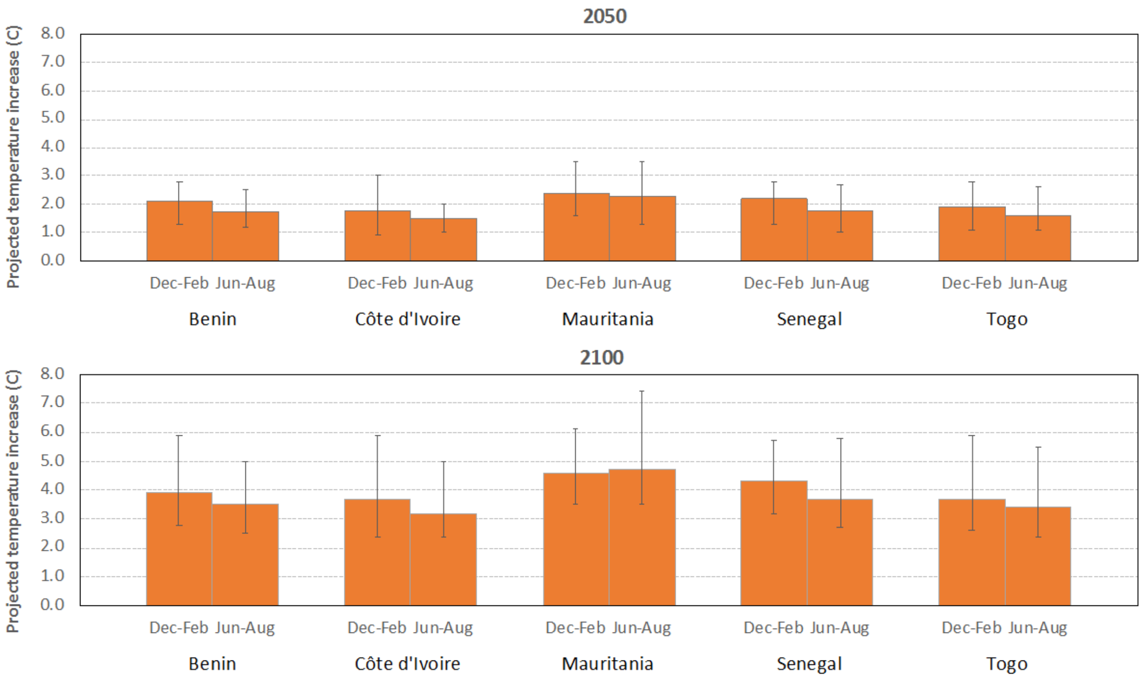
Finally, an evaluation of how climate change will affect the coastline was presented through the analysis of two natural hazards: **coastal erosion** and **coastal flooding**. These are the two most common phenomena occurring along the countries' coastlines and will be exacerbated due to the effects of climate change. Coastline position in the 1984-2015 period was evaluated using Landsat and Sentinel images and projected to the three-time horizons to estimate potential future coastal erosion. To evaluate coastal flooding, maps of coastal areas exposed to floods were generated through simulations based on SLR projection data, combined with 90-meter spatial resolution Shuttle Radar Topographic Mission (SRTM) digital elevation data. The main exposed areas were identified for each country and analyzed through the generation of spatial maps. The following section summarizes the **results** of the study.

[1] Time horizons: 2020-2039, 2040-2059, and 2080-2099.
[2] Exact periods vary slightly based on data availability.

a) **Climate change projections** compared to the 1986-2005 baseline period yielded the following results for the three parameters:

Temperature. A general warming is expected in all five countries (see Figure 1). Temperatures in West Africa are expected to rise by +2°C in 2050 and almost by +4°C in 2100 over most of the region for the RCP 8.5 scenario, with temperatures increasing by approximately 4.6°C in Mauritania in 2100. Temperatures are expected to increase more during the winter months (December-February) than during the summer months (June-August). Except for Mauritania, winter months are expected to be warmer than summer months.

i) Projected changes in temperature under RCP 8.5



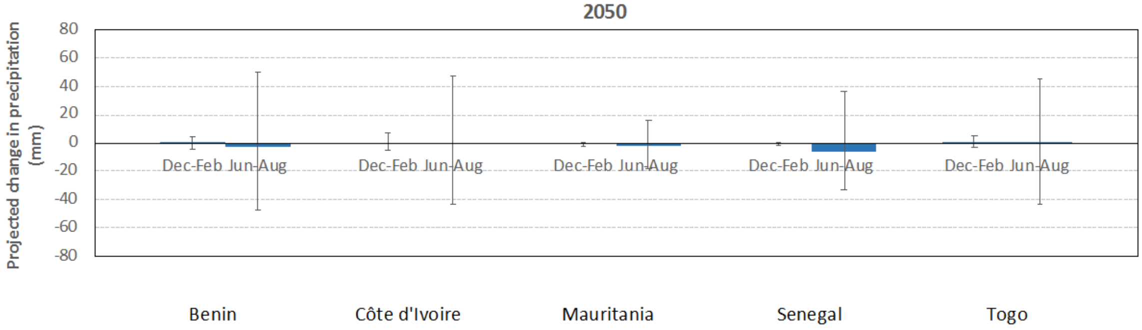
Vertical lines reflect ranges of values.

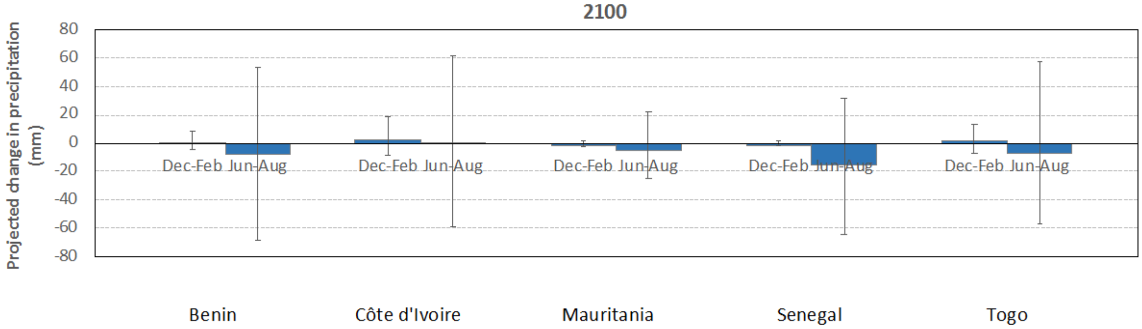
Precipitation. Precipitation projections are characterized by high variability, making future predictions uncertain. There is a general decrease in future precipitation in all countries, except in Côte d'Ivoire,[3] as well as shortening of rainy seasons during the year. Although precipitation is expected be less frequent, extreme precipitation events are expected to occur more often.[4]

[3] Projections for 2100 indicate an increase in precipitation in Côte d'Ivoire.

[4] There is a lack of information about future occurrence, intensity of storm surges, and other extreme phenomena. Although many reports underline that these events will happen more often and with more intensity, there is no detailed evidence on the exact magnitude and on the return period that these phenomena will have in the future.

ii) Projected changes in precipitations under RCP 8.5





Vertical lines reflect ranges of values.

Sea Level Rise (SLR). By 2030, Mauritania and Senegal could experience sea level rise of 0.18m, in the same time period Cote d'Ivoire, Togo and Benin could see 0.1 m rise. By 2050 in Mauritania and Senegal sea levels could rise by 0.6 m; in Cote d'Ivoire, Togo and Benin the rise could be 0.3 m. By the end of the century in all countries over 1m increase in the sea levels was projected. SLR is well defined by IPCC reports at a global scale but poorly defined at local scale, especially in specific African countries. Limited research studies and government reports, that were available, were used to obtain information on projected SLR in the countries. A significant lack of data on SLR for West Africa does not allow for generation of future projections with high confidence. The highest increase, estimated at 1.15 meters by the end of the century, is expected to occur in Benin and Côte d'Ivoire. See Figure 3 below for projected SLR under RCP 8.5.

iii) Projected sea level rise under RCP 8.5

Vertical lines reflect range of values. No data are available for Cote d'Ivoire and Senegal for 2050.

An extensive bibliographic review was undertaken to gather information on the five countries' coastal areas, as well as historical climate trends, to model future climate projections. The information synthesized was used to generate maps to illustrate future hazards of climate change on the coastal areas of the five countries.

b) **Future natural hazards:**

Erosion. Coastal erosion is influenced by multiple drivers, including natural factors (e.g., SLR, wind patterns, offshore bathymetric changes) and human activities (e.g., construction of port infrastructure, dams in rivers, sand mining). Overall, the area expected to be most affected by erosion are the areas south of the port of Nouakchott (likely to lose 40.6 km^2 by 2100), east of Lomé (17.4 km^2 loss by the same year), and the east of Cotonou (12.9 km^2). Other areas at risk include Grand Popo in Benin; Abidjan and Lagoon of Popo in Côte d'Ivoire; Jreida in Mauritania; and the Togolese coastline close to Benin.

Flooding. The study estimated the potential inundation areas for different scenarios related to SLR, tides, and extreme events. When only SLR is considered, the total potential inundated areas in the five countries is estimated at about 6,650 km^2 in 2100, of which 5,260 km^2 is in Mauritania and Senegal combined, 800 km^2 is in Côte d'Ivoire, and 590 km^2 is in Togo and Benin combined. When the effects of tides and extreme events are considered, the potential inundated areas are larger. The locations most exposed to flooding include the lagoons of Mono and Kouffo in Benin; the area between Abidjan and border with Ghana in Côte d'Ivoire; the urban areas of the capital Nouakchott and city of Nouadhibou in Mauritania; the cities of Saint-Louis, Dakar, and Casamance region in Senegal; and the coastal neighborhoods of Lomé in Togo. See Table 1 below for hotspots and vulnerable areas to erosion and flooding in each respective country.

c) **Potential impacts of a permanent inundation:**

The study assessed how flooding and erosion are likely to affect socio-economic conditions in the five countries' coastal zones. The combined impact of the SLR and maximum high tide in 2050 and 2100 were considered the worst possible permanent flood situation. Under RCP 8.5, the inundation areas (total rural and urban areas) cover about 7,231 km² in 2050 compared to the 2015 baseline. In all countries, rural areas are likely to be mostly affected (60 percent of the total). Mauritania is the most exposed country, accounting for 76 percent of the total inundated land. In 2100, permanently inundated area is estimated to be about 9,806 km² compared to the 2015 baseline. Similar patterns of affected land use as in 2050 were seen in 2100. Coastal ecosystems as mangroves and wetlands are observed to be highly exposed to SLR inundation. Similarly, roads connectivity, ports, and cropland could be impacted, causing severe negative effects on local livelihoods.

i) Coastal areas exposed to erosion and flooding						
Benin	Western Area (BJ1-a, BJ1)	Center West Area (BJ1-c, BJ2-a)	Center East Area (BJ2-b, BJ2-c, BJ2-d)	Eastern Area (BJ2-e)		
Côte d'Ivoire	Cap des Palmes-Sassandra	Sassandra-Abidjan	Abidjan-border with Ghana			
Mauritania	Nouakchott	Nouadhibou				
Senegal	Rufisque-Bargny	Saint Louis	Saly Portudal	Casamance		
Togo	First Zone (TG1-a, TG-1b)	Lomé	Second Zone (TG1-c)	Third Zone (TG1-d)	Fourth Zone (TG1-e)	Fifth Zone (TG1-e Benin border)

Conclusion and Recommendations

The study consolidates relevant information on climate change in the five countries in West Africa to describe potential changes in the coastal climate, namely temperature, precipitation, and SLR, as well as related hazards (flooding and erosion) in an organized and quantitative manner. The study sheds light on the physical magnitude of potential hazards on the coastal zones and provides maps of at-risk areas in each country at different time horizons under two different RCPs. The synthesis highlights the need for local level studies and data collection on SLR, precipitation, and extreme events such as storm surges. Only a preliminary analysis on land-use types that could be affected due to the hazards was completed in the study. This needs to be complemented with an in-depth analysis of socio-economic impacts that would provide a more reliable quantitative assessment of projected losses along the coast in the future. See Table 2 for a summary of key findings by country and Table 3 for detailed identification of gaps and recommendations.

ii) Summary of key findings

	Observed Climate Change			Future Climate Change Projections			Climate Change related Hazards	
	Temperature	Precipitation	Sea Level Rise	Temperature	Precipitation	Sea Level Rise	Erosion	Flooding
Benin	Mean annual temperature increased by almost +0.5°C between 1979-2016.	General decrease in precipitation of -0.2 mm/year in 1950-2016 period in Porto Novo station. From 1979, a +0.2 mm/year increase with strong uncertainty of ±0.3 mm/year was observed.	A +0.25 cm/year increase in 1992-2017 period as registered by ESA satellites.	Mean annual temperature expected to rise +1.3° C under RCP 4.5 and +2.1° C under RCP 8.5 by mid-century. Warming in winter months is higher than summer months.	Future projections show decrease over the century in summer months. In winter months, a slight increase is expected.	By end of century, sea level is expected to increase to +81 cm in a range between +75 and +152 cm.	Areas identified to be most affected are western area of the coastline, especially cities of Hillacondji and Grand-Popo. The section of Azizacoue-Abouta, Djomehountin, Cotonoú, and border area with Nigeria are also at risk.	More frequent and intense floods expected. Most exposed sections of coastline are the western and the central western areas. In this report, the surrounding area of Cotonoú has been analyzed.
Côte d'Ivoire	Mean annual temperature increased by almost +0.7°C in 1979-2016 period.	A decrease of -0.5 mm/year in 1950-2016 period in Abidjan airport station. The 1979-2016 period shows a decrease by -0.1 mm/year. This data shows higher trend variability and uncertainty.	Increased about +0.32 cm/year in 1992-2017 period measured by ESA satellites.	Mean annual temperature projected to rise +1.9°C by 2050 in high emission under RCP 8.5.	Mean annual precipitation could decrease by -1.38 to -3.57mm in 2050 under RCP 4.5 and -0.5 to -0.7mm under RCP 8.5.	Sea level is expected to increase to +30 cm in 2070 and +95 cm in 2100 for RCP 4.5. Sea level is expected to increase to +115 cm in 2100 under RCP 8.5.	From west to east, the first section of coastline is stable. From Sassandra to Abidjan, coastline is significantly exposed to erosion. Other areas exposed to erosion are Grand Lahou, Lagune of Popo, and San Pedro.	Heavy precipitation along coastline and sea level rise generate frequent flooding events especially between Abidjan and border with Ghana.
Mauritania	Mean annual temperature increased by almost +0.9°C in 1979-2016 period.	No clear precipitation trend observed. While a decrease of -0.04 mm/year is registered in 1950-2016 period, a positive trend of +0.5 mm/year is observed in 1979-2016 period.	According to ESA data, an increase of +0.32 cm/year in1992-2007 period is measured.	Temperatures are projected to increase by +2.3°C by 2050 and +4.6°C by 2100 under RCP 8.5.	Precipitation is expected to fall by -2 mm in 2050 under RCP 8.5.	Sea level rise is expected to increase up to +60 cm at mid-century under RCP 8.5.	Sandy and low-lying coastline is expected to be severely affected, mainly area in south of port of Nouakchott, area of Jreida, and coastline of Nouadhibou.	Coast is constantly at risk of inundation as extreme weather events will occur more frequently. Urban areas like Nouakchott and Nouadhibou are exposed to coastal flooding.

Senegal	Mean annual temperature increased by almost +0.8°C in 1979-2016 period.	A general decrease from the Dakar station observed in 1950-2016 period (-0.8 mm/year). From 1979, an increase of +0.9 mm/year registered.	An increase of +0.25 cm/year registered by ESA satellites in 1992-2017 period.	Temperatures are projected to increase by +1.3/+2.7°C by 2050s and up to +4.3°C by 2100 under RCP 8.5.	A general decreasing trend in precipitation is likely. However, robust conclusions are difficult to make.	Projections for sea level rise show an increase of more than +1 m by the end of the 21st century.	Most exposed areas are N'Dar Toute-Saint Louis, Fas Boue, Boro Deunde, Kayar, M'Bour-Saly Portudal, Kafoutine-Casamance, Ngalou Sam Sam, Palmarin, and Dijffer.	Relatively low altitudes areas. The most exposed areas are cities of Saint-Louis, Dakar, and Casamance region.
Togo	Mean annual temperature increased by about +0.5°C in 1979-2016 period.	A decrease of -0.1 mm/year in 1950-2016 period. Positive trend in 1979-2016 period, registering a +0.3 mm/year increase.	Sea level increased by about +0.25 cm/year in 1992-2017 period as measured by ESA satellites.	Temperatures projected to increase by +1.1/+2.8°C by end of 2050 and by +2.5°C /+5.6°C by end of century under RCP 8.5.	Projections of change in rainfall present high variability and uncertainty. An increase during winter months and decrease during summer month is shown.	Sea level is estimated to increase about +31 cm by 2050 under RCP 8.5.	Coastline is almost entirely affected by erosion. Most vulnerable areas include sector TG1-c, TG1-d, and TG1-e. Main affected areas identified in south of Lomé and at border with Benin.	Risk of flooding is high along whole coastline, mainly in lower region of city of Lomé and in sector TG1-c.

iii) Gaps and recommendations

	Key Findings	Gaps and Limitations	Main Contribution	Recommendations for Future Studies
General Climate Characteristics	Mauritania and Senegal have a long dry season (Nov-May) with mild and high temperatures (22-32°C) and a short, wet season in summer (Jul-Sep). Waves of 1.2 to 1.7 m come mostly from Northwest. The other three countries have a long rainy season (Apr-Oct) with hot temperatures the entire year (24-32 °C) and waves of 1.2 m coming mostly from the south.	Information about wind and swell directions and magnitude, tides, and currents were usually poorly detailed so was information on storm surge and extreme precipitation events.	A description of the main climate characteristics, e.g., temperature and precipitation patterns, coastal geomorphology, winds regime, and oceanic conditions, are provided at a regional level and analyzed for each country. Directional waves rose were generated for each country to show the frequency and significant height of waves coming from various directions using ERA interim dataset.	Further studies on extreme climatic events such as storm surges and extreme precipitation rainfall are needed.
Observed Climate Change	A general increase of temperature and sea level rise has been observed at a regional level and for each country. With higher data variability, a general decrease of precipitation was also detected in the area of study.	The high variability observed in historical data for rainfall precipitation represents a significant limitation when analyzing evolution of rainfall over the decades. Studies on storm surges and precipitation extreme events were also missing.	Observed data on temperature and precipitation were collected and processed from ERA Interim data series and main coastal city weather stations. Sea level data were obtained from CCKP, and transformed to yearly trends, and analyzed. Return periods and sea level anomalies related to storm surges and precipitation extreme were collected from risk data platforms.	Future studies on past extreme climate events and interpretation of high variability of precipitation and wave events are needed.
Future Climate Change	Temperature and sea level rise are expected to increase, while future projections of precipitation that are expected to decrease in the future show high variability. This does not allow the drawing of accurate conclusions.	Although many studies are available on sea level rise at a global level, a significant data gap has been detected at the regional and at national levels. Information is missing for various time horizons and scenarios (especially RCP4.5). Research on projections of extreme events like storm surges and precipitation are getting initiated. Therefore, reliable results for specific places are difficult to find.	Projection data of main climate parameters were gathered mostly from the World Bank CCKP Portal, but also from scientific reports and national and international documents. The information was summarized in tables and the results were analyzed for each climate parameter.	To understand how sea level rise, storm surges, and extreme climate events will change in the future, further studies will have to be undertaken at regional and national levels.
Climate Change Natural Hazards	Sea level rise, temperature increase, and increase in frequency and intensity of extreme climate events will amplify the phenomenon of erosion and generate more flooding events along the coastline of all countries analyzed. Human intervention on coastal areas will intensify these effects.	Lack of updated studies on the influence of extreme climate events such as storm surges, extreme winds, and rainfall precipitations on erosion and coastal flooding in the region.	Description of erosion and coastal flooding issues at a regional level and their further analysis at the national level was completed. For each country, the most exposed areas were identified, and an analysis of the effects were provided. Maps of erosion (for Mauritania and Senegal) and coastal flooding (for each country) were generated to show the effects of erosion and flooding over the three-time horizons and two climate scenarios.	More studies will be useful to assess the effects that extreme climate hazard may have on coastal erosion and flooding.

Key climate parameters applied to coastal studies

The Intergovernmental Panel on Climate Change (IPCC) reports use temperature, precipitation, and sea level rise as the most important climate change parameters. In addition to the key parameters, extreme events, such as storm surges and flooding, were also analyzed by taking into consideration inland river overflow during extreme precipitation events and high tide conditions which are expected to worsen the effects of sea level rise. During these severe events, precipitation is also a factor that causes river overflow and rainwater accumulation in low coastal areas. Consequently, this combined with high tides and storm surges enhances the negative effects of sea level rise. In summary, the analyzed key parameters in coastal areas are:

- Temperature (Mean changes and evolution)
- Precipitation pattern (Mean changes and evolution)
- Sea level rise (Mean changes)
- Sea conditions (Mean changes and evolution of extreme events

GLOSSARY

To facilitate the comprehension of this study, the reader may find the definitions of the terms mostly used in this study. The definitions presented below are based on the IPCC report (IPCC 2014).

Anomaly
An observation that lies outside the overall pattern of a distribution, a change, or departure from a reference value or long-term average. Temperature anomaly is the difference between the long-term average temperature (i.e., reference value) and the temperature occurring. A climate anomaly is the difference of a future climate compared to the present climate.

Baseline (or reference)
The state against which change is measured. A baseline period is the period relative to which anomalies are computed.

Climate variability
The variations of climate data. Variations in the mean state and other statistics (i.e., standard deviations, occurrence of extremes, etc.) of the climate across all spatial and temporal scales beyond that of individual weather events. It may be due to natural processes in the climate system or anthropogenic factors.

Coupled Model Intercomparison Project (CMIP)

A climate modelling activity from the World Climate Research Programme (WCRP). The programme coordinates results from more than 60 model simulations of different modelling groups worldwide (CMIP-1). For the purpose of this study, we have used CMIP-5 data that takes into account projections using the Representative Concentration Pathways.

Dynamic Evolution
Satellite imagery has been used to analyze coastline change and predict erosive phenomena. Dynamic evolution refers to a prediction of erosion of a determined area of the coastline. This results from projecting in the future the same erosive rate that has been observed through satellite data during a baseline period.

Ensemble
A collection of model simulations characterizing a climate prediction or projection. Differences in initial conditions and model formulation result in different evolutions of the modeled system. This may give information on uncertainty associated with model error and error in initial conditions in the case of climate forecasts and on uncertainty associated with model error, and with internally generated climate variability in the case of climate projections.

Erosion
Process of removal and transport of soil and rock due meteorological phenomena, mass wear, and the action of water courses, glaciers, waves, winds, and groundwater. In this report, we refer to coastal erosion mostly due to the action of waves and sea level rise.

Exposure
Related to places and settings that could be adversely affected by an extreme natural event due to the presence of people, ecosystems, services, resources, or other assets.

Extreme weather events
A weather event that is rare at a particular place and time of year. In this study, it usually refers to drought, heavy rainfall over a season, and storm surge.

Exposure
The presence of people, livelihoods, species or ecosystems, environmental functions, services, resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.

Flood
The overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas that are not normally submerged. In this study we mostly refer to coastal flood due to sea level rise. However, it also refers to river flooding due to precipitation events.

Hazard
The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, hazard usually refers to climate-related physical events or trends, or their physical impacts.

Mean (or arithmetic mean)
The sum of a list of numbers divided by the number of elements in the list.

Median
The "middle value" of a list of numbers. The smallest number that at least half the numbers in the list are no greater than it. It corresponds to the 50th-percentile.

Multi-model ensemble
A group of comparable model simulations that can be used to obtain accurate estimates of a model property through the provision of a larger sample size. Ensembles made with the same model, but in different initial conditions, only characterize the uncertainty associated with internal climate variability. Multi-model ensembles, including simulations by several models, also include the impact of model differences.

Range
Values that are given from the difference between the lowest and highest values of a parameter. In the context of this work, range is provided for future climate change projections and shows extreme values (10^{th} and 90^{th} percentile) of the median value (50^{th} percentile) of a parameter anomaly (e.g., monthly precipitation anomaly).

Reanalysis
A meteorological data assimilation project which aims to assimilate historical observational data spanning an extended period using a single consistent assimilation (or "analysis") scheme throughout.

Representative Concentration Pathways (RCPs)

Climate scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover. In this study we have referred to RCP 4.5 and RCP 8.5. The first one is an intermediate pathway in which the radiative forcing is stabilized, while the second assumes constant emissions after 2100.

Risk
Potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability or likelihood of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. In this report, the term risk is often used to refer to the potential, when the outcome is uncertain, for adverse consequences on lives, livelihoods, health, ecosystems and species, economic, social, and cultural assets, services (including environmental services), and infrastructure.

Satellite measurements
Orbiting around the Earth, satellites provide climate-related atmospheric data that can be used for measurements of atmospheric temperature, radiations, hydrological cycle changes, extreme event characterizations, and circulation indices.

Sea Level Rise
Increases in the height of the sea with respect to a specific point on land. Slow sea level rise is mostly caused by an increase in the volume of the ocean as a result of the melting of land-based glaciers and ice sheets, and changes in water density as a result of the heating of the ocean. Temporal sea level rise by: tides, strong waves and winds, low atmospheric pressure, extreme rainfall events or river overflow events.

Seasonal forecast
A seasonal forecast aims to estimate the change in the likelihood of a climatic event happening in the coming months.

Station measurements
Weather station located in a specific place which collects climatic data as temperature and rainfall to generate historical data.
Storm surge
The temporary increase at a particular locality in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being

the excess above the level expected from the tidal variation alone at that time and place.

Variability
Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate at all spatial and temporal scales beyond that of individual weather events.

Vulnerability
The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm, and lack of capacity to cope and adapt.

METHODOLOGY

Key data extraction from studies

This study was conducted by following two methods. First, a bibliographic review has been carried out to gather and review all available information on climate change in West Africa, and specifically in the five countries mentioned above. Second, based on data collected in previous research, maps and tables of future climate effects (namely, erosion and coastal flooding) have been generated for each area of study to assess the potential impacts of these events on the country's coastlines.

The documents reviewed are primarily academic papers, reports, books, and publicly available web sources. Studies carried out and documents drafted on this subject are rather limited and modest relative to the importance of the issue and urgency to tackle it.

Important information was extracted from the IPCC reports on climate change, from reports released by international organizations, agencies, or private companies, and from academic papers. Other essential sources for this work were government reports and assessments collected from local contacts. These documents contained critical information used for descriptive purposes and data implementation.

Due to the limited number of studies available on this region, information about several climate parameters have not been included in this work. Particularly, information on the West Africa region's future climate parameters present several deficiencies. A specific parameter that is not well determined both at a regional level as well as for every country is sea level rise (SLR). Much information on sea level rise and its future projections are presented in an ambiguous manner meaning that either obsolete climate scenarios (e.g., SRES) are used, or climate scenarios are not even mentioned. Finally, clear projections about extreme events, such as storm surge and extreme precipitation events, are rarely mentioned in the studies. In most cases, they do not present any precise information.

Historical analysis and climate change evidence

Key parameters time series from each country. Historical temperature, precipitation, and SLR series are obtained from various data sources and illustrated to clearly assess climate change in each country.

Monthly temperature and precipitation graphs from 1991 to 2015 for each country are obtained from the World Bank Climate Change Knowledge Portal (CCKP) web page. This data was collected from available country meteorological stations and processed by the Climate Research Unit (CRU) of the University of East Anglia. These graphs are used to characterize country climatology and to define the rainy season.

Temperature and precipitation updated data time series from meteorological stations in each country[5] were collected and processed by the U.S. National Climatic Data Center (NCDC). Data are monthly series from 1901 to 2016 from meteorological stations located in each country's main coastal city as shown below:

- Mauritania, Station NOUAKCHOTT, ID 61442000, elev 1 m, lat 18.1 N lon 15.9 W.
- Senegal, Station DAKAR/YOFF, ID 61641000, elev 24 m, lat 14.7N lon 17.5W.
- Togo, Station LOME AERO, ID 65387000, elev 20 m, lat 6.2N lon 1.3 E.
- Benin, Station PORTO NOVO, ID 65344003, elev 20 m, lat 6.5 N lon 2.6 E.
- Côte d'Ivoire, Station ABIDJAN AERO, ID 65578000, elev 7 m, lat 5.3N lon 3.9W.

This data is quality controlled from NCDC and has been graphed and checked to avoid evident data errors. However, there are uncertainties caused by many factors such as sensor type or position changes, lack of routine calibration, among others.

Mean yearly temperature data series are computed and represented from 1979 to 2016 using each

[5] Temperature and precipitation time series from meteorological stations were provided by World Bank project contacts.

station data. Trends and trend uncertainties are calculated for this period by optimal sum of squared errors interpolation method and error to trend propagation method respectively. For precipitation, the same analysis is undertaken. However, due to the high variability observed in this parameter, the time period was increased by beginning the analysis period in 1950 instead 1979.

Monthly sea level series for each country are given by the European Space Agency (ESA) under the Climate Change Initiative project. The altimetric data from the country coastline is obtained from the World Bank's Climate Change Knowledge Portal web page (CCKP) and later averaged to annual height measurements. The monthly averaged Sea Level Anomalies (SLA) corresponds to the SLA grids computed after merging all altimetric mission measurements from satellite sensors together into monthly grids with a spatial resolution of a quarter degrees using a Mercator projection. Country coastline SLA grid points are averaged to obtain a country SLA time series. Altimetric anomaly annual time series for each country is processed to obtain trends and trend uncertainty by applying the same methodology than for the temperature and precipitation time series. The linear relation is then used to obtain the total change in sea level. Trend uncertainty from linear slope and intercept uncertainty are propagated using the linear relation to obtain the total change uncertainty.

Era-interim dataset. To obtain trends and variability of the main variables for the time horizon 2015, data series are acquired and analyzed. For this purpose, 40 year-long (1979-2018) Era-Interim reanalysis data series (Dee, D. P. et al. 2011) from the European Centre for Medium-Range Weather Forecasts (ECMWF) are used in this study to support the historical analysis. While the meteorological stations are in land, very close to the main coastal cities, Era-interim points nearest to the center of each country coastline are located at sea. The Era data consider the general state of the atmosphere assimilating many observations while it is executing in big grid cells of 0.75° x 0.75° and 60 vertical levels, that is 80 x 80 km within vertical structure from the surface up to 0.1 hPa.

This model assimilates observations from buoys, land meteorological stations, and remote sensing. Therefore, the model can provide accurate information about climatic conditions (D. Dee. 2009) with good results in climatic trends and anomalies for temperatures and precipitation compared to direct observations from stations (Cornes et al. 2013). An important advantage is that ERA series contain oceanographic parameters such as significant wave height and wave direction that can be used to analyze the coastal sea state and conditions. From a 3-hour time resolution and 0.75º spatial resolution data series, it is possible to obtain the following atmospheric and oceanographic statistical indices:

- Temperature annual series in coastal areas, anomaly and variability of the latest 10 years period (2008-2017) for 2015 analysis, compared to a 20 year baseline period (1986-2005).
- Precipitation annual series in coastal areas, anomaly and variability of the latest 10 years period (2008-2017) for 2015 analysis, compared to a 20 year baseline period (1986-2005).
- Extreme sea condition study with a number of days per year with significant waves height greater than 3, 2.5, and 2 m respectively for the complete dataset period (1979-2017).

ERA-interim reanalysis are computed using the ECMWF global model for which available observation data from many sources are assimilated during the model run. There are mainly two uncertainty factors: 1) the observation data assimilation scheme used in the model while it is running, and 2) internal model parameterization scheme for the different parameters.

The anomaly or change for temperature and precipitation series is the mean period value difference obtained each month. Variabilities are standard deviations from the anomaly time series for each month. Data series from Era interim dataset are obtained in five grid points over a sea area close to the coast of each of the five countries as shown in Figure 1. The objective is to obtain general coastal temperature and precipitation time seasonal anomalies in the last ten years and sea condition data series with time annual trends in each coastal area. These are open areas far from complex terrain elements (mountains) or complex coast shapes. Therefore, geographical variabilities in Era estimations are small in large coastal areas. In the case of precipitation in Mauritania and

Senegal, seasonal precipitation between June and October is incrementing to the south as shown in the next chapters. Therefore, spatial variability is also incrementing in this direction. This is a much more difficult parameter to study due to its high temporal and spatial variability along countries with extended coastlines. Resulting precipitation historical changes, trends, and anomalies obtained in the present study are limited to coastal areas near the most populated cities.

In Figure 1b the temperature for 00 hours UTC, September 1, 2018 is almost the same in large coastal areas. For Togo coastal point 5a, it was moved to the closest point to the south (5b) to obtain the reanalysis information related to oceanic parameters. Requested reanalysis parameters are shown in Table 1. They are acquired from the January 1, 1979 to September 31, 2018 every 3 hours to later average them to daily measurements. The precipitation is a daily accumulation in mm.

Figure 1: a) Map of wave period in order to see model discrimination between land and sea. b) Map of 2 meters temperature (°C). Both at 00 hours UTC, September 1, 2018. Model grid points are selected over sea points to also extract oceanic parameters as shown in Table 1

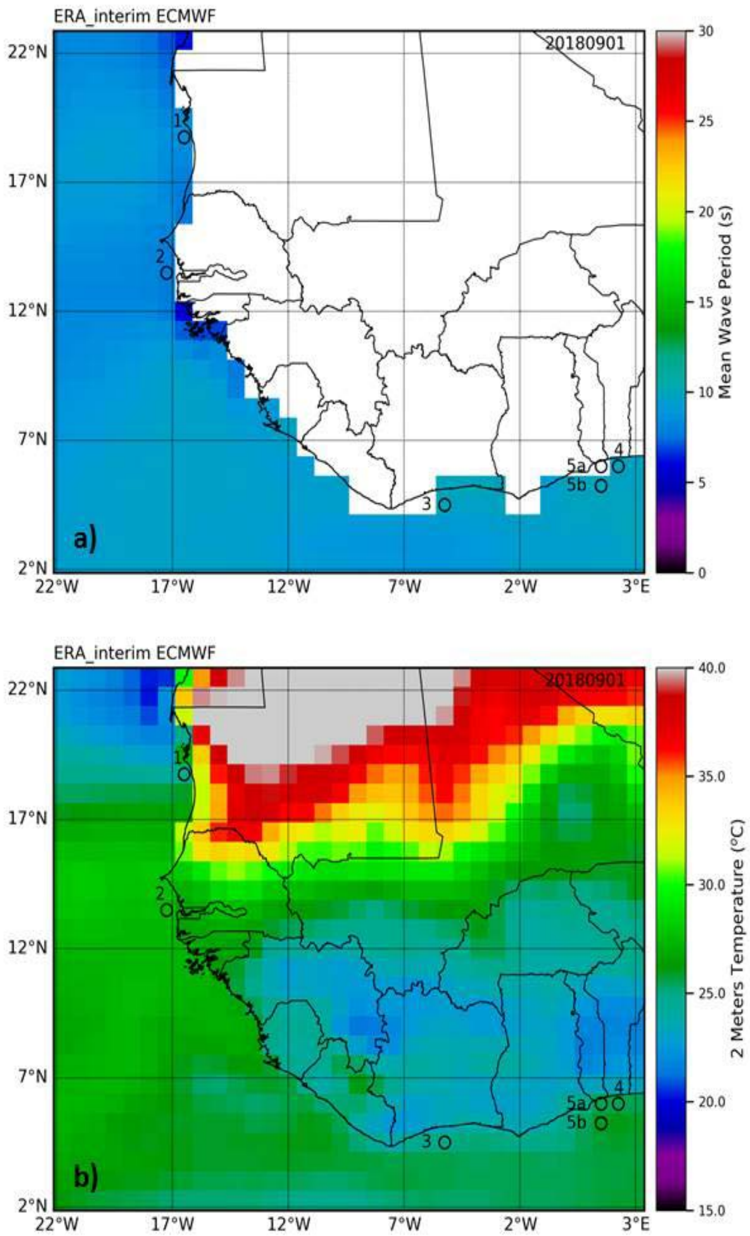


Table 1: Era-Interim extracted daily parameters in each location point and coordinates		
Atmospheric	**Oceanographic**	**ERA Grid Point coordinates**
Mean 2 meters Temperature **10 meters U wind component** **10 meter V wind component** **Mean sea level pressure** **Total daily precipitation**	Sea surface temperature Mean wave direction Mean wave period Significant height of combined wind waves and swell	1)Mauritanian coast, 18.75°N, 16.5°W 2)Senegal coast, 13.5°N, 17.25°W 3) Côte d'Ivoire, 4.5°N, 5.25°W 4)Benin coast, 6.0°N, 2.25°E 5)Togo coast 5a)Atmospheric: 6.0°N, 1.5°E 5b)Oceanographic: 5.25°N, 1.5°E

Climate data projection extraction for each country

Projection data for each country are obtained mainly from the World Bank Climate Change Knowledge Portal (CCKP). Data used in this portal is described in the CCKP metadata document (CCKP 2017). Projections are generated from the fifth iteration of a globally coordinated experiment collection known as CMIP5 (Taylor et al. 2012) providing information for the scenarios RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5. Results for RCP 4.5 and RCP 8.5 are obtained for the present study for each country and time horizons, mostly for 2030. The CCKP-CMIP5 collection consists of 35 models. For the African ensemble, results from 16 models were available as shown in Table 2.

Table 2: Climatic models for the African ensemble			
Model	**Modeling Center**	**Institution**	**Terms of Use**
BCC_CSM1_1 **BCC_CSM1_1_M**	BCC	Beijing Climate Center, China Meteorological Administration	unrestricted
CCSM4	NCAR	National Center for Atmospheric Research	unrestricted
CESM1_CAM5	NSF-DOE-NCAR	National Science Foundation, Department of Energy, National Center for Atmospheric Research	unrestricted
CSIRO_MK3_6_0	CSIRO-QCCCE	Commonwealth Scientific and Industrial Research Organization in collaboration with the Queensland Climate Change Centre of Excellence	unrestricted
FIO_ESM	FIO	The First Institute of Oceanography, SOA, China	unrestricted
GFDL_CM3 **GFDL_ESM2M**	NOAA GFDL	Geophysical Fluid Dynamics Laboratory	unrestricted
GISS_E2_H **GISS_E2_R**	NASA GISS	NASA Goddard Institute for Space Studies	unrestricted
IPSL_CM5A_MR	IPSL	The Institute Pierre Simon Laplace	unrestricted

MIROC_ESM MIROC_ESM_CHEM	MIROC	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	non-commercial only
MIROC5	MIROC	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	non-commercial only
MRI_CGCM3	MRI	Meteorological Research Institute	non-commercial only
NORESM1_M	NCC	Norwegian Climate Centre	unrestricted

As described in the CCKP metadata document, because all original model outputs are offered on their own native grids, the multi-model CMIP5 model collection is re-gridded to a common resolution of 1°x1° through bi-linear interpolation.

For each model, and for each of the four selected variables, 20-year climatology scenarios were generated. The 'baseline' interval (1986-2005) was derived from the historical simulations, while the future climatology (2020-2039, 2040-2059, 2060-2079, 2080-2099) were computed for all RCPs. This climatology consists of 12 monthly average values and one annual mean value established over the respective time windows (sums for precipitation).

A simple bias correction step was performed on the model's temperature data using the CRU-TS3.24 data (Harris and Jones 2014), as the observational baseline. Each model's mean temperature was adjusted by the bias in their annual mean. For precipitation, this correction was not performed because of large uncertainties across the different gridded observational datasets that are available.

For each model, each variable, and for each of the four future time windows, anomalies for each month as well as the annual value were computed and assessed relative to their corresponding historical reference period (1986-2005). The anomalies from each of the models in the collection, and for every 20-year climatological period in the future, ensemble values were calculated that describe how the collection of 16 CMIP5 models on average project the climatological changes using the median (50th-percentile) of the individual model values and the extreme values. Along with the mean value of the ensemble, the range of each climatological anomaly is provided through the high (90th-percentile) and low (10th-percentile) values for the projected data.

Because individual models might potentially exhibit substantial biases, this composite approach of an ensemble characterization is significantly more useful for depicting the future climate than a direct ensemble visualization generated on the raw climatology of each of the individual climate model. The main uncertainty factor of an ensemble based on multi-model runs is the different internal model parameterization schemes that cause a spread of parallel results.

Coastal inundation maps caused by SLR, tides, waves, and extreme precipitation events

SLR is a crucial parameter related to coastal inundation and erosion hotspot identification. Effects of SLR in coastal areas dramatically increase when SLR extreme events caused by strong wind, waves, and precipitation occasionally occur. From reports and SLR indices in countries' tables, Tables 3 and 4 were developed with key numbers to make simulations to identify coastal areas exposed to floods. For these simulations, 90 meters spatial resolution Shuttle Radar Topographic Mission (SRTM) digital elevation data files (Jarvis et al. 2008, Reuter et al. 2007) available for the five African countries were used to evaluate costs of inundated areas worldwide as described in previous studies, Nicholls, R. et al. (2008) and S. Jevrejeva et al. (2018).

The SRTM vertical axis is set to EGM96 geoid that is the orthometric elevation and therefore is a proper approximation to elevation from mean sea level. SRTM Data from coastal areas are obtained from web sources[6] and processed to correct low confidence height points using the nearest high confidence points. Once the SRTM DEM (Digital Elevation Data) is processed, the SLR simulation is performed for each circumstance described in Tables 3 and 4 (SLR + mHT, SLR + MHT, SLR + mHT + Storm Surge event, SLR + mHT + Precipitation Extreme). The results obtained with the simulation are shown for each country throughout maps of exposed coastal areas to floods and with tables that measured the inundated areas in square kilometers with particular interest for the urban areas developed along the coast. The tables can be found in Annex 1. Here, also low areas far from the coast were considered as there is a risk of being inundated in the next time horizons (2050 - 2100) while the mean sea level is slowly rising. These are considered as exposed areas to inundation and where no human and development activities should be planned.

Sea level values shown in Tables 3 and 4 come from values shown in the climate change projection tables in the present report for each country (Tables 8, 11, 14, 17, and 20). Data in each table for sea level parameter are obtained from IPCC and other official studies. It is important to underline the challenges to estimate reliable sea level rise in the five countries due to scarcity of studies focused in these specific regions and countries. As shown in these tables, many SLR values were not found for different RCPs or time horizons. Therefore, the five countries are grouped into two climatic areas:

1. Dry Sahelian countries (Mauritania and Senegal)
2. Wet south Western African countries (Côte d'Ivoire, Togo and Benin)

For Mauritania and Senegal (Table 3), sea level projection results come from (IOC 2009), Perrette et al. (2012), and Niang et al. (2014). Variability value on SLR (first line) depends on variability results from different studies for the different grouped countries. For Mauritania and Senegal, variability shown in Table 3 are taken from Tables 8 and Table 11.

The mean high tide (mHT) and maximum high tide (MHT) are measured from mean sea level. Therefore, it is half of the complete tide range. Tides of Table 3 are obtained from a study driven by Diaw et al. (2016) for Senegal and Senhoury et al. (2016) for Mauritania while the results about Togo, Benin, and Côte d'Ivoire are shown in Table 4. In both tables, data about severe events that affects sea level, such as strong waves and extreme precipitation events, are also considered. Information about storm surge were collected from Vousdoukas et al. (2018), from DG-Eau (2015) about strong swells for Benin and from Antea Group b (2017) regarding the situation in Togo.

Mean and maximum high tides variabilities in both tables are obtained using the WXTide software executed for each country's main coastal city. Mean and maximum high tide values from reports were also assessed using this software. Tide variability is added to the SLR variability. An increment of sea level of 1 meter due to storm surge events is given for the West Africa Region as shown in the study of Vousdoukas et al. (2018). These events, generated by strong winds and waves directed towards the coast, need sustained winds (lasting more than 5 hours) of 12 m/s or greater and with a fetch length of 400 to 700 kilometers as described by the Simple Coast toolkit described by Giardino et al. (2017). These wind conditions can occur once every two years in any of the countries analyzed in this study. Storm surge event is combined with mHT rather than with MHT because the former occurs with much greater frequency of occurrence (two times per day) in respect with the latter (two or three times per month), as shown in the last column of Tables 3 and 4.

An increment of coastal water level of 1.40 meters generated by strong precipitation events in the nearby coastal lakes and rivers is obtained from the UNISDR Global Assessment Report (2015). This corresponds to the first 25 percentile of the second flood level, between 1.1 and 3 meters, that are set in the 25 years return period maps for each of the five countries. In this approximation it is assumed that expected storm surge levels (1 meter) and extreme precipitation level (1.4 meters) remain the same for all the century.

[6] http://srtm.csi.cgiar.org/

Table 2: Sea Level Rise (SLR) estimates in meters from model projections for Mauritania and Senegal, adding effects of high tides and extreme events from the most frequent issue to the lowest							
SLR Projections in meters for Mauritania-Senegal	RCP 4.5			RCP 8.5			Frequency of inundation occurrence
	2030	2050	2100	2030	2050	2100	
SLR (Mean value and variability)	*	0.20 ±0.32	0.86 ±0.45	0.18 ±0.02**	0.60 ±0.46	1.06 ±0.65	Continuous
SLR + mHT mHT = 0.60 ± 0.30 m		0.75 ±0.60	1.41 ±0.75	0.73 ±0.30	1.15 ±0.75	1.61 ±0.95	Semi-diurnal tide, two times per day
SLR + MHT MHT = 0.80 ± 0.30 m		0.95 ±0.60	1.61 ±0.75	0.93 ±0.30	1.35 ±0.75	1.81 ±0.95	Two or three times per month
SLR + mHT + Storm Surge event (+1.00 m)***		1.75 ±0.60	2.41 ±0.75	1.73 ±0.30	2.15 ±0.75	2.61 ±0.95	One time every two years
SLR+ mHT +Precipitation Extreme(+1.40 m)***		2.15 ±0.60	2.81 ±0.75	2.13 ±0.30	2.55 ±0.75	3.01 ±0.95	25 years return period

* No SLR value found for RCP4.5 for 2030.

** Variability not available by the reports in each country, this variability value was obtained from the difference of sea level rise projection in Mauritania (18 cm, table 8) and Senegal (20 cm, Table 11).

*** No variability value is available.

Table 3: Sea Level Rise (SLR) estimations in metres from model projections for Cote d'Ivoire, Benin and Togo, adding effects of high tides and extreme events from the most frequent issue to lowest

SLR Projections for Cote d'Ivoire-Benin-Togo	RCP 4.5			RCP 8.5			Frequency of inundation occurrence
	2030	2050	2100	2030	2050	2100	
SLR	*	0.20 ± 0.10	0.95 ± 0.45	0.10 ± 0.06	0.31 ± 0.16	1.03 ± 0.60	Continuous
SLR + mHT **mHT = 0.60 ± 0.30 m**		0.70 ± 0.40	1.45 ± 0.75	0.60 ± 0.45	0.81 ± 0.45	1.53 ± 0.90	Semi-diurnal tide, two times per day
SLR + MHT **MHT = 0.70 ± 0.30 m**		0.90 ± 0.40	1.65 ± 0.75	0.80 ± 0.45	1.01 ± 0.45	1.73 ± 0.90	Two or three times per month
SLR+mHT+ Storm surge event (+1.00 m)**		1.70 ± 0.40	2.45 ± 0.75	1.60 ± 0.45	1.81 ± 0.45	2.53 ± 0.90	One time every two years
SLR+mHT+ Precipitation Extreme (+1.40 m)**		2.10 ± 0.40	2.85 ± 0.75	2.00 ± 0.45	2.21 ± 0.45	2.93 ± 0.90	25 years return period

* No SLR value found for RCP4.5 for 2030.

** No variability value is available.

Coastal erosion evaluation maps and tables

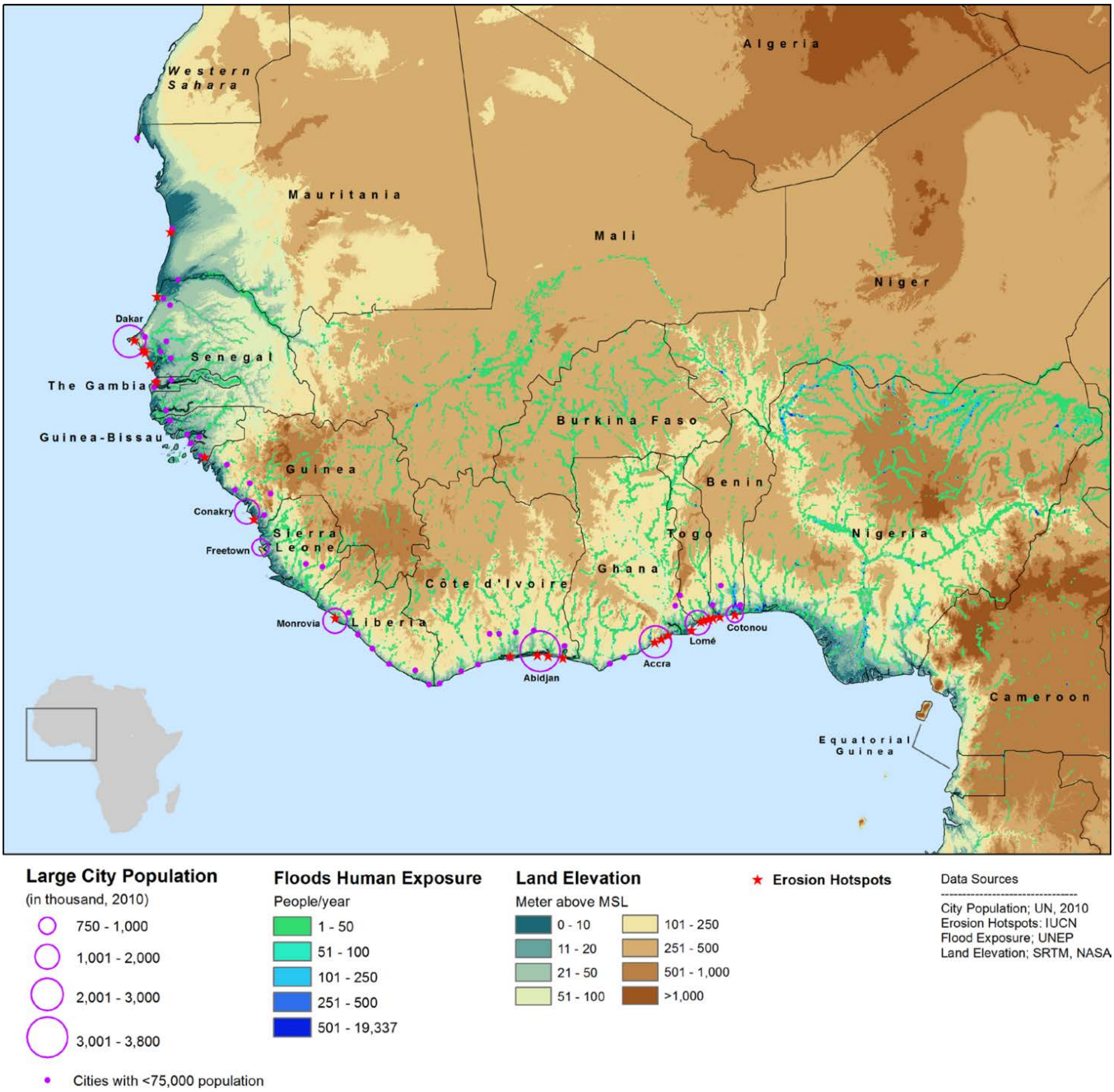
In this work, the phenomenon of coastal erosion has been studied by combining the information provided in the literature with the analysis of satellite imageries. By using satellite data, it has been possible to compare images from the past with recent images, observe how the coastline has changed over the years, and how it will potentially change in the future. To assess how the coastline has changed in the past, we used the following approach. First, we set a baseline period to evaluate the situation of the coastline and marked the coastline. The baseline period has been set for 1984, as satellite images from earlier years were not useful for the purpose of these study due to their low quality. Second, we overlapped more recent satellite images from 2015 and calculated the eroded areas by marking the new shape of the coastline.

After observing how the coastline changed in the past, we estimated how it will change in the future by using a dynamic evolution method. First, to assess how much the coastline will be eroded in the near future, we calculated the erosive rate of the period 1984-2015 and projected it to the time horizon 2030. We then calculated the eroded areas for the time horizons 2050 and 2100 by overlapping the inundation maps that were generated to assess the exposed areas to coastal flooding and riverine inundation. In this way, we were able to detect the low-lying areas and evaluate the effect of coastal erosion under the two RCP scenarios. A similar method was applied in previous studies about the coastlines of Togo, Benin, and Côte d'Ivoire (IMDC 2017d.

REGIONAL SUMMARY

The region of West Africa can be divided into two main eco-geographic areas: the area of Sahel, where Mauritania and Senegal are located, and the area of the Gulf of Guinea, where Benin, Côte d'Ivoire, and Togo lie close to each other (IIED 2005). See Figure 2.

Figure 2: Map of West Africa



Source: WB 2016.

Characteristics of coastal zones

The coast of West Africa extends from Mauritania to Benin over more than 10,000 kilometers (UEMOA 2016). The majority of the West Africa coastal zone is composed mostly of sandy shorelines, while rocky coasts represent less than 3% of the estimated shoreline. Considering its physical characteristics, the coastline can be divided in five distinct major coastal profiles from North to South (UEMOA 2010):

- From Mauritania to the Cape Verde peninsula: a straight coastal region composed for most part of sandy formations and vast expanses of low-lying salt marshes situated below the seal level in some places.

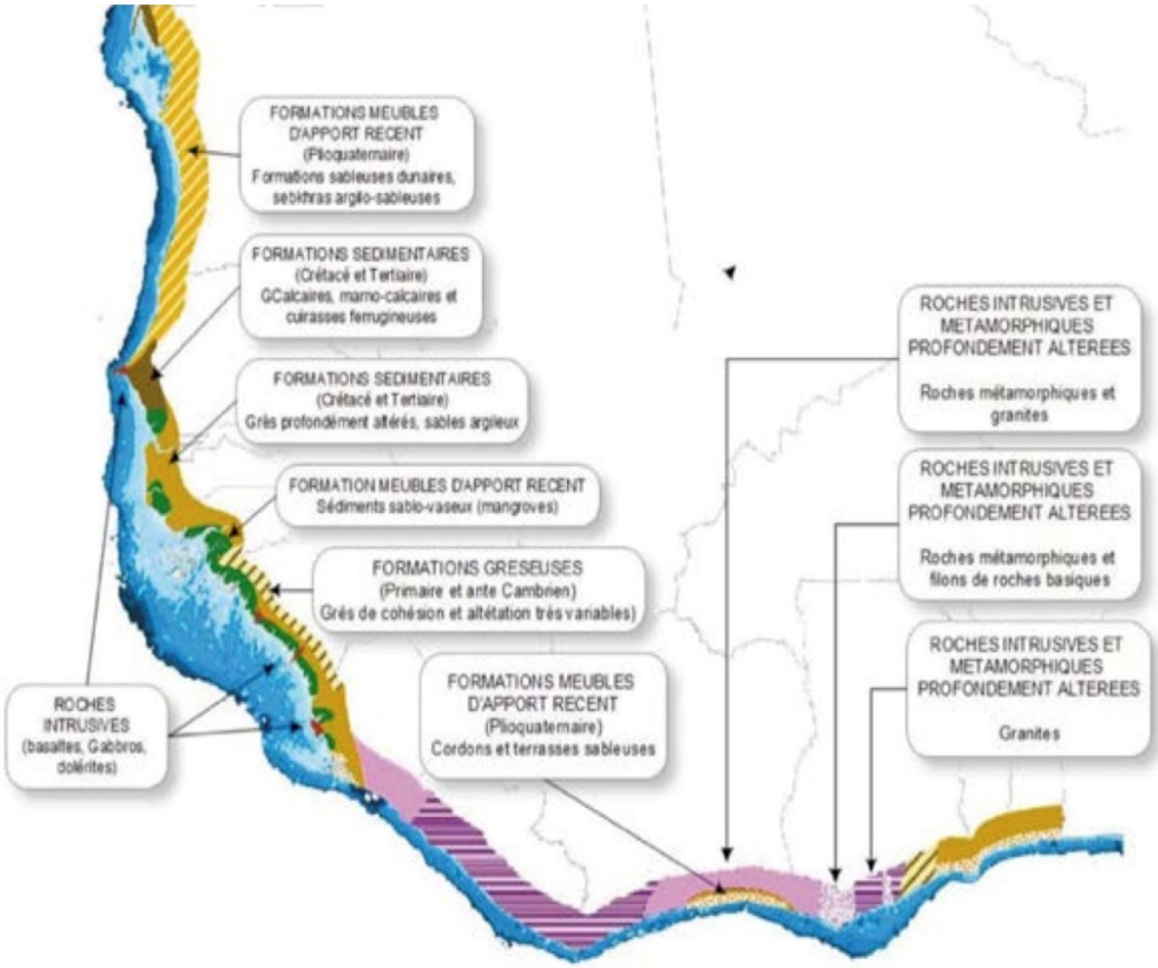
- From Cape Verde peninsula to Basse Casamance in Senegal: a coastal region with headlands and softened coves characterized by rocky outcrops of sandstone and fragile cuirass.

- From Siné Saloum in Senegal to Shebro islands in Sierra Leone: a coastline characterized by the presence of mangroves.

- From Liberia to West of Côte d'Ivoire: a coastal zone of rocky headlands and sandy coves.

- From West of Côte d'Ivoire to Benin: two large sediment basins of soft coastlines characterized by important lagoon and channel systems parallel to the coast and situated behind a sandbank that is very narrow in places (lidos).

Figure 3: Physical characteristics of West African coastline



Source: UEMOA 2010.

General climate characteristics in the West Africa coastal zone

The region of West Africa is geographically bounded by the Atlantic Ocean to the west and south and by the Sahel-zone to the north and to the east. On average, the region is around 300 meters above sea level with only a few mountainous regions (Riede et al. 2016). The climate along the coast of West Africa is of an equatorial type. However, considerable differences exist based on the seasonal distribution of precipitation. Based on the difference in the amount of rainfall, it is possible to identify three climatic zones in West Africa (IIED 2005):

- *Sahelian climate zone*: a semi-arid region with only one rainy season lasting no more than 3 months with less than 500mm and a maximum rainfall occurring in August;
- *Sudanian climate zone*: a sub-humid zone with precipitation ranging from 200 mm to 1000 mm;
- *Gulf of Guinea climate zone*: a tropical humid climate with an average of annual rainfall higher than 1500 mm.

Temperature

Annual temperatures in the region are in the range of 26-30°C with significant overnight temperatures and near-surface humidity in winter: in the Sahel night-time temperatures regularly fall below 10°C with relative humidity below 50 percent; on the Guinea Coast minimum temperature is not less than 18°C with a high level of humidity.

Rainfall

Rainfall is a decisive indicator of climate in West Africa and an essential element due to its influence on agriculture which forms the basis of the region's economy. Though difficult to analyze, an overall decrease in annual rainfall has been observed since the 1960s, ranging from 20-40 percent depending on the area, while arid zones have experienced more prolonged and frequent droughts (USAID 2012).

Tides

The tides are mainly semidiurnal for the whole zone with two daily maxima and two daily minima. The semidiurnal tide occurs almost simultaneously along the relevant part of the coast with an average range of about 1 meter (Giardino et al. 2016). Other studies agree with this tide range in general as shown in the next table. Only the first case of Mauritania corresponds to a study made using old data from a study from 1995 (Mohameden 1995) that considers data recorded from one measurement station before the construction of the port of Nouakchott. Here it is shown a slightly different result compared to the tide data shown in Table 3 obtained from the WXTide software for the area along the Nouakchott city coast combined with the Dakar city coast in Senegal.

Table 4: Information about tides in the five countries of the study

Country	Type	Average Range	Source
Mauritania	Semidiurnal	0.93 m	Niang et al. 2010
Senegal	Semidiurnal	± 1 m (0.50 -1.40 m)	Gueye et al. 2010
Benin	Semidiurnal	± 1 m	Laboratoire de Géologie, Mins et Environnement 2010
Togo	Semidiurnal	± 1 m	Blivi et al. 2010
Côte d'Ivoire	Semidiurnal	± 1 m (0.40 - 1.30 m)	Yao et al. 2010

Extreme Weather

In the past two decades, extreme weather events such as storms and severe flooding have become more frequent and intense especially in the coastal zones (UEMOA 2010). The wind is a persistent south-westerly monsoon modified by land and sea breezes in the coastal areas. Wind speeds vary between 0-5 m/s during the night and 1.5-2 m/s during the day with weaker line squalls and heavy rain and strong winds of short duration occurring occasionally (Giardino et al. 2016). Waves reaching the coastline can originate from the weak local monsoon surface wind or by swells that are produced by storms occurring in the southern part of the Atlantic Ocean. Locally generated waves rarely exceed 1.25 meters in height with a maximum period of 3-4 s, while swell-waves can reach an average height of 1-1.5 meters with periods varying between 8 and 20 s, although heights of 2-3 meters and more can occur. Dominant wave propagation direction is S-SW.

Observed climate change at the regional level in West Africa's coastal areas

Temperature

Observed trends across West Africa show an increase of average temperatures slightly higher than the global average. Between 1961 and 2000, the number of cold days and nights have decreased while the number of warm days and nights have increased (Niang et al. 2014). An average temperature increase of +0.5-0.8°C was registered in the region for the period 1950-2010 (USAID 2018).

Precipitation

A decrease in total precipitation was registered from 1901 to 2013. In the area concerning Senegal and Gambia, it represented -6%, and in Côte d'Ivoire it was limited to -3%. No changes in precipitation over this period have been observed in the area of

Togo and Benin. However, recently from 1983 to 2013, total rainfall has increased up to +4% in both countries.

Sea Level Rise
The historical tide gauges show that in the past 100 years, sea level has risen around 20 centimeters. The spatial distribution of the sea level rise signal is nonetheless far from uniform (Goussard et al. 2014). SLR has increased up to +8.4 cm from 1942 to 2012 in Dakar, Senegal, and a greater increase of about 25 cm was registered since the 1930s in Takoradi, Ghana (USAID 2018).

Future climate change projection

The evolution of climate change in this area is characterized by significant uncertainty and is still subject to further studies. The Fifth Assessment Report (AR5) from the Intergovernmental Panel on Climate Change (IPCC) represents the most extensive work on climate analysis and the main source of information on future projections. The report concludes that Africa is one of the most vulnerable continents due to its high exposure and low adaptive capacity (Niang et al. 2014).

Temperature
Although future temperature trends show uncertainty, this does not compromise the credibility of projections. According to the *Atlas of Global and Regional Climate Projections* (IPCC Atlas 2013), the temperature in West Africa is expected to rise to +1.25°C in 2050 and to +1.8°C at the end of the century for the RCP 4.5 and +2°C in 2050, and almost +4°C in 2100 over most of the area of the region for RCP 8.5.

Precipitation
The projected changes in rainfall trends by the 2050s are less certain than for temperature. For vast parts of West Africa, climate models do not agree on whether rainfall will increase or decrease, and in many cases, models show significant trends in both directions (Hartley at al. 2016). Due to the inability of GCMs to resolve convective rainfall and complex topography of the region, precipitation projections in the CMIP5 archives show inter-model variation for amplitude and direction of change, thus generating low to medium confidence in the robustness of regional precipitation change (Niang et al. 2014). Although the mean precipitation response in West Africa is less robust than in East Africa, the increase in the number of extremely wet seasons is comparable in both, increasing to roughly 20% (i.e., 1 in 5 of the seasons are extremely wet compared to 1 in 20 in the control period in the late 20th century) (Christensen et al. 2007).

Sea level rise (SLR)
Sea level will rise because of thermal expansion of water masses due to warming of ocean surface temperature, reduction of liquid water storage on land, and loss of land ice from mountain glaciers, ice caps, and ice-sheets. SLR represents a threat for West Africa coastal communities and is linked to various coastal hazards such as storm surges, inundation of low-lying areas, beach erosion, and damage to coastal infrastructure and ecosystems (Nicholls et al. 2007).

SLR is not uniform around the world but changes in every region due to different characteristics such as shifting surface winds, expansion of warming ocean water, addition of melting ice, as well as distribution of land ice or sediment compactions and tectonics. Decennial regional sea level changes may differ substantially from a global average, showing complex spatial patterns which result from dynamic oceanographic processes, movements of the sea floor, and changes in gravity due to water mass redistribution (land ice and other terrestrial water storage) in the climate system (Church at al. 2013).

There is a significant lack of information about SLR data in the West Africa region that does not allow the generation of future projections with high confidence because very few regional climate models or empirical downscaling have been constructed to assess climate change scenarios in the area (Boko et al. 2007). Although this rise cannot be estimated accurately, a rise greater than the global average is expected (UEMOA 2012). According to the literature (IPCC 2014, CSE and IUCN 2017), in the whole region of West Africa, sea level is expected to rise up to +0.26 m in 2050 and +0.47 m in 2100 under RCP 4.5. Under RCP 8.5, sea level is expected to reach +0.30 m in 2050 and between +0.52 and 0.98 m at the end of the century (see Table 6). Note that these values that refer to the regional area may change when more detailed areas are considered, as shown in Table 3 (Mauritania and Senegal) and Table 4 (Togo-Benin and Côte d'Ivoire). The impacts of rising sea level are already visible on the West Africa coast. This happens especially when heavy swell periods combine with storm surges.

Storm Surges

Storm surges have exceeded 1 meter in Senegal and Benin, surpassing decennial wave heights, and causing consistent damage to human settlements, goods, means of production, and essential infrastructure (UEMOA 2017). SLR, combined with increased intensity of extreme events, could cause frequent flooding and submerge entire areas, causing considerable damage. Storm surges may further contribute to changes in sea level extremes, but the small number of regional storm surge studies and uncertainty in changes in tropical and mid-latitude cyclones at the regional scale means there is low confidence in storm surge change projections (Wong et al. 2014).

Storm surges and extreme precipitation events are both linked to tropical cyclonic events hitting a coastal area with low sea level pressure, heavy precipitation, strong winds, and waves. West Africa is out of the paths of most dangerous tropical cyclones as shown in Figure 4a obtained from the UNISDR Global Assessment Report (2015) Risk Platform. In the last 50 years it has been registered as tropical cyclones in their initial growth stages, affecting some of the WACA countries as shown in Figure 4b, causing local floods and wind damage. They mostly move from east to west, i.e., from continent to ocean from July to October.

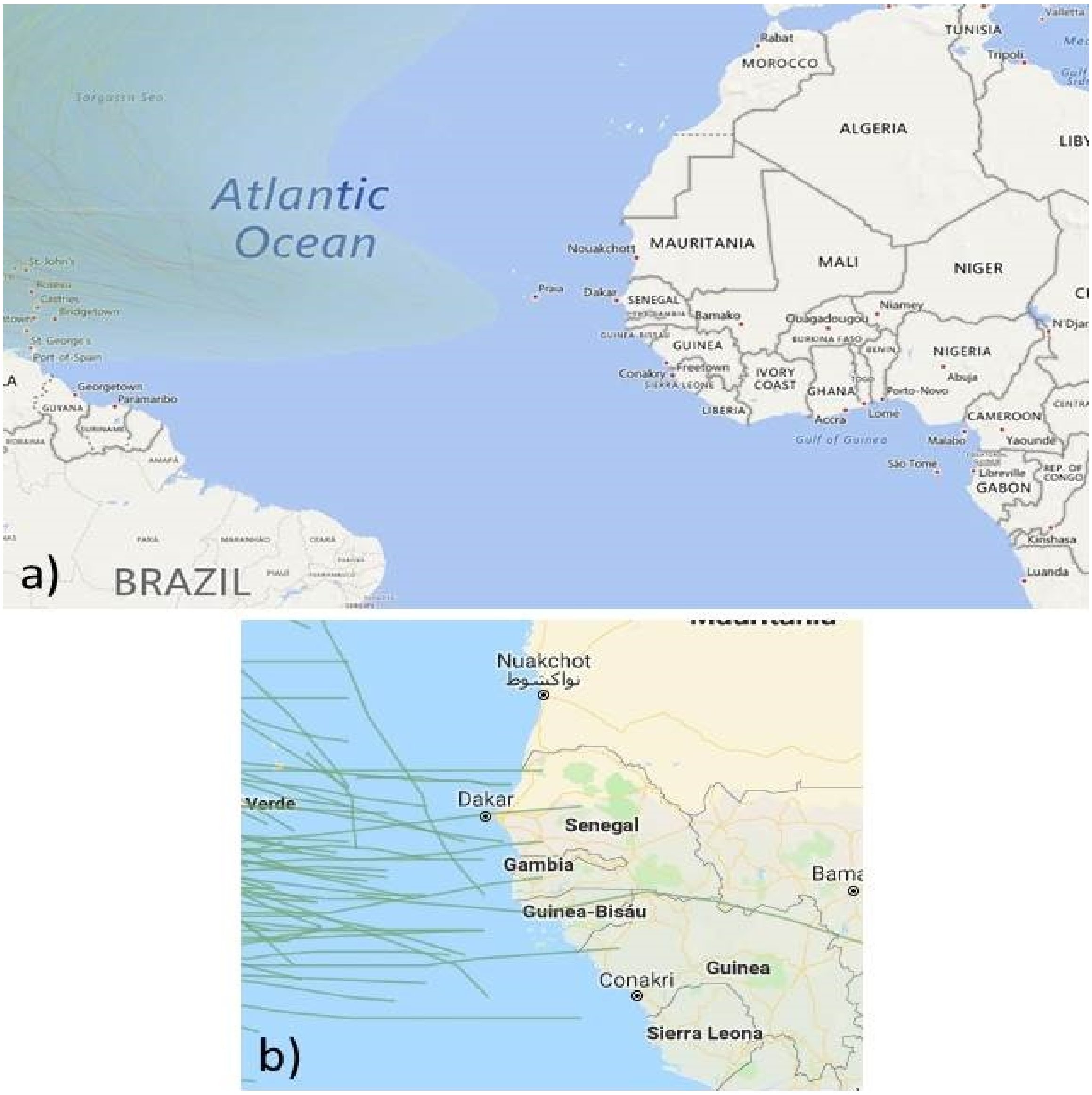
Table 5: Climate change parameters in West Africa.

Key Climate Variable	Representative concentration Pathways	2015-2025		2046-2065		2080-2100		Projection data source	Publication source
		Change	Range	Change	Range	Change	Range		
Sea Level Rise (cm)	RCP 4.5	*	*	+26	+19/+33	+47	+32/+63	Based on 21 CMIP5 models	IPCC 2014
	RCP 8.5	*	*	+30	+22/+38	+63 (CSE, IUCN 2014)	+45/+82		
Precipitation (%)	RCP 4.5	-10%/-20%	-0.5-/40% (USAID 2012)	Oct-Mar +5%	-10%/ +20%	Oct-March + 5%	-10%/+10%	42 CMIP5 models have been run for RCP 4.5 and 39 for RCP 8.5	IPCC 2013
				Apr-Sept 0%	-10%/ +10%	Apr-Sept + 5%	-10%/+10%		
	RCP 8.5		*	*	*	Dec-Feb + 6%	- 2%/ +13%	21 global models in the MMD were run for the A1B scenario that corresponds to (RCP 6-8.5)	Christensen et al. 2007
				*	*	Jun-Aug +2%	- 2% / + 7%		
Temperature (C°)	RCP 4.5	*	*	Dec-Feb +1.25	+1/+2	Dec-Feb +1.8	+1/+3°C	42 CMIP5 models have been run for RCP 4.5 and 39 for RCP 8.5	IPCC 2013
		*	*	Jun-Aug +1.25	+1/+2	Jun-Aug +1.8	+1/+3°C		
	RCP 8.5	*	*	+ 2°C (Riede et al. 2016)	*	Dec-Feb + 3%	+2.7%/+3.5%	21 global models in the MMD were run for the A1B scenario that corresponds to (RCP 6-8.5)	Christensen et al. 2007
						Jun-Aug + 3.2%	+2.7%/+3.7%		

Trends and range of values obtained from literature, IPCC reports, and internal government reports. The data projections extracted from IPCC reports take the period 1986-2005 as a baseline period. The other studies considered in this table use very similar baseline periods

* No change or variability data is available.

Figure 4: a) Paths of well-developed tropical cyclones from the mid-Atlantic, they mostly move from east to northwest. b) Tropical Cyclones track in their initial growth state leaving the African continent. (Source: UNISDR Global Assessment Report (2015) Risk Platform)



Climate change and natural hazards

Because of their proximity to the sea and because of the strong increase in human activities, coastal areas are severely vulnerable to the impacts of climate change. West Africa coastlines are highly populated and are the center of the main economic activities and infrastructure. The natural hazards that occur in this area include phenomena such as earthquakes, volcanic activity, landslides, tsunamis, tropical cyclones, and other severe storms, tornadoes, and extreme winds, coastal flooding, forest or bush fires, and smoke generated by those fires, droughts, sandstorms, and infestations (UEMOA 2016). However, coastal areas are mostly affected by erosive phenomena and flooding events. Therefore, their analysis will be proposed in the next paragraphs and for each country in the following chapters:

Erosion

One of the most serious consequences of climate change on West Africa coastal areas is erosion. The erosion of coasts is driven by both natural and human related factors. SLR is one of the major natural drivers of coastal erosion, but other factors such as altered wind patterns, offshore bathymetric changes, or reduced fluvial sediment input have significant impacts. Changing precipitation patterns, for example, decrease overall rainfall volume, causing reduction in the flow of rivers in the region, and leading to a decrease in sedimentation deposits that fosters erosion.

On the other side, the effect of human activities is detrimental and can exacerbate erosion in multiple ways, namely the construction of ports' infrastructure that disrupt the coastal drifts (witnessed in Nouakchott, Abidjan, Lomé, or Cotonou), the construction of dams that affects estuarine systems and hinders the transport of sediments, coastal sand and gravel mining, a very destructive and poorly managed (or unmanaged) practice that alters the beach fauna and flora, and has an impact on losing protection against storm surge and wave attack and construction of seafront buildings that result in the disappearance of beaches. The combination of these factors, both natural and anthropogenic, has led to severe land and shoreline loss over the coastline of West African countries (WACA 2016).

Flooding

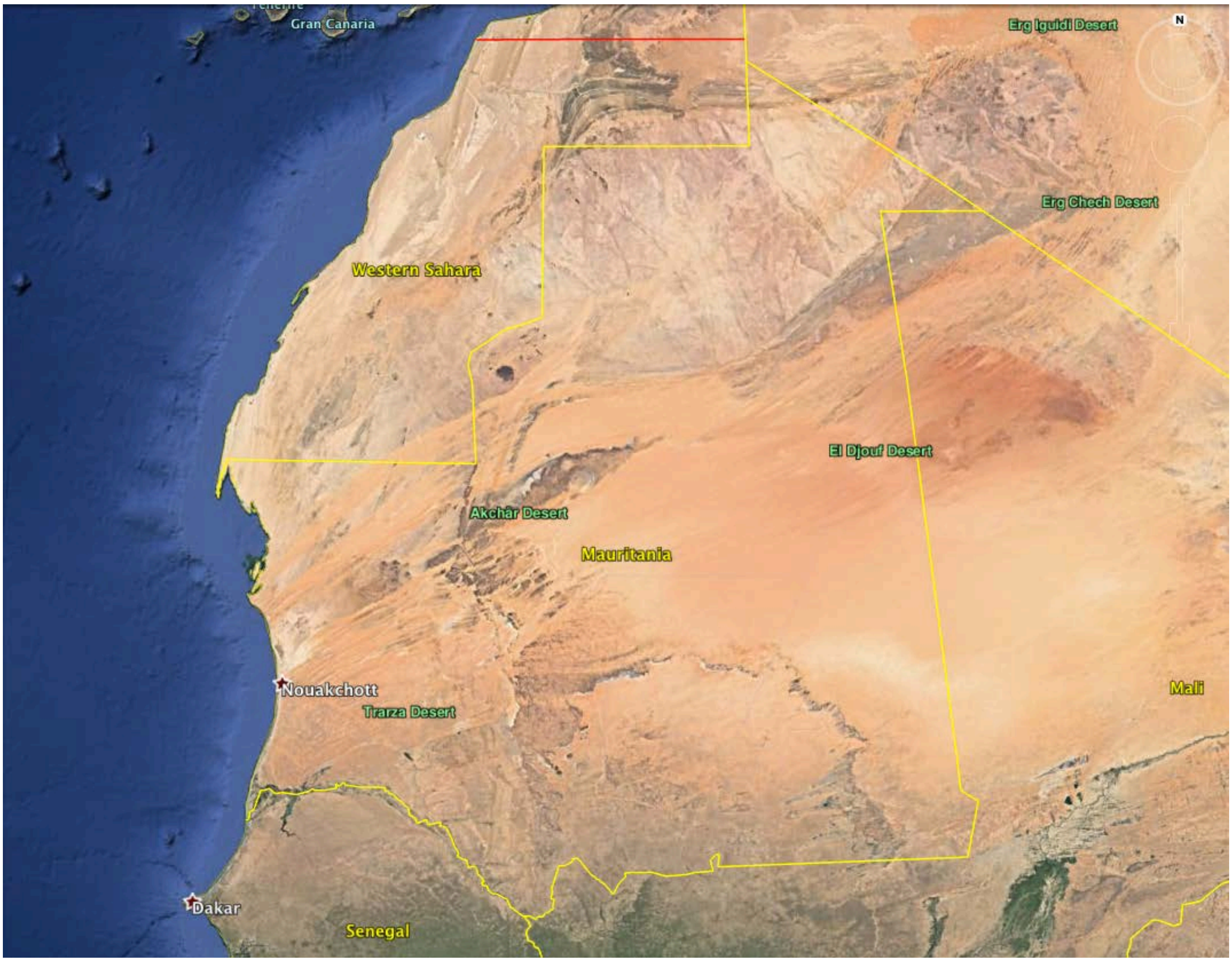
The increase in the intensity of precipitation and reduction in the return periods of certain extreme events along with SLR represent the major causes of coastal flooding of littoral zones. The West Africa region is one of the regions in the world with coastal zones and deltas that are the most exposed to risks of flooding due to high exposure of many areas to the mean SLR. When SLR is associated with extreme natural events, such as storm surges or extreme precipitation, the risk of flooding becomes even greater and low-lying coastal areas become more vulnerable.

Salt water intrusion

Although SLR cannot be estimated accurately in the region, a rise greater than the global average is expected. As mentioned above, this phenomenon will increase the frequency of storm surges, determine the erosion of coastlines, and generate flooding on low-lying areas with destructive effects. Another natural hazard that is expected to occur is related to more frequent intrusions of saline waters which may gradually make aquifers unfit for consumption and agriculture (the advancement of the saltwater wedge, alteration of freshwater lenses, and surface aquifers).

MAURITANIA

Figure 5: Map of Mauritania



Source: Google Earth.

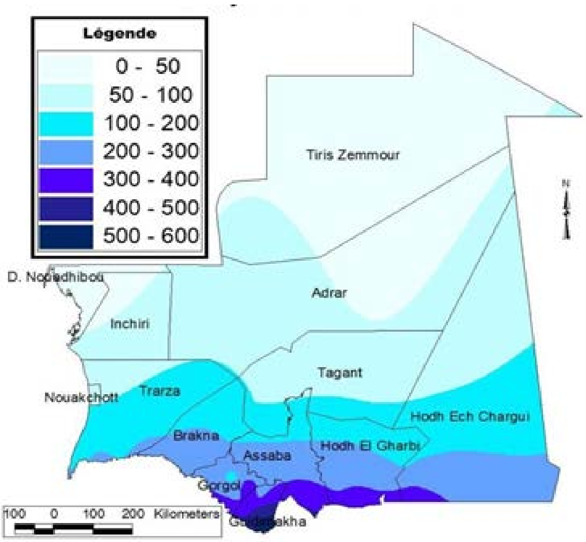
General climate characteristics of Mauritania

Three-quarters of Mauritania's territory is covered by the Sahara Desert, and the remaining quarter is located in the Sahelian zone. Both areas are characterized by a coastal zone and a mainland. The coastline in each climate area is characterized by relatively high humidity and small daily and annual variations in temperature. The mainland area shows much greater variations in temperature, both daily and annually, and an extreme dryness in the atmosphere, particularly in the Saharan region, which experiences a very low annual rainfall with high evaporation (MEDD 2004). Mauritania is therefore one of the most vulnerable countries to the effects of desertification that is worsened by winds in the country.

General data in Figure 8a obtained from the CCKP website for Mauritania show that temperatures are higher from April to September, and peaking in June, with mean values reaching up to nearly 36°C, while the lowest temperatures are recorded in December and January. The winds in Mauritania are generated by three main currents blowing throughout the year: the marine trade wind and the summer monsoon that bear precipitation, and the dry continental trade wind linked to the Sahara anticyclones.

Rainfall is very irregular from a minimum recorded of 5 mm to a maximum peak of 241 mm registered on a time horizon of 40 years (Senhoury et al. 2016). Storms are infrequent. However, it is observed that the frequency and intensity have increased since the 1990s. Prior to this date, storms have not occurred more than two times per year, while after this date, the rate has exceeded three times per year (Senhoury et al. 2016). Figure 6 shows precipitation intensity distribution in Mauritania, revealing that rainfall intensity increases towards the southern border of the country. In this sense, the coastal zone presents a more arid pattern, except for the area south of Nouakchott which is more prone to rainfall, with records ranging from 100 to 200 mm.

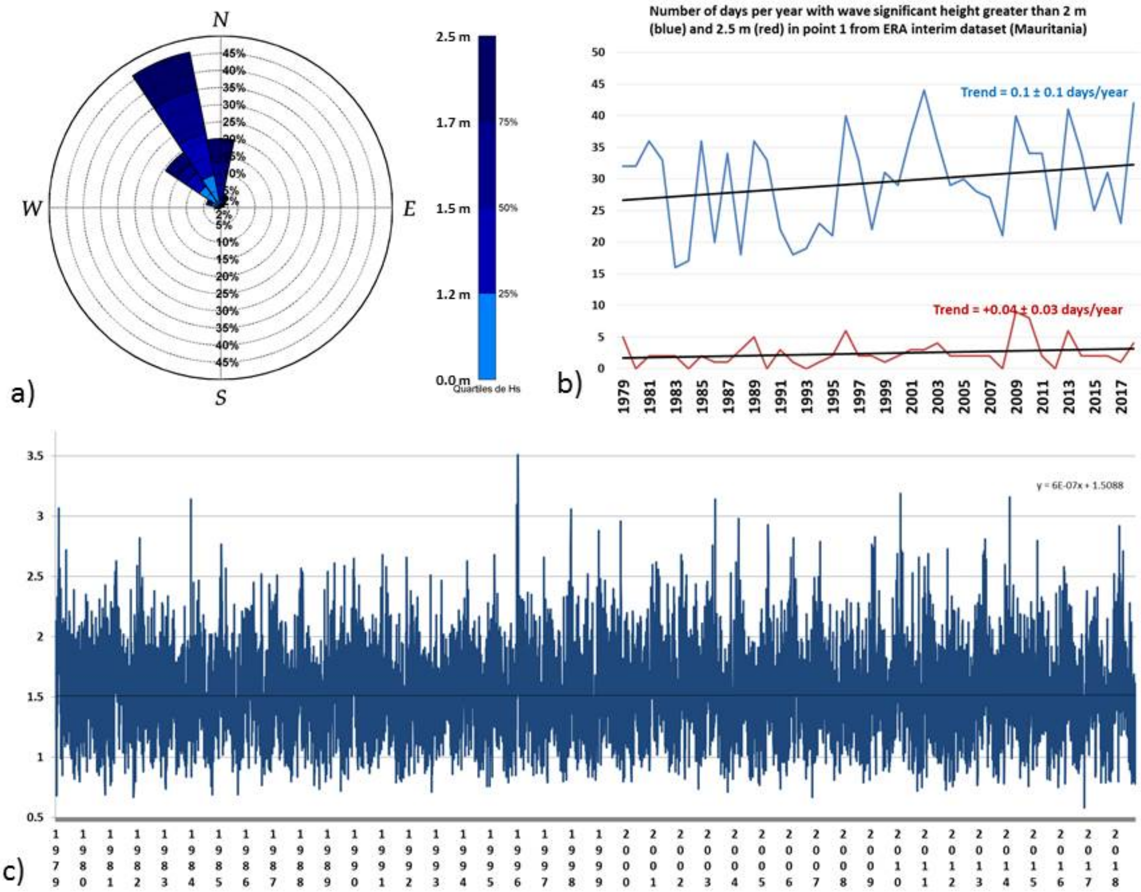
Figure 5: Distribution of isohyets from normal 1981-2010 (Map based on the rainfall records of AGRHYMET/RIM)



Source: MEDD 2014.

Two winds regimes are active in the area of Mauritania: the Atlantic monsoon that carry rain and the dry NNE trade winds linked to the Sahara anticyclones. The most frequent winds come from the NNW to the NW sectors (representing 39 percent of annual conditions) and from the N and NNE sectors (21 percent of the time) (Elmoustapha et al. 2007). Tides are mainly semidiurnal and the regime is microtidal, with maximum ranges attaining 2 meters during high spring tide conditions. Waves come mostly from NNW and NW with a mean height between 0.8 m and 2.0 m exceeding very rarely the height of 2,5 m as observed from ERA interim data analysis (Figure 7c). It is worth noticing, however, that according to the data time series shown in Figure 7c, the number of days with wave of a significant height exceeding 2 meters seems to increase in 1 day each ten years with a positive trend of 0.1 day/year. However, this data registers a high variability of ± 0.1 day/year that is between 0 and 0.2 day/year as shown in Figure 7b.

Figure 6: Oceanographic data from ERA-Interim in grid point 1 (18.75°N, 16.5°W) in front of the Mauritanian coast. a) Direction and significant heights of waves, b) Number of days per year with significant wave height greater than 2 and 2.5 m with linear trend, and c) Daily significant wave height time series from January 1979 to September 2018



Observed climate change in the coastal area and hotspots

Temperature

According to the ERA-Interim results shown in Table 7a from the analysis on the Mauritania coastal grid point in 18.75°N, 16.5°W, the mean temperature in the period 2008-2017 has slightly decreased -0.13°C during the winter months compared to the reference period 1986-2005. The variability of these data is high, and therefore not very reliable. In the same time horizon, the temperature has increased +0.58°C during the summer months (June-August) with a range between 0.27°C and 0.89°C. Figure 8 shows monthly series of temperature from the Nouakchott station (18.1ºN, 15.9ºW) provided by the World Bank from the U.S. National Climatic Data Center (NCDC). Here it observed an increase of the mean temperature during the period 1979 to 2016 with an annual temperature linear trend of +0.02°C/year.

Precipitation

The monthly average precipitation rates have revealed minor changes using ERA interim comparing the last ten years for the period 2008-2017 with the 1986-2005 period with generally very high variability in summer and winter. While during the winter months it is not possible to draw any conclusion due to the high variability, during the summer period it seems there is an increase of 0.02 mm (between -0.05 and 0.09 mm) from the ERA data as shown in Table 7a. Figure 8c shows how average rainy season precipitation (from June to October) in Nouakchott station seems to decrease during the longer period 1950-2016. However, starting from the 1970s, average rainy season precipitation has witnessed a significant increase of 0.5 ± 0.1 mm/season.

Sea level rise

A positive trend of 0.32 ± 0.06 cm/year is obtained from ESA satellites in the coast of Mauritania with respect to the sea level measured during the period from 1992 to 2007 as shown in Figure 8b and Table 7b. Assuming that this annual trend remains constant in the whole 15 years period (1992-2007), the total sea level change is 4.9 ± 1.4 cm. These numbers are obtained from the regression line ($y = 0.32 \cdot x - 0.3$) shown in Figure 8b with mathematical propagation of slope (trend) uncertainty (±0.06 cm/year) and offset uncertainty (±0.5 cm) as explained in the methodology section.

Table 6:

a) Change and variability of the last 2008-2017 period compared to the 1986-2005 period using the ERA grid point 1 (18.75°N, 16.5°W) data serie located in the coast of Mauritania

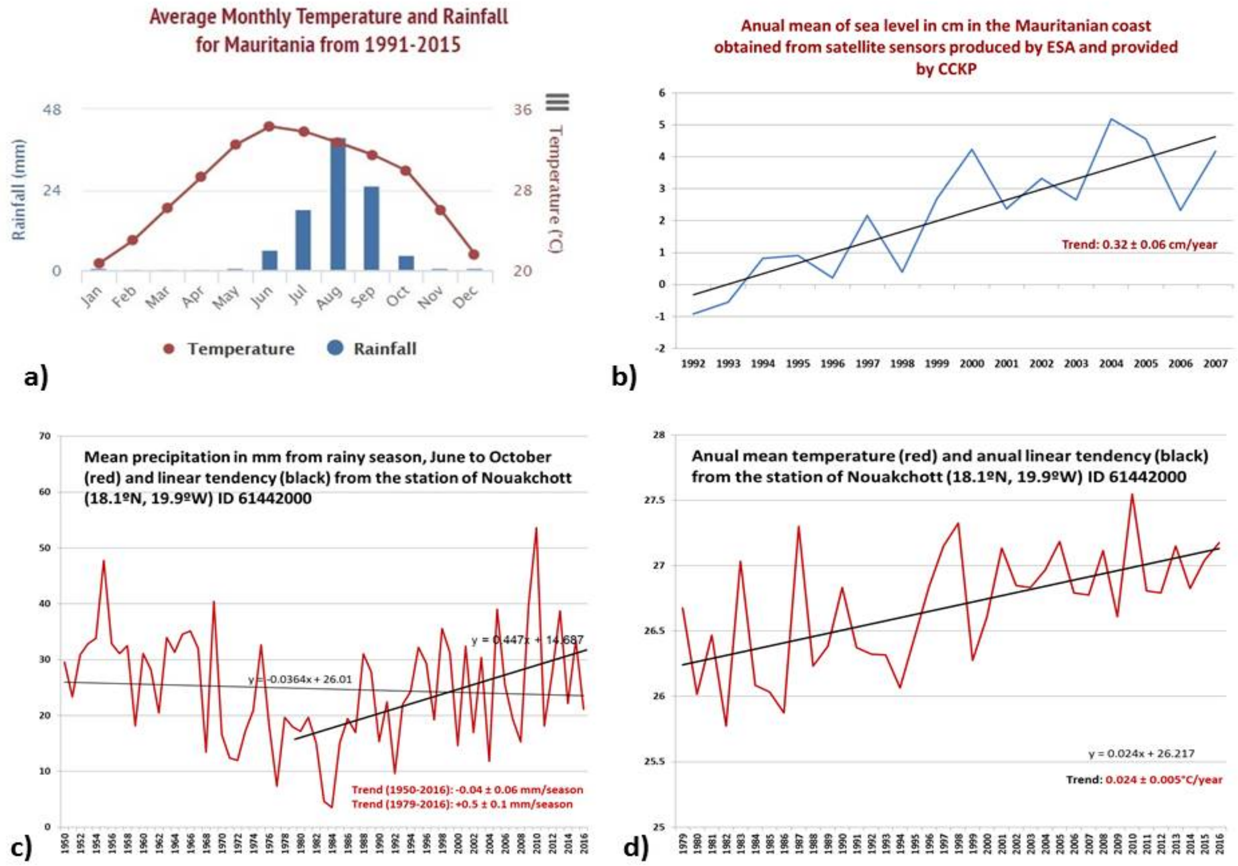
Parameter	Source data and used data period range	Dec-Feb		Jun-Aug	
		Change	Variability	Change	Variability
Temperature (C°/month)*	ERA-Interim **1986-2017**	-0.13	±0.16	0.58	±0.37
Precipitation (mm/month)*	ERA-Interim **1986-2017**	-0.05	±0.16	0.02	±0.10

b) Annual series trend and trend uncertainty

Parameter	Source data and used data period range	Trend	Trend uncertainty
Sea level rise (cm/year)**	ESA satellite altimeters **1992-2007**	0.32	±0.06
Temperature (C°/year)**	Nouakchott station (ID 61442000) **1979-2016**	0.024	±0.005
Precipitation (mm/rainy season)***	Nouakchott station (ID 61442000) **1979-2016**	0.5	±0.1
	Nouakchott station (ID 61442000) **1950-2016**	-0.04	±0.06

* Based on monthly averages from initial daily ERA dataset. Changes and variabilities between the two periods are obtained each month and later averaged for 3 winter or 3 summer months.
** Based on monthly measurements that are annually averaged.
*** Based on monthly measurements averaged from June to October (rainy season).

Figure 7: a) Country Mean monthly temperature and precipitation climatology from 1991 to 2015 obtained from CCKP web page for Mauritania. b) Country Annual mean sea level time series from 1992 to 2007 and trend. c) Mean seasonal (June to October) precipitation time series from 1950 to 2016 with trends for different periods on a station location. d) Mean annual temperature time series from 1979 to 2016 with trend on a station location



Future climate change projections

Temperature

A clear increase in temperature is expected to occur in the future for each time horizon and under both RCPs (see Table 8). A faster warming of the interior regions is occurring in the country compared to those closer to the coast. Summer months are projected to be slightly warmer than winter months, primarily between June and September (World Bank 2018b). In the period 2020-2039, the temperature is expected to increase about 1.1°C under RCP 4.5 and 1.3°C under the higher greenhouse gas emissions pathway RCP 8.5. Projections for the period 2040-2059 show an increase in temperature of more than 1.7°C for RCP 4.5 and almost 2.3°C for RCP 8.5. At the end of the century, temperature is expected to increase more than 2.2°C for RCP 4.5 and around 4.6°C for RCP 8.5.

Precipitation

Although the available information indicates that precipitation will decrease over the next century, the high variability shown in data does not allow to predict the trend with complete accuracy. Table 8 shows a higher decrease of precipitation during the summer months (June-August) instead of the winter season (December-February). A decrease of about 0.7 mm is expected to occur for the 2020-2039 time horizon under RCP 4.5 and of almost 0.6 mm under RCP 8.5, the latter showing a higher variability in the results.

In 2050, a decrease of 0.6 mm is expected to occur under RCP 4.5 and 1.1 mm for RCP 8.5, while for the end of the century the precipitation is expected to decrease 1.4 mm under RCP 4.5 and 2.5 mm under a RCP 8.5. Rainy seasons will experience a shortened duration but extreme precipitation events will occur with higher frequency, especially in the southern areas of the West African Sahel. The chance that precipitation will occur less frequently but with more intensity may lead to overall drier years and to an intensification of desertification for the country with the chance of more flooding events occurring.

Sea level rise

It is anticipated that in Mauritania, SLR will proceed at a faster rate than global averages with greater chances of coastal erosion and flooding events (World Bank 2018b). As shown in the table below, SLR is expected to reach up to +60 cm in 2050 under RCP 8.5, while in 2100 it could increase to +86 cm under RCP 4.5 and +106 cm for RCP 8.5.

Table 7: Climate change projections in Mauritania. The data are presented according to two RCP scenarios and for three time horizons that are compared to the reference period (1986-2005). Temperature and precipitation changes and variabilities are provided by the CCKP. The change is the multimodel median (50th-percentile) and variability is represented by multimodel 10th-percentile and 90th-percentile respectively

Key Climate Variable	Representative concentration Pathways	2020-2039		2040-2059		2080-2099		Projection data source	Publication source
		Change	Range	Change	Range	Change	Range		
Sea Level Rise (cm)	RCP 4.5	*	*	*	*	(2090-2099) +86	+66/+111	Projected total SLR for 4 components combined (OD, MGIC, GIS, AIS)	Perrette et al. 2012
	RCP 8.5	(2020) + 18 (IOC 2009)	*	(2050) + 60 (IOC 2009)	*	(2090-2099) +106	+78/+143		
Precipitation (mm)**	RCP 4.5	Dec-Feb -0.06	-1.4/+0.8	Dec-Feb -0.03	-1.6/+1.2	Dec-Feb -0.19	-2.01/+1.1	Results from 16 global circulation models (GCMs) are available for the African ensemble using the CCKP	CCKP
		Jun-Aug -1.4	-11.5/+6.4	Jun-Aug -1.17	-13.3/+14	Jun-Aug -2.58	-15.2/+19.9		
	RCP 8.5	Dec-Feb -0.08	-4.6/+7.4	Dec-Feb -0.2	-2.1/+0.9	Dec-Feb -0.3	-2.2/+1.2		

		Jun-Aug -1.23	-8.5/+20	Jun-Aug -2	-17.5/+16.0	Jun-Aug -4.7	-24.9/+22.1		
Temperature (C°)**	RCP 4.5	Dec-Feb +1.1	+0.6/+1.8	Dec-Feb +1.8	+1.7/+3	Dec-Feb +2.22	+1.2/+3.3		
		Jun-Aug +1.2	+0.6/+2.0	Jun-Aug +1.74	+0.9/+3.0	Jun-Aug +2.35	+1.3/+4.1		
	RCP 8.5	Dec-Feb +1.4	+0.6/+1.9	Dec-Feb +2.4	+1.6/+3.5	Dec-Feb +4.6	+3.5/+6.1		
		Jun-Aug +1.3	+0.7/+2.1	Jun-Aug +2.3	+1.3/+3.5	Jun-Aug +4.7	+3.5/+7.4		

* No change or variability data is available.

** Based on monthly measurements averaged for winter or summer seasons.

Climate change and natural hazards in Mauritania

Because of climate change on one side, and considering the topography of the littoral zone on the other, the shoreline of Mauritania is sensitive to the phenomena of erosion and flooding in several areas. Furthermore, despite the repetitive drought cycles that the country has experienced in the past, much of the population has moved towards the coastal cities and making them more vulnerable to the impact of these hazards. A description of future natural hazards in Mauritania is discussed below.

Erosion

As stated in the methodology, the study of coastline change has been carried out through the analysis of satellite imageries to gauge the extent of coastal erosion and to predict where further retreat is likely to occur (Figure 9). The effects of climate change, coupled with unsustainable human activities and illegal practices, are determining the erosion of the country's coastline and exposing it to further threats. As shown in Table 8, SLR is expected to increase up to +60 cm by 2050 under the RCP scenario 8.5. At the end of the century, this increase is expected to reach +86 cm according to RCP scenario 4.5 and +106 cm for RCP 8.5. Due to this increase, the beach will retreat and land will be lost with dangerous consequences, especially in the populated areas. Table 9 shows projections of coastal erosion in the most vulnerable areas of the country.

The results presented below indicate that erosion has caused morphological changes and generated land loss in the majority of hotspots analyzed. Only in two cases, the coastline has incremented presumably because of sediment accumulation due to the presence of infrastructure or artificial barriers. Nouakchott, for example, will witness a loss of -7.66 km^2 in 2050 under the RCP 4.5 and of -27.3 km^2 under RCP 8.5. Under the same scenario, a loss of -40.6 km^2 is expected to occur in 2100. Together with climate change, human activities are worsening the situation. For example, the construction of the *Port de l'Amitié*, carried out without taking into consideration the environmental impact assessment that was drafted (Senhoury A. et al. 2016), determined a change in the sedimentary transportation and a change in the evolution of the coastline. As a result, the northern area of the port witnessed a severe siltation of the coast, while the southern area suffered a significant erosion.

Other anthropogenic activities such as sand removal, construction of buildings on the coastal dune, recreational activities, uncontrolled grazing by animals, and the use of dune vegetation as firewood have also contributed to undermining the coastal system and creating new beaches. Today, 18 beaches have been identified and many of them are located on the coastal dune of Nouakchott.

Flooding

Flooding, salt intrusion, and loss of wetland biodiversity pose a great threat for the country. As sea level rises and natural sand dune defenses crumble, the coast is at risk of permanent inundation. This will negatively impact population settlements, aquatic resources, crop productivity, coastal erosion, and biological diversity. The strongest flooding events occur during the month of August and can affect both urban and rural areas (CCKP). Mostly below the city level, Nouakchott is also at risk of rising groundwater levels, seawater intrusion, and heavy rains resulting in flooding. A simulation using the numbers in Table 8 and SRTM as Digital Elevation Map (DEM) base map is performed around the city of Nouakchott, resulting in a large flood vulnerable area as shown in Figure 10 and Table A1-2 of Annex 1.

Only in the area shown in Figure 10a of 9,452 km^2, the inundation exposed area, taking the SLR+MHT case, is 621 km^2 for RCP 4.5, 2050 (6%) and 1,012 km^2 for RCP 8.5, 2,100 (11%) (See Table A1-2 of Annex 1). The main reason is that the coastal area is very flat and low in general along many kilometers to mainland with areas below sea level. The intensity of the floods has generally increased with a relatively high increase in the north and northwest of the country, low in the center, and medium to high in the south (MEDD 2014). All other low-lying coastal areas are significantly vulnerable to the risks of marine incursions and floods. Inland zones in the northwest and southeast are particularly vulnerable to erosion. For this reason, climatic disasters affecting the coastal zone will affect the economic growth of Mauritania, a country where the coastline represents both a singular ecosystem and the main pole of economic development.

Hotspots

Most of the sections of the coastline analyzed in Mauritania have shown erosion in the 1984-2015 period (see Table 9). Additionally, because of the low altitude of the country's coastal areas, sea level rise and storm surges will increase the possibility of coastal flood and damage the population and infrastructure that lie along the littoral. The hotspots identified for the purpose of this work are the cities of Nouakchott and Nouadhibou, not only because of the mere exposure to natural hazards, but mainly because of their vulnerability, being respectively the political and economic capitals of Mauritania:

Nouakchott

The capital of Mauritania, Nouakchott, is the largest and the most populated city of the country and lies on the Atlantic coastline. The city has developed rapidly over a low elevation plain protected by coastal dune bars which are a primary barrier from coastal tides. The erosion of the capital's coastline has been determined by both natural factors and human intervention. SLR, storm surge, and a strong southward sediment transportation determined by the action of waves coming from the north have combined with the negative effects of the construction of harbors, illegal sand extraction, and new urban development.

As shown in Table 8, erosion has occurred in the south of the port of the city which created a significant deficit of sediments. The extreme fragility of the coastline that protects the city from the sea, the anarchic exploitation of this coastline, and the development of unsuitable infrastructure made the coastline extremely vulnerable, exposing a significant part of the city to the risk of flooding. Ruptures in the protective dunes along the coast are a threat to low-lying areas of the city. Figure 9a shows an example of the Nouakchott coastline where the Port has affected the sand movement. The coastline has changed.

According to our estimations, in 2050 under the RCP 4.5 scenario, the area exposed to flooding by SLR will be limited to the North of the city. Under the RCP 8.5 scenario, this area will significantly increase, affecting other exposed areas along the coastline. Figure 10a shows different sections of the coast that have been studied, while Figure 10b focuses on the area surrounding Nouakchott and the urban area of this city. SLR areas, marked in gray, are those that are affected permanently due to low terrain height and slow increment of sea level caused by climate change. SLR plus annual mean high tides (mHT) in light pink color show how inundation might occur two times per day due to the semidiurnal character of tides in Mauritania.

One to three times per month the maximum high tide (MHT) plus SLR can reach new areas as shown in pink color. Special events with much lower frequency such as storm surges (one time every 2 years) and strong precipitation (one time every 25 years) are added to the SLR plus the mHT and displayed in inundation maps with dark pink and orange colors respectively. In Figure 10b, it is shown that part of the urban areas between the white line and the sea will be affected by inundation, especially the area close to the port which is also affected by coastal erosion as shown in Figure 9a.

Nouadhibou

The erosive phenomenon in Nouadhibou is less pronounced than in Nouakchott. Three small eroded areas are detected in the east of the city from inspection of satellite images from 1984 to 2015 as shown in Figure 9b and described in Table 9. In the city of Nouadhibou, the risk of flooding is less pronounced due to the shelter that impedes the large swells to penetrate the *Baie du Lévrier* (less than 0.2 meters on average) with a maximum tidal range of about 2 meters. In this area, the currents are also weak (0.05 to 0.25 m/s in direction South and South-West).

Figure 8: a) Coastline changes in the Nouakchott city coast and Port. b) Area of Nouadhibou, north of Mauritania. Green lines represent the coastline in 1984 while yellow lines the coastline in 2015. Red points are the areas affected by erosion since 1984 and green points, areas of sand accumulation

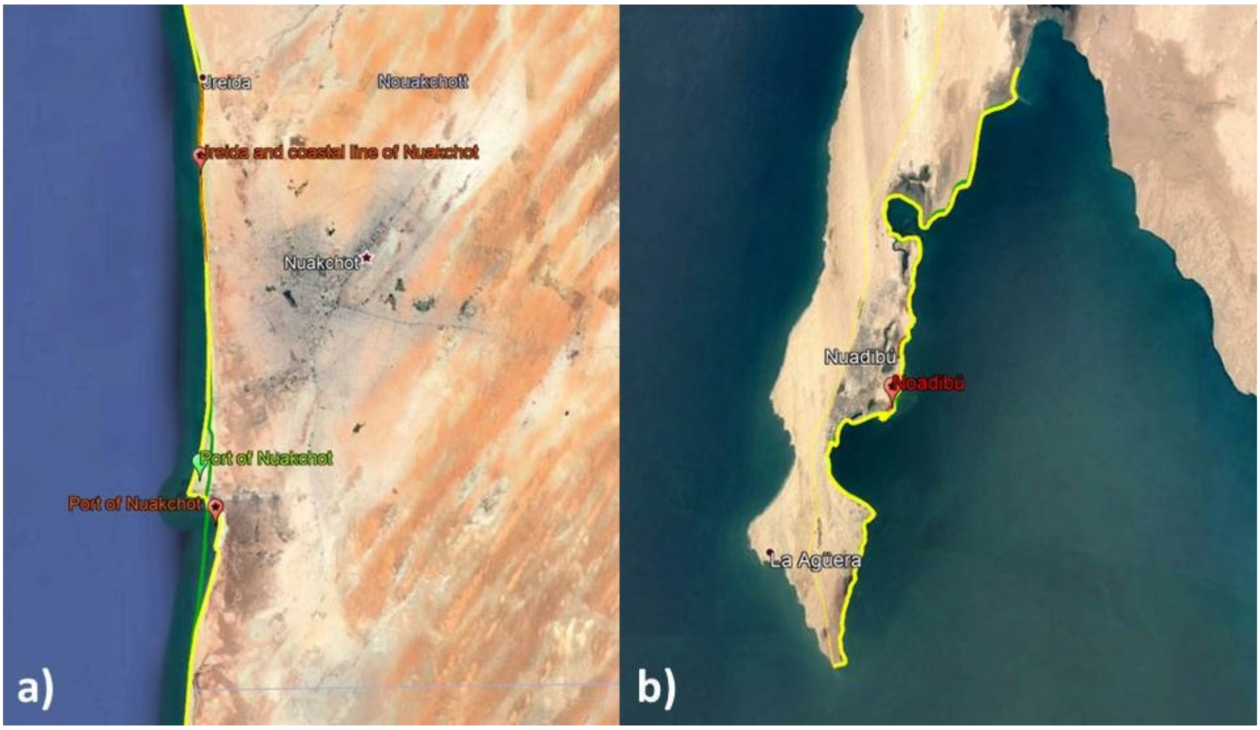


Table 8: Main areas affected by erosion in Mauritania and projections for three time horizons and two RCP scenarios						
Name of affected place (INC: Increment, ERO: erosion)	**1984 - 2015**	**1984 – 2030**	**1984 - 2050**		**1984 – 2100**	
	Satellite observed	Sat observed + Dynamical evolution (RCP 4.5 and RCP 8.5)	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Port of Nouakchott (Increment) (17.9983°N, 16.0298°W)	+2.20 km2	+3.44 km2	+3.44 km2	+3.44 km2	+3.44 km2	+3.44 km2
Port of Nouakchott (Erosion) (17.9776°N, 16.02237°W)	-3.23 km²	-4.82 km²	-7.66 km²	-27.3 km²	-36.1 km²	-40.6 km²
Jreida and coastal line of Nouakchott (Erosion) (18.1376°N, 16.02966°W)	-0.73 km²	-1.10 km²	-2.18 km²	-3.11 km²	-3.1 km²	-7.46 km²
Nouadhibou (Erosion) (20.91807°N, -17.0195°W)	-0.40 km²	-0.60 km²	-0.96 km²	-1.51 km²	-1.85 km²	-2.30 km²

Figure 9: a) Estimation of areas exposed to inundation caused by SLR (including tides, storm surge and extreme precipitation), in the surrounding of Nouakchott city in Mauritania using SRTM height data. Sea level rise values are shown in Table 3. Areas in blue are those higher than 50 m. b) Inundation maps superposed on urbanized areas of Nouakchott city (between the white line and the coast)

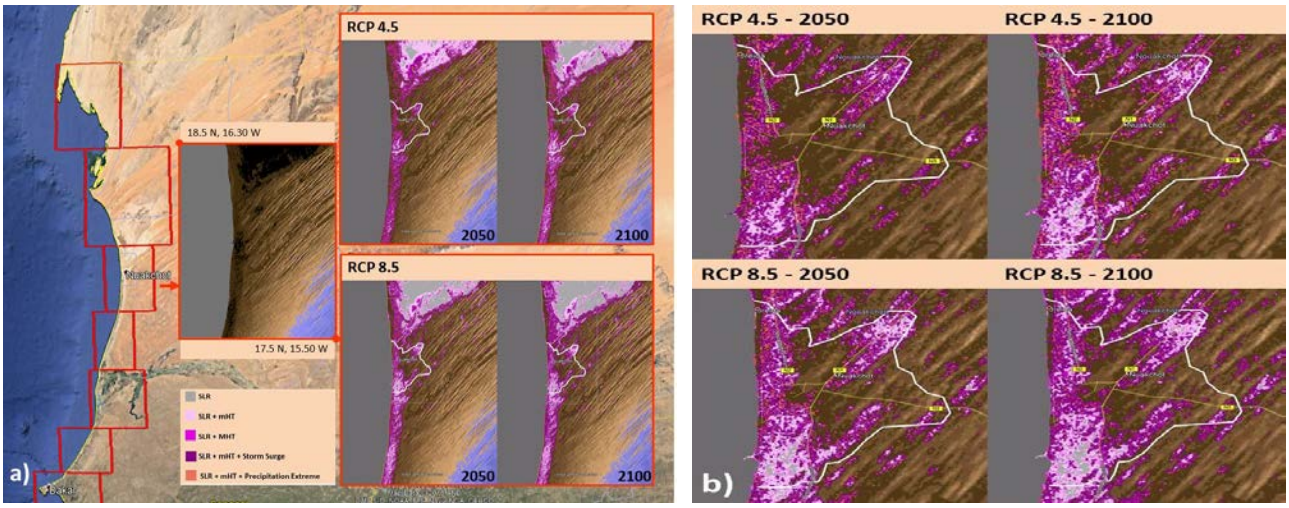
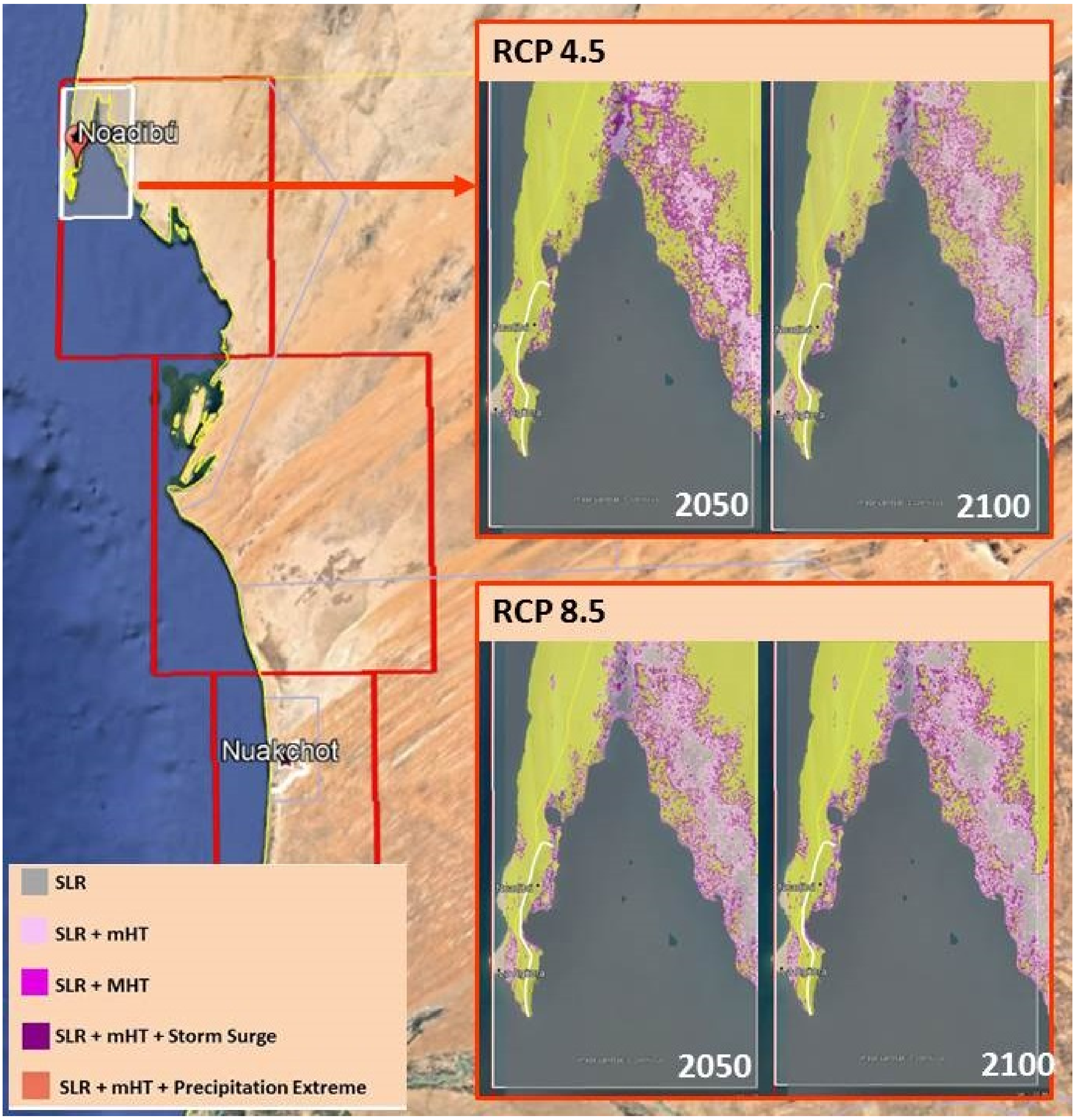


Figure 10: Estimation of exposed areas to inundation caused by SLR (including tides, storm surge, and extreme precipitation) in the surrounding of Nouadhibou city. Main urban areas are to the west of the white line and vulnerable to inundation issues. Areas not affected by projected inundations are in green



SENEGAL

Figure 11: Map of Senegal

Source: Google Earth.

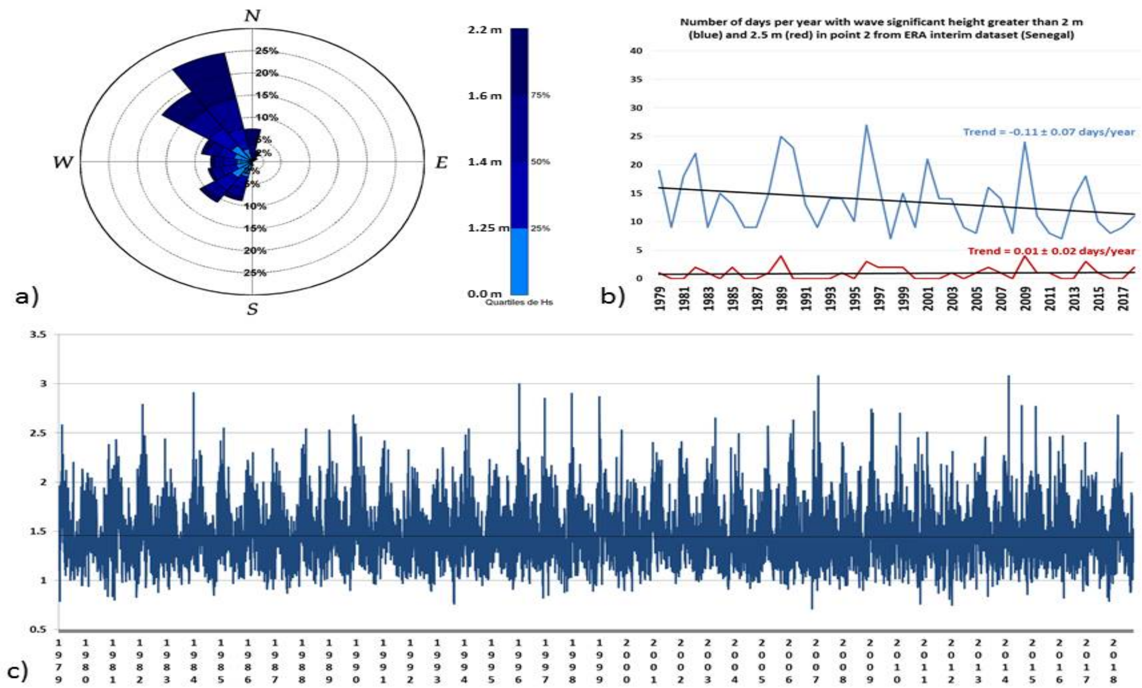
General climate characteristics of Senegal

The coastline of Senegal extends for 531 kilometers, crosses six administrative regions (Saint-Louis, Louga, Thiès, Dakar, Fatick, and Ziguinchor), is inhabited by 60% of the country's population (around 7.8 million of the estimated 13.5 million people), and accounts for 68% of GDP (World Bank 2014). Three types of coastline can be distinguished in the country's littoral (Diaw et al. 2016):

- A rocky coastline in the area of Cap-Vert and of the Petite Côte;
- Mangrove estuary: common within the river mouths of the major rivers like the Senegal River and the ones in the southern area (Sine-Saloum and Casamance);
- Sandy beaches are the most common and form the majority of the Grande Côte and Côte Nord.

Senegal has a Sahelian climate in the north and a sub-Guinean climate in the south. The country is characterized by the alternation of a dry season (from November to May) and a wet season (from June to October). Temperatures are rather homogeneous countrywide. From October to November and from mid-February to April, the highest temperatures reach 26°C. From July to September, temperature reaches around 30°C. Annual precipitation goes from 300 mm in the north to 1,200 mm in the south with strong variation from yearly (Egis International 2013). The isohyet 500 mm can be found in the north center of the country while isohyet 1,000 mm can be found in the south. In the period 1980-2010, the highest amount of annual precipitation was recorded in Ziguinchor (1400 mm) and the minimum in Podor (200 mm) (Diouf 2017).

Figure 12: Oceanographic data from ERA-Interim in grid point 2 (13.5°N, 17.25°W) in front of the Senegal coast. a) Direction of waves, b) Number of days per year with significant wave height greater than 2 and 2.5 m with linear trend and c) Daily significant wave height time series from January 1979 to September 2018



Regarding oceanographic conditions, Senegal has a cold and hot season with two very different current characteristics: the current of the Canaries and the Equatorial current. In addition, as shown in Figure 13a, there are three large swells present: the swell of NNW which takes place all year, the swell of SSW appearing during the winter period, and the swell of W occurring around November. Although the wave height data show that from 1996 waves higher than 3 meters have occurred more often than before (Figure 13c), it is also possible to observe that the frequency of waves higher than 2 meters has decreased over time (Figure 13b). The country has semidiurnal tides with extreme heights range from +1.60m to -0.50m with a mean amplitude of around 1 meter (Diaw et al. 2016).

Observed climate change in the coastal area and hotspots

Temperature

According to the data collected from ERA Interim regarding the climate change that occurred during the period 2008-2017, temperature has registered a decrease of -0.36°C during the winter months (December to February) and an increase of +0.05°C during the summer months (June to August) compared to the period 1986-2005. From 1979 to 2016, an increase of the annual temperature is observed in Dakar as measured in the weather station (Figure 14d). As shown in Figure 14a, during the 1991-2015 period, warmer months are March to July, but temperatures are lower during the summer in the rainy season with a peak in October. The coldest months are December and January, but mean temperature remains over 24°C even during this period.

Precipitation

According to Figure 14a, an indirect relation between rainfall and temperature was observed in Senegal during the period 1991-2015: Starting from January, the temperatures start to rise while precipitation is very low or absent, while during the summer months the temperature tends to drop with an increase in precipitation. However, in general terms, mean seasonal precipitation has decreased -0.8±0.2 mm/season (from June to

October). From 1950 to 2016, an increase of 0.9±0.3 mm/season was registered between 1979 and 2016 (Figure 14c). As shown in Table 10a, from the analysis of ERA data it is possible to observe that an increase of 0.77 mm/month was registered in the last ten years (2008-2017) during the period June-August compared to the period 1986-2005.

Sea level rise

On the basis of the Dakar tide gauge records, it is considered that during the last century, SLR has increased to an average of 1.4 mm per year (MEPN 2006). According to ESA satellite measurements provided by CCKP (Figure 14b and Table 9a), an increase of 0.25 ± 0.06 cm per year is measured from 1992 to 2007. Assuming that this annual trend remains constant in the whole 15 years period from 1992 to 2007, the total sea level change is 3.7 ± 1.3 cm. These numbers are obtained from the regression line ($y = 0.25 \cdot x - 0.5$) shown in Figure 14b with mathematical propagation of slope (trend) uncertainty (±0.06 cm/year) and offset uncertainty (±0.5 cm) as explained in the methodology section.

Table 9:
a) Change and variability of the last 2008-2017 period compared to the 1986-2005 period using the ERA grid point 2 (13.5°N, 17.25°W) data series located in the coast of Senegal

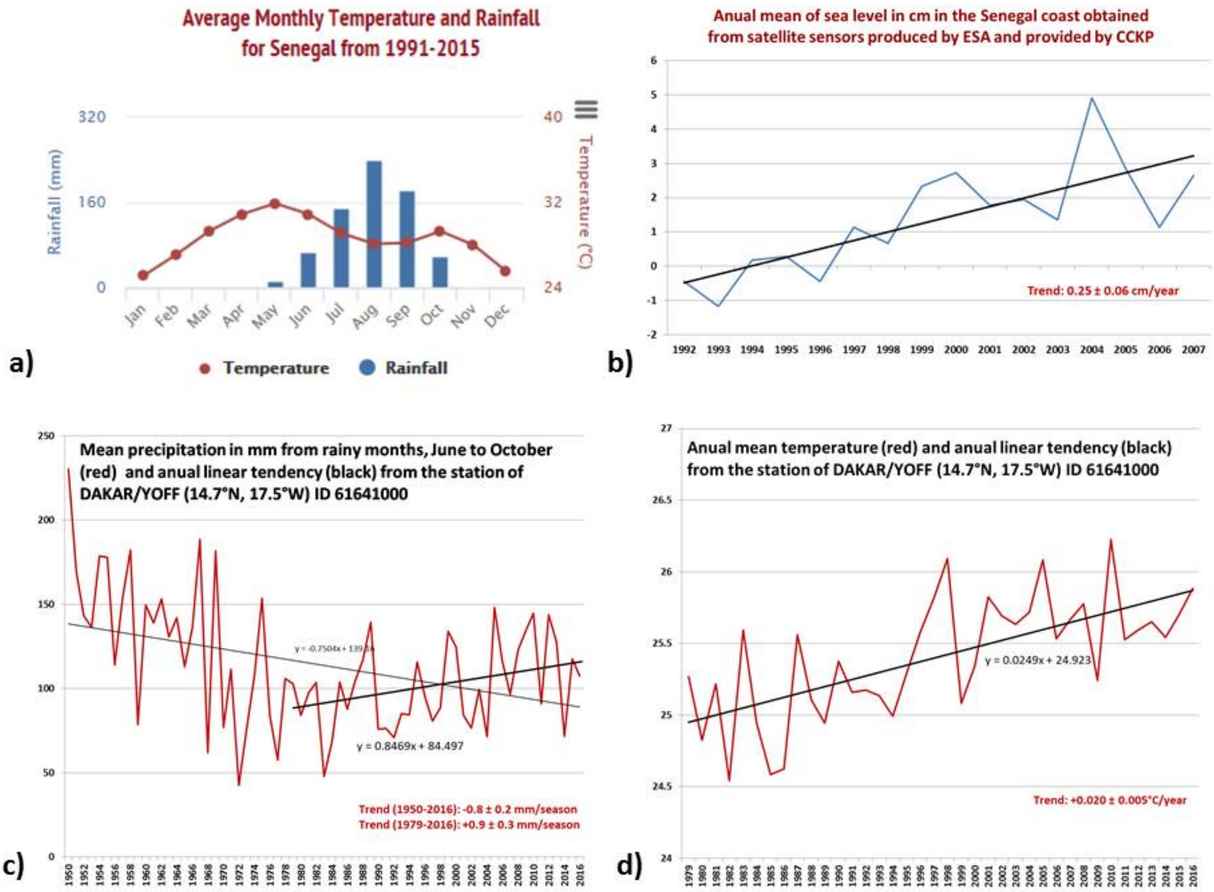
Parameter	Source data and used data period range	Dec-Feb		Jun-Aug	
		Change	Variability	Change	Variability
Temperature (C°/month)*	ERA-Interim **1986-2017**	-0.36	±0.32	0.05	±0.10
Precipitation (mm/month)*	ERA-Interim **1986-2017**	-0.01	±0.06	0.77	±0.50

b) Annual series trend and variability using ESA Satellite altimeter and temperature and precipitation trends using data from meteorological station in Dakar city

Parameter	Source data and used period	Trend	Trend uncertainty
Sea level rise (cm/year)**	ESA satellite altimeters **1992-2007**	0.25	±0.06
Temperature (C°/year)**	DAKAR/YOFF Station (ID 61641000) **1979-2016**	0.020	±0.005
Precipitation (mm/rainy season)***	DAKAR/YOFF station (ID 61641000) **1979-2016**	0.9	±0.3
	DAKAR/YOFF station (ID 61641000) **1950-2016**	-0.8	±0.2

* Based on monthly averages from initial daily ERA dataset. Changes and variabilities between the two periods are obtained each month and later averaged for 3 winter or 3 summer months.
** Based on monthly measurements that are annually averaged.
*** Based on monthly measurements averaged from June to October (rainy season).

Figure 13: a) Country Mean monthly temperature and precipitation climatology from 1991 to 2015 obtained from CCKP web page for Senegal. b) Country Annual mean sea level time series from 1992 to 2007 and trend. c) Mean seasonal (June to October) precipitation time series from 1950 to 2016 with trends for different periods on a station location. d) Mean annual temperature time series from 1979 to 2016 with trend on a station location



Future climate change projections

Temperature

Future climate projections show a clear increase in temperature and the rather low variability of results, proving the consistency of this trend. As shown in Table 11, a higher increase of temperature is expected to occur during the winter months rather than summer months. For the 2030 time horizon, temperature will increase between 0.9° and 1.07°C (with a variability of 0.55°-1.49°C) under RCP 4.5 and of more than 1°C (with a variability of 0.62°-1.66°C) under RCP 8.5 with a higher increase during the December-February period. In 2050, the temperature is expected to increase an average of 1.44°C under RCP 4.5 (with a variability of 0.75°-1.86°C) and between 1.78° and 2.17°C under RCP 8.5 (with a variability of 1.13°-2.75°C). In 2100, an increase of 2°C has been forecasted under RCP 4.5, while an increase of almost 4°C is expected under RCP 8.5 (with a variability of 2.93°-5.7°C). The trend about future projections shows a clear increase in temperature. However, projections data for the end of the century present a rather high variability in comparison with more recent time horizons, which makes the former less reliable.

Precipitation

Although data presents high variability, a clear decreasing trend of precipitation is shown in future climate projections of Senegal. Unlike for temperature, precipitation is expected to be higher during winter months and to decrease significantly during the summer. For the time horizon 2030, monthly precipitation is expected to decrease 2.8 mm under RCP 4.5 with a substantial difference between winter months (-0.05 mm) and summer months (-5.6 mm) with values ranging between -14.86 mm and +7.8 mm. Under RCP 8.5, the trend is similar and precipitation is expected to decrease 2.35 mm (with a range of -13.6/+12.54 mm).

Projections for 2050 show a decrease between -0.04 and -3 mm, with the values ranging from -16.2 to +12.17 mm under the RCP 4.5, and a decrease of almost -3.2 mm under RCP 8.5 with a range of -17.13 /+18,2 mm. For the end of the century, a decrease of almost -3 mm is expected to occur under RCP 4.5, although a high range of values (between -16.82 and +26.03 mm) is shown in the data. For the same time horizon, a decrease of -7.5 mm is projected under RCP 8.5 with a much higher decrease happening during summer months (-15 mm) rather than during winter months (-0.1 mm). The mean value shows a range between -33.05/+16.35 mm. In such cases, precipitation projection results should be taken with extreme caution due to the high uncertainty.

Sea level rise

According to the data examined, in 2030 SLR will increase 20 cm (Egis International) under RCP 8.5. In 2050, an increase of 25 cm is expected to occur under RCP 4.5 (Niang et al. 2014) with a range of +7/+39 cm, while for RCP 8.5 data show an increase of +30 cm. In 2100, SLR of +86 cm under RCP 4.5 although a very high range of +66 /+111 cm is shown in the mean ensemble. A wide range of values related to the mean value is also shown under RCP 8.5: SLR is expected to increase +106 cm with extreme values ranging between +78 and +143 cm (Perrette et al. 2012). The high variability far from the poles is caused mainly due to high uncertainties in climate forcing given by Global Climate Models (GCMs). In this case, 18 global models from the CMIP5.

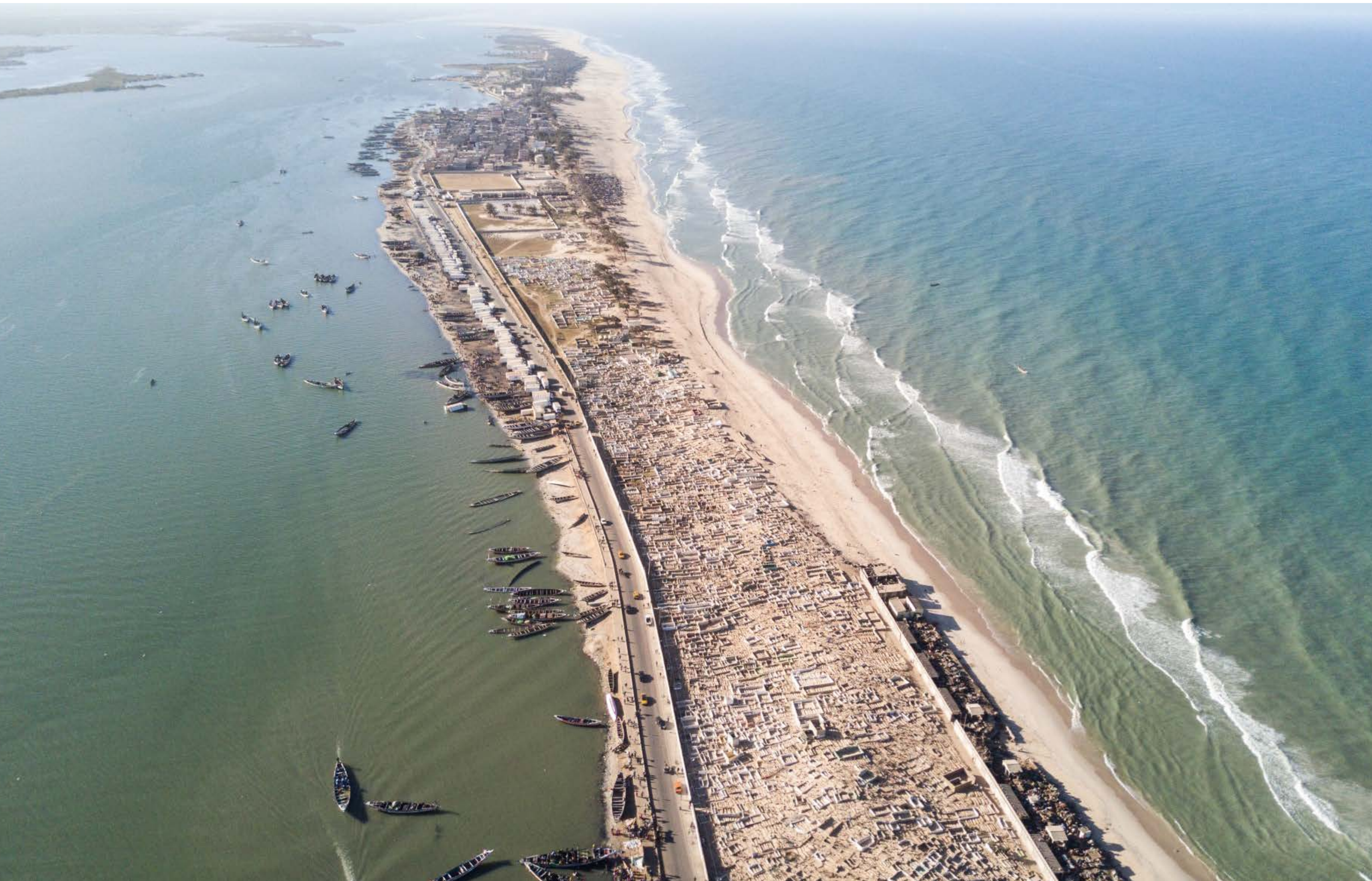


Table 10: Climate change projections in Senegal. The data are presented according to two RCP scenarios and for three time horizons that are compared to the reference period (1986-2005). Temperature and precipitation changes and variabilities are provided by the CCKP. The change is the multimodel median (50th-percentile) and variability is represented by multimodel 10th-percentile and 90th-percentile respectively

Key Climate Variable	Representative concentration Pathways	2020-2039		2040-2059		2080-2099		Projection data source	Publication source
		Change	Range	Change	Range	Change	Range		
Sea Level Rise (cm)	RCP 4.5	*	*	(2050) +20 (Niang et al. 2014)	(2050) +7/+39	(2090-2099) +86	+66/+111	Projected total SLR for 4 components combined (OD, MGIC, GIS, AIS)	Perrette et al. 2012
	RCP 8.5	(2030) +20 (Egis International)	*	*	*	(2090-2099) +106 cm (Niang et al. 2014)	+78/+143		
Precipitation (mm)**	RCP 4.5	Dec-Feb -0.05	-1.7/+0.6	Dec-Feb -0.04	-1.1/+0.84	Dec-Feb -0.13	-0.9/+1.0	Results from 16 global circulation models (GCMs) are available for the African ensemble using the CCKP	CCKP
		Jun-Aug -5.6	-28/+15	Jun-Aug -3	-31.3/+23.5	Jun-Aug -5.65	-32.7/+51.1		
	RCP 8.5	Dec-Feb -0.2	-1.2/+0.5	Dec-Feb -0.2	-1.27/+0.55	Dec-Feb -0.1	-1.7/+1.1		
		Jun-Aug -4.5	-26/+24.6	Jun-Aug -6.48	-33/+36	Jun-Aug -15	-64,4/+31,6		
Temperature (°C)**	RCP 4.5	Dec-Feb +1.1	+0.7/+1.5	Dec-Feb +1.6	+1/+2.2	Dec-Feb +2.2	+1.3/+3.4		
		Jun-Aug	+0.4/+	Jun-Aug	+0.5/+1.5	Jun-Aug +1.8	+0.5/+2		

		+0.9	1.4	+1.3					
	RCP 8.5	Dec-Feb +1.2	+0.7/+1.7	Dec-Feb +2.2	+1.3/+2.8	Dec-Feb +4.3	+3.16/+5.7		
		Jun-Aug +1.0	+0.5/+1.6	Jun-Aug +1.8	+1.0/+2.7	Jun-Aug +3.7	+2.7/+5.8		

* No change or variability data is available.

** Based on monthly measurements averaged for winter or summer seasons.

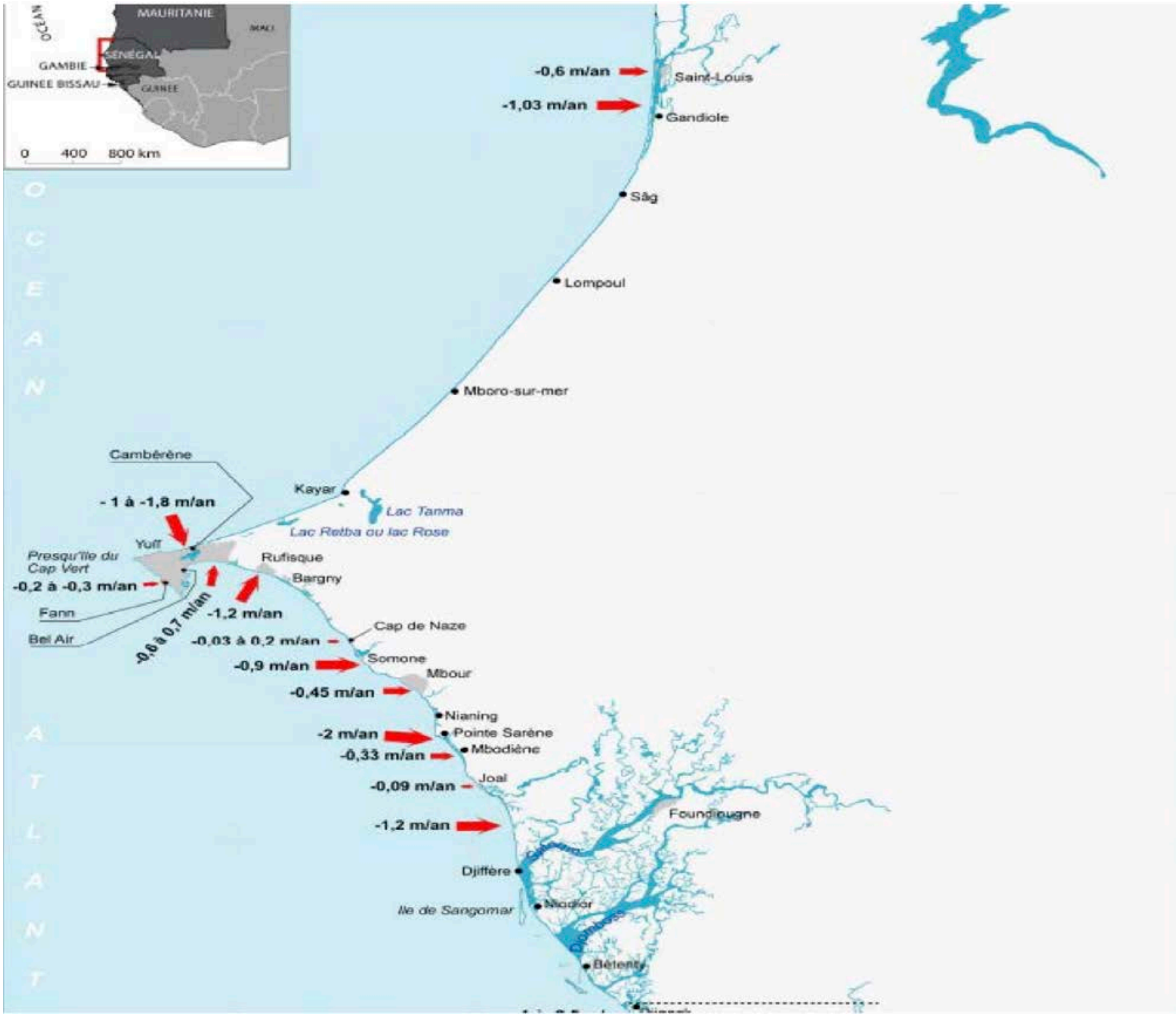
Climate change and natural hazards in Senegal

Coastal erosion, droughts, and floods are currently the natural hazards that pose the greatest threats to the country's coastal areas. On one side, sea-level changes and increased intensity of storm surges are leading to coastal erosion and represent a major threat to the population and economy of Senegal. On the other side, floods are occurring more frequently than droughts, but droughts have more severe consequences and affect more people per event (CCKP). A description of the main natural hazards in the area is provided as follows:

Erosion

Erosion varies according to the sector of the coastline, ranging from 0.5 to 2 m per year (DEEC 2015). The causes are both natural and human related. SLR will affect the coastline of Senegal by accelerating erosion, generating flooding of low-lying coastal areas, and increasing in the salinization of land and of surface and underground water resources. Both the speed and magnitude of land loss vary according to the area. Figure 15 highlights the rate of erosion along the coastline of Senegal, while Table 12 shows the land loss that affected the most exposed coastal areas along with future projections for three-time horizons and two RCP scenarios. According to Niang et al. (2014) sea level rise will increase +20 cm in 2050 under the RCP 4.5, while at the end of the century it will reach +86 cm under RCP 4.5 and +106 cm under RCP 8.5. This increase will determine a significant loss of land, especially in the coastal areas of Ngalou Sam Sam and Palmarin in the south and N'Dar Toute in the northern part of the country. The morphological evolution of the coastline is also disturbed by anthropogenic actions such as the anarchic occupation of the areas due to rapid urbanization towards the coast, the lack of planning and compliance with regulations, particularly in the occupation of the public maritime domain, and the multiplication of dams on the course of the rivers and other protection infrastructure often poorly dimensioned.

Figure 14: The rate of erosion of sandy coastlines per year from the 1950s. Almost every coastal city in Senegal is affected by erosion. The most vulnerable zones to erosion will be Saint-Louis, Mbao-Bargny, and the area of the Petite Côte included between Ndangane and Dijiffere



Source: MEPN 2006.

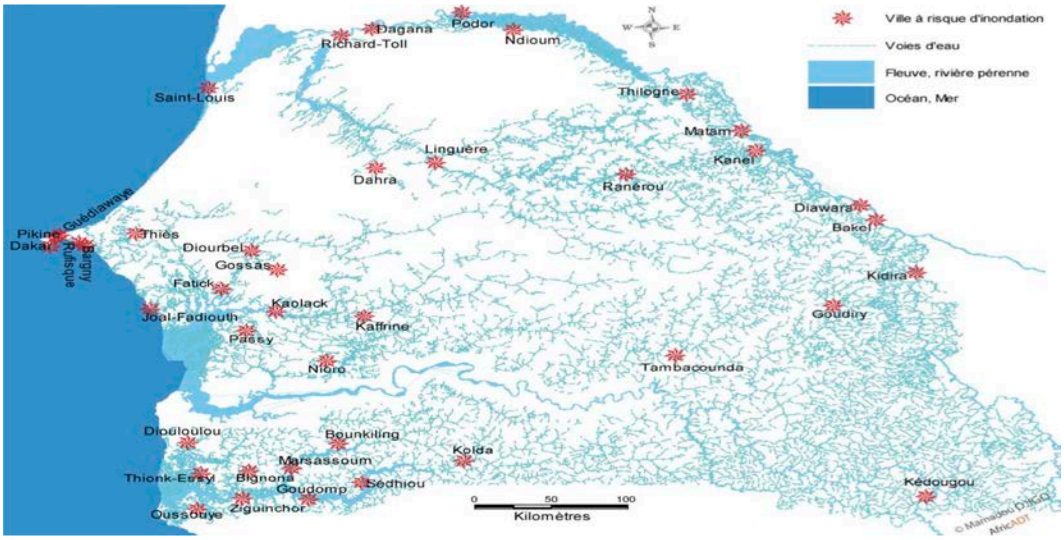
Flooding

Senegal is characterized by relatively low altitude regions hills (581 m) from the Southeast to the coastal areas in the West (10 to 1 m). It is drained by an important hydrographic network constituted by large river systems, the Senegal River, the Gambia River, the Casamance River, the Kayanga River, the Sine, the Saloum, the valleys of Car-Car and Ferlo, and their numerous tributaries that ramify throughout the national territory (Diouf 2017). Floods in the country are the result of river overflows due to heavy rains, a combination of heavy rains and insufficient drainage infrastructure, and storm surges leading to salt-water intrusion into agricultural lands. The effect of SLR will be accentuated during periods of maximum high tide or in case extreme storm surges or extreme precipitation occurs.

Table 3 shows how much SLR will increment over three time-horizons and under two different RCP scenarios if combined with these phenomena. The results of SLR simulations were generated to show the chances of flooding for the major coastal cities and shown in Figure 17 and Figure 18 where the area of Saint Louis and the area of Dakar are respectively depicted. In Figure 17, it is possible to observe the city of Saint Louis laying on a sandy bank surrounded by the Senegal River that at least one time every ten years overflows and causes damages. The northern area of the city is very flat and low with lakes that are filled with salt water due to SLR in days with maximum tide. Under the RCP 4.5 scenario, the area vulnerable to flooding events is clearly incremented in the north and along the whole coastal area along the river. Under the RCP 8.5 scenario in 2100, most of the northwest areas are threatened in case of occasional storm surge events.

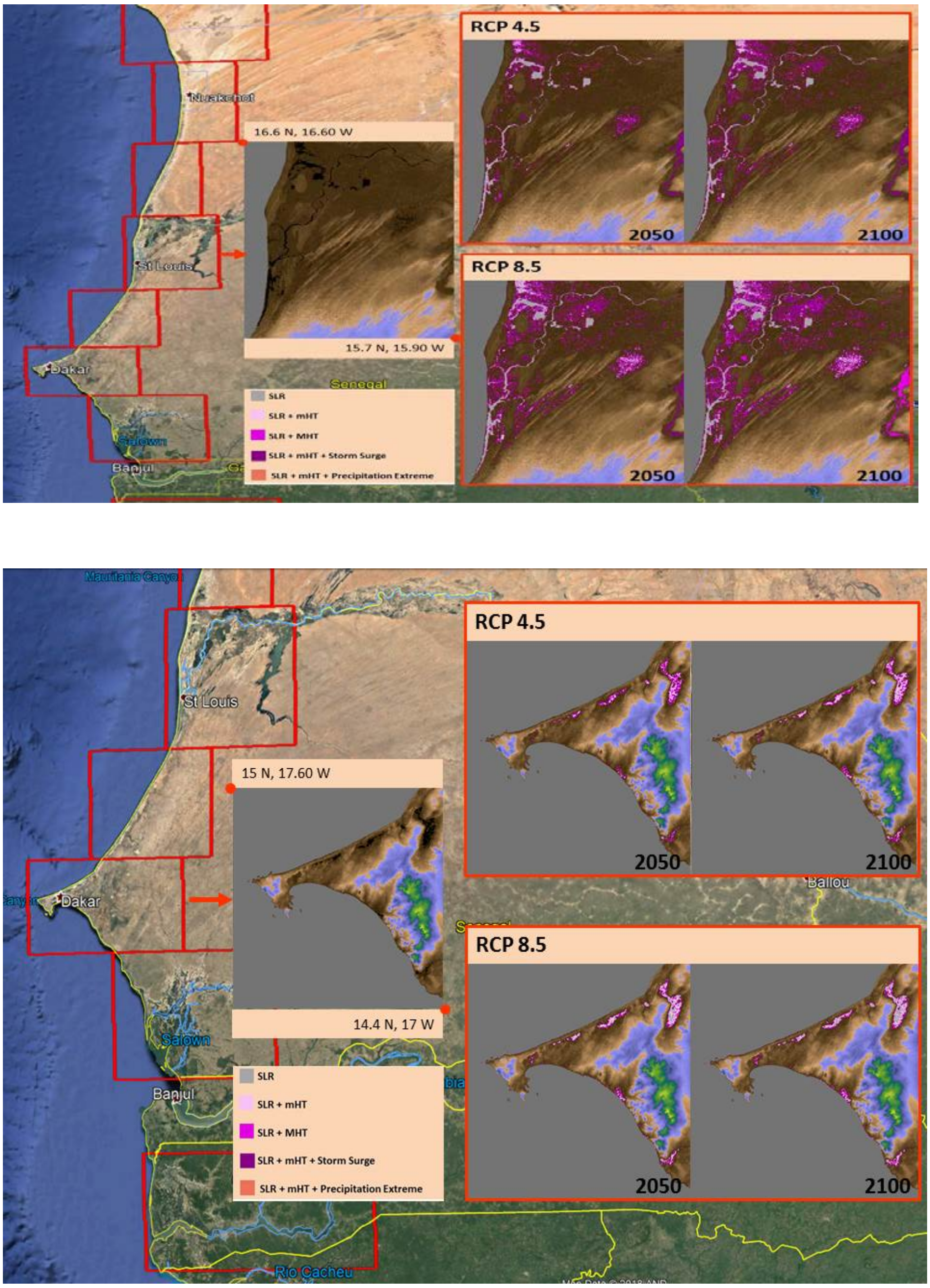
Figure 18 shows the Dakar area and the populated areas close to the city and coast (Yenne Tode) seem to be threatened in 2100 for RCP 8.5. Figure 17 shows different sections of the coast that have been studied, and in the example, the area surrounding St. Louis. According to estimations, in the RCP 4.5 scenario the area exposed to flooding by SLR is limited to the North of the city and at the riverside of Salown river in 2050, while in the RCP 8.5 scenario the exposed area is larger and also includes an area in a more interior zone. Further information about the country's coastal areas exposed to flood are provided in Tables A1-3, A1-6, A1-7, A1-8, and A1-9 of Annex 1.

Figure 15: Most exposed cities in Senegal to inundations. The problem of inundation is threatening all the most important cities of Senegal. This problem affects the low-lying coastal areas especially during the rainy season. Cities close to the river mouths are also affected by river inundation



Source: Diouf 2017.

Figure 16: Estimation of flood vulnerable areas due to SLR in the surrounding of Saint Louis city in Senegal using SRTM height data. Sea level rise values are shown in Table 11. Areas in blue are those with terrain elevation higher than 50 m



Hotspots

According to the Third Communication Report of the Government of Senegal (MEDD 2015a), the three main vulnerable areas to erosion are Saint Louis, Rufique-Bargny, and Saly Portudal. In Saint Louis, erosion phenomena are particularly significant in the neighborhoods located along the île de Ndar (Goxxu Mbac, Ndar Tout, and Guet Ndar). The coastal area of Rufisque-Bargny has been subject to erosion for a long time, and the construction of several infrastructures to protect the coastal areas are an evidence of the fight against erosion. The most important causes of coastal erosion in the area of Saly Portudal are sea level rise, the effect of storm waves, the illegal extraction of marine sand for construction purposes, and the construction of buildings and tourist infrastructure. For the purpose of this work and its importance, the region of Casamance has also been included in the description. A more detailed description of the hotspots is provided as follows:

Saint Louis

The effect of natural, extreme events in these parts of the coast of Saint Louis is becoming stronger due to a major presence of human settlements and infrastructure that are being built in very vulnerable areas. The biggest concern comes from the artificial breach that was realized in the Langue of Barbarie lagoon to prevent river flooding of the city of Saint Louis. Created in October 2003 to avoid the risk of river inundation, today it has witnessed a severe enlargement that can increase the risk of marine flooding. The simulations conducted to analyze the influence of sea level rise on the possibility of river inundation after the opening of the breach show that an increase of 0.5 m in the sea level will be enough to inundate the île of Saint Louise and submerge it completely in case of a 1 m increase (Durand et al. 2013).

Currently, the Senegal River provokes inundations every ten years with harmful consequences for the low-lying areas surrounding the river. Considering the high uncertainty about future projections of precipitation, it is difficult to assess whether this situation will become worse or better. However, since projections are assessing a positive trend in sea level rise, it is estimated that in 2080 the inundations that will happen every ten years will be of the same intensity as those that happen every fifty years nowadays and could affect 150,000 people (Egis International 2013). The most vulnerable parts of the city are the new city center, on the eastern bank, the cité coloniale, and the fishermen village of Guet Ndar. The most vulnerable is the cité coloniale due to its position and extremely low altitude (Durand et al. 2013).

Rufisque-Bargny

Coastal erosion has been a major threat in this area for an extended period. The construction of protection infrastructure has been a response to this threat. Due to sea level rise, all settlements that have not implemented any measure of protection will have to retreat from the current position. In 2080, 60 percent of beaches will probably disappear due to sea level rise and its erosive impact, and 300 buildings, 250 of which are housing 2,250 people, will be adversely affected (Egis international 2013).

Saly Portudal

The main causes of erosion in the coastline of Saly are due to sea level rise, the action of storm surges impacting directly on the littoral and displacing a significant amount of sediment, the illegal extraction of sand and sediments for construction purposes, and the high presence of buildings (hotels and residences) along the coastline.

A study of the erosive phenomenon in this region conducted through the analysis of satellite images shows that a land loss of 142.96 m^2 has occurred between 1984 and 2015 from erosion (Table 12). By taking into consideration the dynamic evolution of the coastline, the area is expected to retreat further and lose 212.06 m^2 in 2030. In 2050 a land loss of 225,56 m^2 is expected to occur under RCP 4.5 and of 232,90 m^2 under RCP 8.5, while for the end of the century the area will witness a loss of 225.56 m^2 under RCP 4.5 and of 268.95 m^2 under RCP 8.5.

Casamance

Covering the wettest area of the country, this region is named after the river that crosses it and that divides it into three main parts: Upper, Lower, and Middle Casamance. The erosion of its coastlines combined with the sea level rise are forcing the population to retreat and displace the settlements into safer places. The decrease of rainfall and the contraction of the rainy season have had effects on all operating systems of the environment and determined the increase of salinity of the water and soil. This climate degradation led to an economic shortfall that generated a massive migration of young people towards urban centers, and the rise of social and economic problems (Fall et al. 2016).

A study about the dynamic evolution of the coastline of this area is shown in Table 12. The study was conducted for the city of Kafoutine through satellite images to assess the magnitude of the area affected by coastal erosion over time, and to analyze the potential land loss that will occur in the future. Figure 20a shows the coastal area where part of the main coastal city of Kafoutine and north of the Casamance River with mangroves are affected by the erosion and inundation. The exposed coastline to erosion and inundation with mangroves is indicated by the green line. In addition, the western area of the region, shown in Figure 20b as dark brown has a very low terrain level with respect to mean sea level and is subject to inundation as shown in Figures 20c and 20d. Here the loss of cultivated areas due to sea water irruption or salinization can affect an estimated area of 932.6 km^2 in 2100 under RCP 8.5 (see SLR+MHT option in Table A1-8, Annex 1).

Figure 17*:* Main satellite observed erosion hotspots in Senegal

Figure 18: a) Exposed areas to coastal erosion in the Casamance region, coastal line in green, exposed area with mangroves. b) Map showing height from mean sea level derived from SRTM data and inundation due to sea level rise only two extreme scenarios are shown in c) and d) respectively for the Casamance region

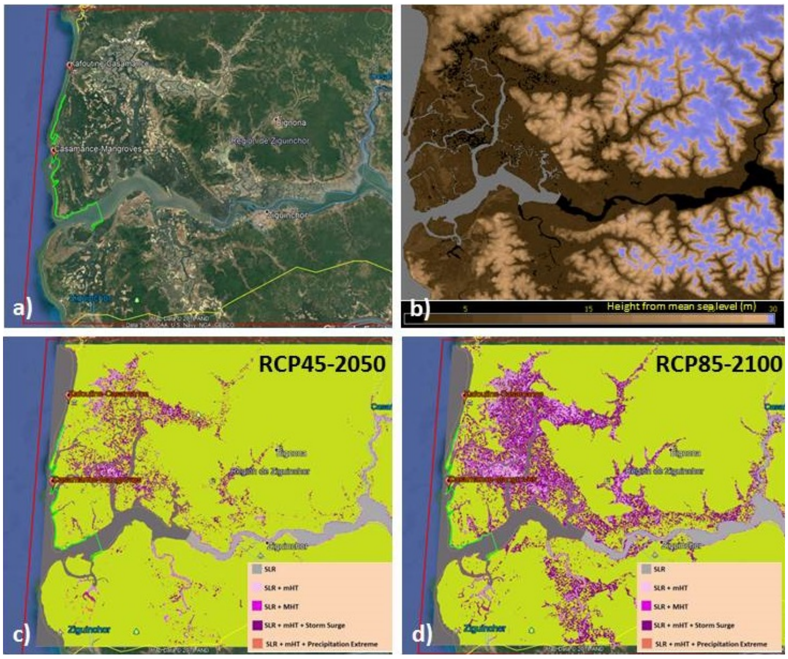


Table 11: Main areas affected by erosion in Senegal and projections for three time horizons and two RCP scenarios						
Name of klm files (INC: Increment, ERO: erosion)	**1984 - 2015**	**1984 - 2030**	**1984 - 2050**		**1984 - 2100**	
	Satellite observed (area in km^2)	Sat observed + Dynamical evolution (RCP 45 and RCP 85)	RCP 45	RCP 85	RCP 45	RCP 85
N'Dar Toute-Saint Louis (Erosion) (16.0316° N, 16.5096°W)	-0.34 km^2	-0.52 km^2	-0.54 km^2	-0.60 km^2	-0.58 km^2	0.72 km^2
Fas Boue (Erosion) (15.2681° N,16.8486°W)	-38.05 m^2	-55.9 m^2	-55.9 m^2	-55.9 m^2	-55.9 m^2	-55.9 m^2
Boro Deunde (Erosion) (15.1866° N, 16.9074°W)	-98.54 m^2	-148.72 m^2	-148.72 m^2	-148.72 m^2	-148.72 m^2	- 148.72 m^2
Kayar (Erosion) (14.9157° N, 17.1242°W)	-108.63 m^2	-161.7 m^2	-161.7 m^2	-183.8 m^2	-184.3 m^2	-187.0 m^2
M'Bour-Saly Portudal (Erosion) (14.4382° N, 17.0088°W)	-142.96 m^2	-212.06 m^2	-225.56 m^2	-232.90 m^2	225.56 m^2	- 268.95 m^2
Kafoutine-Casamance (Erosion) (12.9235° N, 16.7536°W)	-128.49 m^2	-188,.83 m^2	-188.83 m^2	-191.50 m^2	-195.93 m^2	- 2045.3 2 m^2
Ngalou Sam Sam (Erosion) (14.0457° N, 16.7734°W)	-0.19 km^2	-0.36 km^2	-0.59 km^2	-0.77 km^2	-0.73 km^2	-0.81 km^2
Palmarin (Erosion) (14.0043° N, 16.7693°W)	-0.18 km^2	-0.26 km^2	-0.28 km^2	-0.61 km^2	-0.42 km^2	-0.62 km^2
Djiffer (Erosion) (13.9361° N, 16.7638°W)	-0.23 km^2	-0.34 km^2	-0.34 km^2	-0.35 km^2	-0.37 km^2	-0.38 km^2

* No change or variability value is found.

** Based on monthly measurements averaged for winter or summer seasons.

TOGO

Figure 19: Map of Togo

Source: Google Earth.

General climate characteristics of Togo

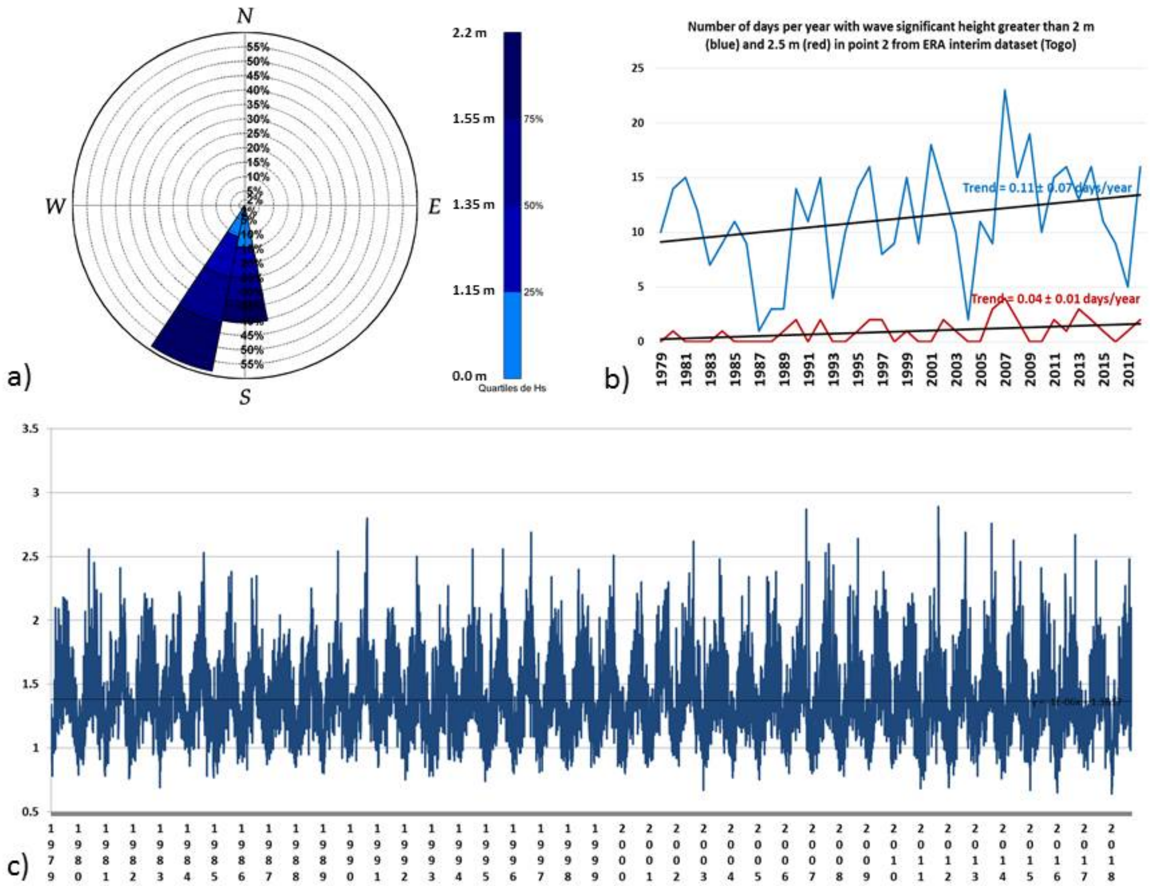
The coastline of Togo is located between the borders of Ghana and Benin. It extends for 50 km on the Atlantic Ocean and is part of a major regional sand barrier complex in the Gulf of Guinea. Its beaches present a longshore-uniform low tide terrace, and a steep and alongshore-uniform lower beach face and persistent upper beach face cuspate morphology cut into a well-developed berm (Giardino et al. 2016). Mono River, the 400 km long major river in the country, forms the boundary with Benin.

The climate of Togo is tropical Guinean type, characterized by a medium temperature of 27°C and a mean monthly temperature ranging between 25 and 29.5°C, peaking in the month of March and reaching lowest levels in August with winds parallel to the coastlines with an average speed of 2 to 4 m/s. There are two rainy seasons: a long season of precipitation from March to July during which almost three quarters of precipitation occurs, and a short rainy season from September to November (CICG 2010). The annual mean precipitation varies from 1,000 mm to 1,300 mm, and the distribution varies yearly.

The winds coming from the ocean play an important role in creating waves and ocean currents that affect the coastline of Togo. Southwestern winds are the most recurrent winds in the Gulf of Benin during the year, especially between July and September (Antea Group b 2017). The tides are semidiurnal with a tidal range of 1 m.

Three types of waves can be distinguished on the coastline of Togo (Antea Group b 2017): long waves with a period greater than 10 s originated far offshore; wind waves with a period of 5 to 10 s, originated closer onshore, and waves of very low period lower than 5 s. In the Gulf of Guinea, waves are generally long and generated on a latitude between 40° and 60° south of the Atlantic Ocean (Antea Group b 2017). Because of the geographical orientation of Togo's coastline, it is exposed to waves of the South and Southwest components. Southwest is the direction that contributes to the highest waves (Figure 22a) from August to September (CICG 2010). The medium height is of 1.5 m. However, the frequency of high waves (over 2.5 m) have increased after 1996 (Figure 22c). There are three main currents that influence the coastline of Togo: the current of Guinea, the cold current of Benguela, and the longshore current, the principal source of sediment transportations towards the east.

Figure 20: Oceanographic data from ERA-Interim in grid point 5b (5.25°N, 1.5°E). a) Direction of waves. b) Number of days per year with significant wave height greater than 2 and 2.5 m with linear trend. c) Daily significant wave height time series from January 1979 to September 2018



Observed climate change in the coastal area and hotspots

Temperature

As Figure 23a shows, temperature has been increasing from September to March and decreasing from April to August in the 1991-2015 period. Data collected from ERA Interim on the coastal grid point 4a also show that in the last ten years from 2008 to 2017, an increase in temperature of +0.13°C has occurred during the winter months with a variability of ±0.16°C and of +0.17°C with a variability of ±0.20°C during the summer months compared to the 1986-2005 period. However, the high variability associated with both of these data shows a sign of weak accuracy, which suggests considering the information with caution. Despite the variability of data, the observed annual mean temperature data series in Togo (Figure 23d) shows an increase pattern of 0.25 ±0.06 C°/year that states a clear trend.

Precipitation

According to data collected in the Lomé airport station, a general decrease of rainfall has occurred from 1950 to 2016 (Figure 23c). However, the variability of this trend (±0.1 mm/year) is similar to the trend itself (-0.1 mm/year). Therefore, this result must be taken with caution. On the other side within this period, an increase in precipitation (+0.3 mm/year) has been registered during the period 1979-2016. These data show a lower variability of

±0.2 mm/year, proving that the increase is more likely to occur.

During the last ten-year period (2008-2017), ERA-interim data show a decrease of -1.03 mm/month in the June-August period with a variability of ±0.76 mm/month compared to the 20 years period of reference (1986-2005). During winter months, this data shows a variability (±0.58 mm/month) greater than precipitation change (-0.46 mm/month), which means the information is inconsistent.

Sea Level Rise

In Figure 23b and table 13b, a positive trend of 0.25 ± 0.04 cm/year is obtained from ESA satellites in the coast of Togo with respect to sea level observed during the period 1992-2007. Assuming this annual trend remains constant in the whole 15 year period (1992 to 2007), the total sea level change is 3.7 ± 0.9 cm. These numbers are obtained from regression line (y = 0.37·x - 2.4) shown in Figure 23b with mathematical propagation of slope (trend) uncertainty (±0.04 cm/year) and offset uncertainty (±0.3 cm), as explained in the methodology section.

Table 12:

a) Change and variability of the last 2008-2017 period compared to the 1986-2005 period using the ERA grid point 5a (6.0°N, 1.5°E) data series located in the coast of Togo

Parameter	Source data and used data period range	Dec-Feb		Jun-Aug	
		Change	Variability	Change	Variability
Temperature (C°/month)*	ERA-Interim 1986-2017	0.13	±0.16	0.17	±0.20
Precipitation (mm/month)*	ERA-Interim 1986-2017	-0.46	±0.58	-1.03	±0.76

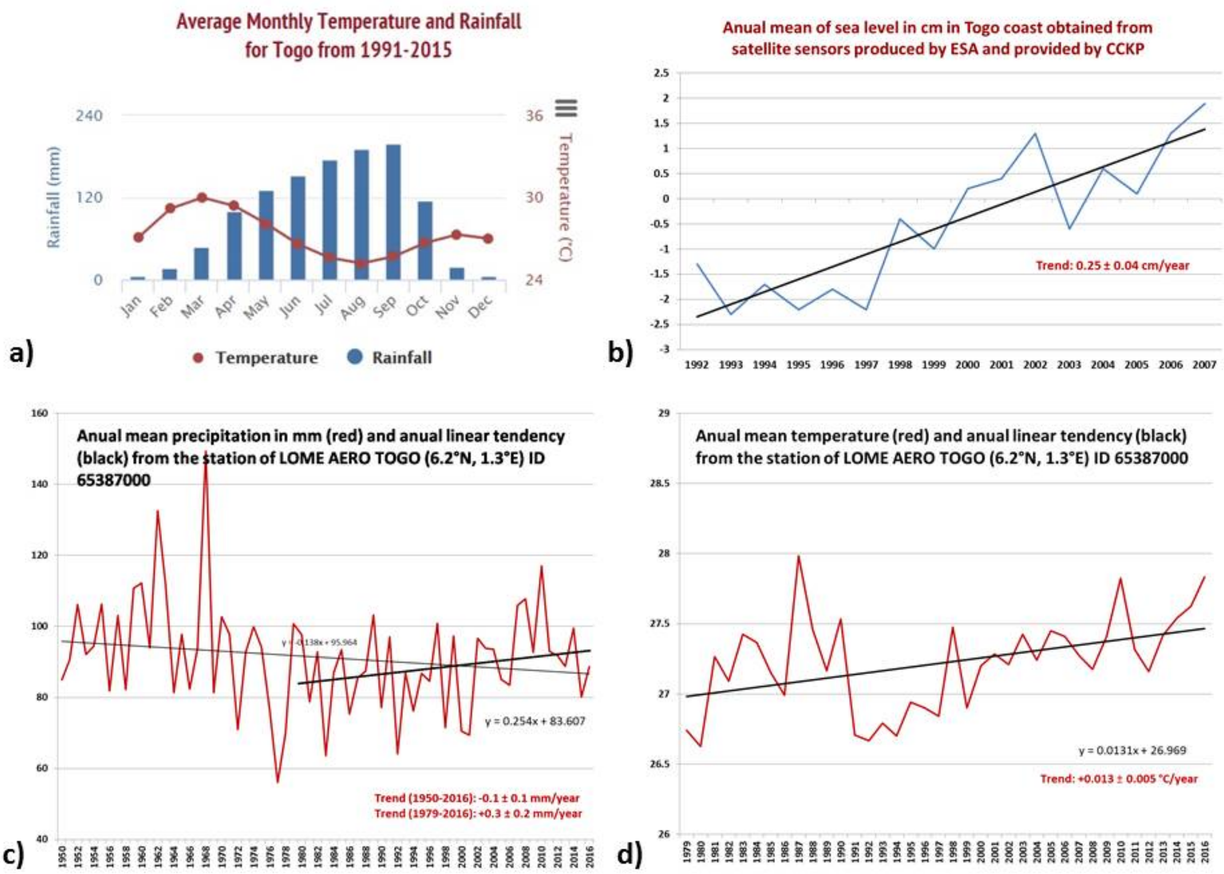
b) Annual series trend and variability using ESA Satellite altimeter and temperature and precipitation trends using data from meteorological station in Lomé city

Parameter	Source data and used data period range	Trend	Trend uncertainty
Sea level rise (cm/year)**	ESA satellite altimeters 1992-2007	0.25	±0.04
Temperature (C°/year)**	LOME AERO Station (ID 65387000) 1979-2016	0.013	±0.005
Precipitation (mm/year)**	LOME AERO station (ID 65387000) 1979-2016	0.3	±0.2
	LOME AERO station (ID 65387000) 1950-2016	-0.1	±0.1

** Based on monthly averages from initial daily ERA dataset. Changes and variabilities between the two periods are obtained each month and later averaged for 3 winter or 3 summer months.*

** Based on monthly measurements that are annually averaged.

Figure 21: a) Country Mean monthly temperature and precipitation climatology from 1991 to 2015 obtained from CCKP web page for Togo. b) Country Annual mean sea level time series from 1992 to 2007 and trend. c) Mean annual precipitation time series from 1950 to 2016 with trends for different periods on a station location. d) Mean annual temperature time series from 1979 to 2016 with trend on a station location



Future climate change projections

Temperature

According to CCKP climate projections, the temperature in Togo is projected to rise progressively during the 21st century, reaching an average increase of +3.55°C by the end of the century under the most extreme climate scenario (RCP 8.5). A higher increase of temperature during the winter months (December to February) is expected compared to summer months (June to August). In 2030, temperatures are projected to increase almost +1°C for both RCP scenarios with a range of +0.51°/+1.3°C under RCP 4.5 and +0.51°/+1.5°C under RCP 8.5. In 2050, the temperature is expected to rise +1.3°C under RCP 4.5 (values ranging +0.72°/+2.08°C) and +1.75°C under RCP 8.5 (with the data showing a range between +1.1 and +2.73°C). Finally, the projections for the time horizon 2100 estimate an increase of +1.7°C (with a range of +1.1°/+3°C) for RCP 4.5 and of +3.55°C under RCP 8.5 (Table 14).

Precipitation

Projections of precipitation follow an opposite trend compared to temperature projections,

showing a gradual decrease of values over the century and greater reductions of amount during summer months. Although the collected data show a trend of decline in precipitation, the high variability of the data makes projections for rainfall highly uncertain. Specifically, over the period 2020-2039 and according to RCP 4.5, precipitation is expected to decrease -0.82 mm during the winter months (December to February) and -2.3 mm during the summer months (June to August).
Under RCP 8.5, the projections for the same time horizon present a similar trend during summer months but show an increase of +0.28 mm during the winter months. Under both scenarios, precipitation data during summer months display a high variability, therefore hindering the reliability of the projections. As shown in Table 14, the other two time-horizons (2040-2059 and 2080-2100) also show a higher variability of data regarding projections during the summer months.

Sea Level Rise

It is estimated that in 2025, sea level will rise +9.76 cm for the scenario RCP 8.5 (Perrette et al. 2012) with a range between +7.3 and 13.4 cm. In 2050, sea level rise is expected to increase +31 cm under RCP 8.5 (with values ranging from +23.3/+39 cm) and at the end of the century projections show an increase of more than 90 cm with a range of +87 to +152 cm (Perrette et al. 2012, Republique Togolaise 2016).

Table 13: Climate change projections in Togo.

Key Climate Variable	Representative concentration Pathways	2020-2039		2040-2059		2080-2099		Projection data source
		Change	Range	Change	Range	Change	Range	
Sea Level Rise (cm)	RCP 4.5	*	*	*	*	*	*	
	RCP 8.5	(2025) + 9.76	(2025) +7.3/+13.4 (CCKP)	(2050) +31 (Perrette et al. 2012)	+23.3/+39.0	(2100) + 90.28 Republique Togolaise 2016	(2090-2099) +87/+152	
				+30.5 (CCKP)		+90.3 (CCKP)	+64.7/+120	
Precipitation (mm)**	RCP 4.5	Dec-Feb -0.82	-4.6/+5.3	Dec-Feb +0.5	-4.4/+5.6	Dec-Feb +0.2	-6.5/+4.5	Results from 16 global circulation models (GCMs) are available for the African ensemble using the CCKP
		Jun-Aug -2.3	-27/+37.6	Jun-Aug -2.2	-37.2/+37.7	Jun-Aug -3.9	-41.3/+46.4	
	RCP 8.5	Dec-Feb +0.3	-4.6/+5	Dec-Feb +0.2	-3/+5	Dec-Feb +1.3	-6.6/+13.4	
		Jun-Aug -0.2	-24.6/+33	Jun-Aug +1.0	-43/+45	Jun-Aug -7.0	-57.2/+57.6	
Temperature (°C)**	RCP 4.5	Dec-Feb +1.0	+0.5/+1.4	Dec-Feb +1.4	+0.6/+2.2	Dec-Feb +1.8	+1.1/+3.2	
		Jun-Aug +0.8	+0.5/+1.3	Jun-Aug +1.2	+0.8/+2	Jun-Aug +1.62	+1.1/+2.8	
	RCP 8.5	Dec-Feb +1.1	+0.5/+1.6	Dec-Feb +1.9	+1.1/+2.8	Dec-Feb +3.7	+2.6/+5.9	
		Jun-Aug +0.9	+0.6/+1.5	Jun-Aug +1.6	+1.1/+2.6	Jun-Aug +3.4	+2.4/+5.5	

The data are presented according to two RCP scenarios and for three time horizons that are compared to the reference period (1986-2005). Temperature and precipitation changes and variabilities are provided by the CCKP. The change is the multimodel median (50th-percentile) and variability is represented by multimodel 10th-percentile and 90th-percentile percentile respectively

* No projection change or variability is available.

** Based on monthly measurements averaged for winter or summer seasons.

Climate change natural hazards in Togo

The major natural risks in Togo include flooding, drought, high winds and storms, coastal erosion, and disease epidemics. As future climate change will worsen coastal erosion and lead to loss of goods and services, floods will provoke damage to infrastructure and cultivated land affecting thousands of people and resulting in millions of dollars of losses (WB 2018). In the following sections, these two natural hazards will be discussed in detail:

Erosion

Sea level rise will exacerbate coastal erosion and contribute to coastline recession that is already occurring at a consistent pace. In 2050, sea level rise is expected to reach around +30 cm under RCP 8.5. At the end of the century, it will increase around +90 cm under the same scenario (see Table 14). As a result, the country's coastline will retreat (Figure 24) at a different rate depending on the area of interest (Figure 25). As already seen before, sea level rise will represent a bigger threat if combined with other elements such as maximum high tide (happening two or three times per month), storm surge events, and extreme precipitation.

As shown in Table 4, sea level rise in 2050 may reach up to about +2 m if a storm surge event occurs during the time of maximum high tide and up to around +2.40 m if combined with extreme precipitation. In 2100, these figures are expected to reach +2.65 and +3 m respectively. Except for the capital Lomé, the risk of coastal erosion is high over the entire coastline of Togo and very high between the city of Aného and border with Benin (Antea Group b 2017). In this area, a land loss of about -4.88 km^2 is expected to occur by 2050 and -8.56km^2 by the end of the century (see Table 14).

Furthermore, in Togo human actions have had a significant influence on the erosive phenomenon of the country's coastline. The new littoral dynamics are being modified after the creation of hydroelectric dams, such as the Akosombo Dam that has slowed the flow of the river, both upstream and downstream, reduced the river's contribution, accelerated shoreline retreat, the construction of the port of Lomé in 1964, and the illegal extraction of sand and gravel for building purposes (CICG 2010). The current conditions of coastal physical oceanography combined with future climate change events (storm surges, sea level rise, and extreme precipitation) have caused and will continue causing damage and losses on the country's coastline. In Figure 24, it is possible to observe the morphological change of the country's coastline over the century. In Figure 25, the most vulnerable areas to erosion are highlighted. If these projections occur, several effects will result such as the complete destruction of fishing villages; loss of agricultural land and coconut plantations; threat of seaside and economic structures (hotels, industries, habitats, etc.); and destruction of road infrastructure (UNECA 2015).

Table 14: Main areas affected by erosion in Togo and projections for three time horizons and two RCP scenarios				
Name of affected place (INC: Increment, ERO: erosion)	**1984 - 2017**	**1984 - 2030**	**1984 - 2050**	**1984 - 2100**
	Satellite observed	Sat observed + Dynamical evolution (RCP4.5 and RCP8.5)	RCP 4.5-8.5	RCP 4.5-8.5
Lomé South (6.184447°N, 1.410670°W)	-4.4 km^2	-6.22 km^2	-7.96 km^2	-17.4 km^2
Border with Benin (6.250596°N, 1.695142°W)	-2.47 km^2	-3.46 km^2	-4.88 km^2	-8.56 km^2

Flooding

The coastal zone of Togo is exposed to two types of flood risk: river floods and marine (or coastal) floods. The risk of fluvial and lagoon flooding is very high throughout the littoral zone due to the subsurface phreatic zone, the strong waterproofing of certain soils, the inadequacy of the sanitation network, the uncontrolled urbanization of the coastline, mismanagement of waste, occupation of low-lying areas, low slope, etc. The risk of coastal flooding has always been reported on the coast of Togo with significant damage in coastal villages. This phenomenon generally occurs during the April-May and July-September periods in accordance with the season of strong winds and higher swells.

In the last decades, coastal flooding events have occurred more frequently with one or two extreme events per year. Between 1925 and 1992 the country has registered 60 inundations with the most damaging episodes occurring in August 2007. As already mentioned in the previous paragraph, Table 4 shows projections about sea level rise and its combination with medium and maximum high tide and extreme weather events such as storm surges and extreme precipitation. These two last phenomena are expected to have the greatest impact on sea level rise: in case of extreme storm surge, an increase of around 1.7 m would occur in 2050 under both RCP scenarios, and of around +2.50 m at the end of the century. In addition, clear inundation exposed areas are observed in Figure 26, accounting for this issue for both scenarios. In case of extreme precipitation, sea level would rise to 2.15 m in 2050 and 2.95 m in 2100 for both scenarios. However, effects of this issue alone are not well observed in our inundation maps (Figure 26). A more substantial study is required to assess these effects.

As a result, between 20 to 35 percent of the coastal areas that do not currently experience flooding would then be inundated (WB 2018). The most exposed areas would be: Aflao, Kodjoviakopé, Adawlato, Ablogamé, Katanga, Gbétsogbé, Baguida, Tropicana, Avépozo, Kpogan, Afiadégnigba, Kossi-Agbavi, Gbodjomè, Dévikèmè, Nimagnan, Agbodrafo, Kpémè, Gounoukopé, Assou-Condji, Vodougbé, Aného, and Sanvee-Condji (Antea group b 2017). Table A1-13 in Annex 1 shows an estimation of potential inundation areas.

Hotspots

The most vulnerable areas of the coastline are shown in Figure 25 and are the littoral of Kpogan/Agbavi (TG1-c), the beaches of Robinson/Ramatou (TG1-b), the littoral of Agbodrafo (TG1-d), the lagoon of Anécho (TG1-e), and the area of Tropicana hotel (TG1-e). Starting from the western border with Ghana, a description of the erosive phenomena and of flooding events is provided for the hotspots highlighted in Figure 25 (Antea group b 2017).

- ***First Zone (TG1-a, TG-1b)***
  For three decades, the sediment has been deposited on the west facade of the port, therefore widening the beach. In sector TG1-a, the intensity (speed) of erosion is low and alternates with weak accumulation of sediments, while in the TG1-b sector the erosion risk scale is greater but still negligible. Regarding the risk of marine flooding, the level in this area is moderate to high.

- ***Lome***
  Along the eastern section of Lomé harbor, an annual erosion rate of 20 m has been recorded and will likely increase in the future. This erosion induced by sea level rise will likely lead to the proliferation of informal settlements and displaced populations, while the lower region of the city is already highly exposed to flooding. Here is where 40 to 50 percent of the population lives and 80 percent of infrastructure, industries, and hotels are located, making this area extremely vulnerable to high socio-economic damage. According to a dynamic evolution study of the coastline of Lomé conducted with satellite image observations, a land loss of 4.44 km^2 occurred during the 1984-2015 period. By projecting the same rate of erosion that has occurred during this period for the time horizon 2030, the area would witness a loss of -6.22 km^2. Finally, when maps of inundation for 2050 and 2100 are overlapped, a loss of -7.96 and of around -17.4 km^2 is expected to occur by 2050 and by the end of the century respectively. Since the maps of inundation that were generated and that have been used to evaluate the effects of erosive phenomenon on the country's coastline do not show significant differences between the two RCP scenarios, the data provided only delivers one result for each time horizon (see Table 15).

- ***Second Zone (TG1-c)***
  From the 1980s, the entire coastline east of the port of Lomé was affected by erosion at a variable rate depending on the different segments of the coast. At the sub-regional scale, however, the area is considered subjected to erosion, characterized by periods of submersion, and destruction of habitats and infrastructure. The erosion risk in this area is thus high as well as the risk of coastal flooding. The coastal area between Katanga and Kpogan is particularly exposed to episodes of isolated storms which generate washover phenomena that provoke the submersion of beaches and threaten many villages located on the coastline.

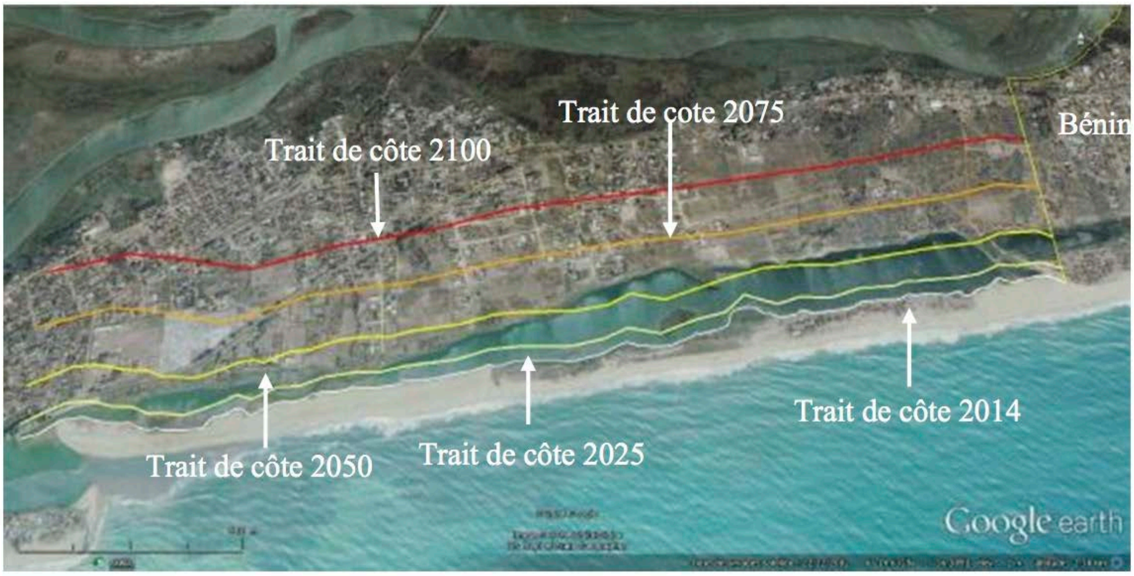
- ***Third Zone (TG1-d)***
  The risk of erosion in this area is also high. The erosion rate currently calculated in this zone varies between -8 and -10 m/year. Yet, in some areas it can reach -15 m/year. The TG1-d segment is subject to severe storm surges, particularly between April through July-September. Marine floods are then generated and damage is registered annually.

- ***Fourth Zone (TG1-e)***
  This area corresponds to the zone TG1-e according to MOLOA and is determined as an area of high priority intervention with intensive and regular monitoring-observation. As with sector TG1-d, the extreme phenomena that occur in this area generate marine flooding events and threaten human settlements and infrastructure.

- ***Fifth Zone (TG1-e Benin border)***
  The area is a 2.62 km long sub-segment

mainly marked by erosion and aggravated by the protection works carried out in Aného. An average retreat of -8 m/year is observed in this sector. The sandspit has receded to such an extent that it has reduced the area of the lagoon between the road and shore.

Figure 22: Expected coastline reduction due to erosive effect



Source: MERF 2015.

Figure 23: Characterization of the coastline of Togo and area division according to MOLOA (Antea group b 2017)

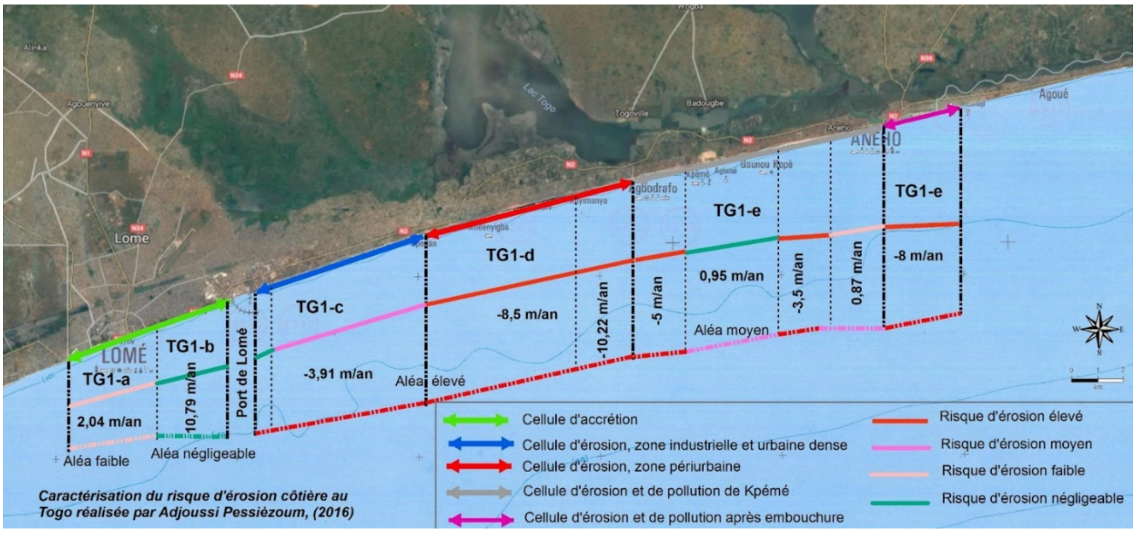
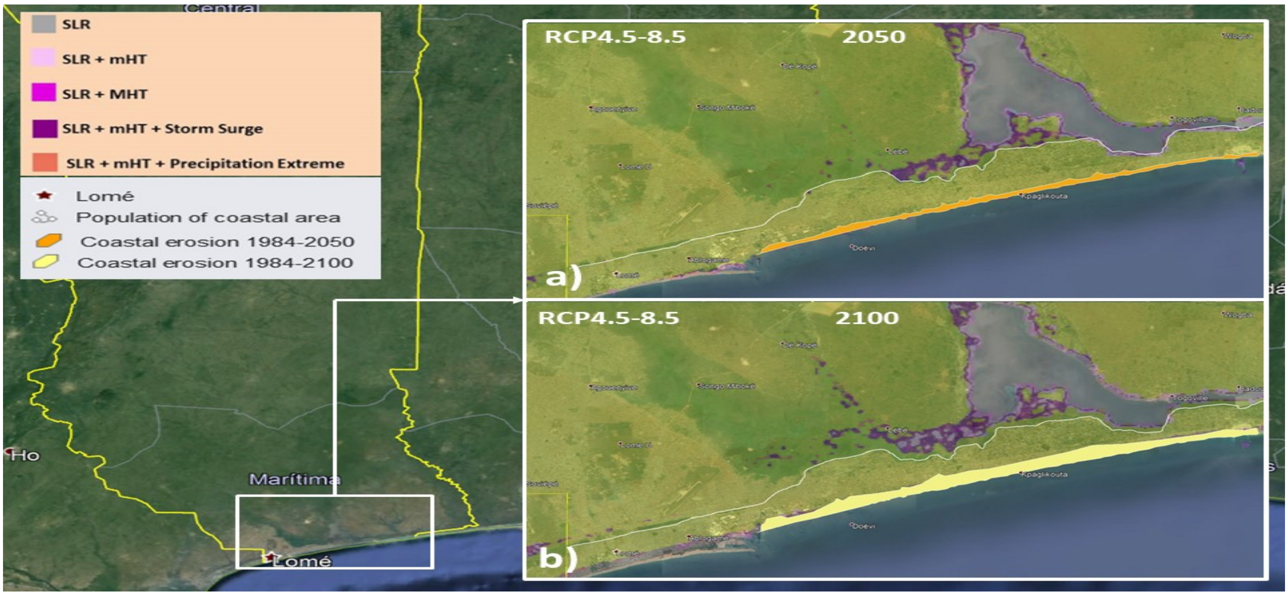


Figure 24: Inundation and erosion exposed areas on Togo Coast for both RCPs and time horizons on the surrounding areas of Lomé city. The main urban areas are located between the white line and the coast of Benin



BENIN

Figure 25: Map of Benin

Source: Google Earth.

General climate characteristics of Benin

The coasts of Benin have the same morphological features as those of Togo and are mainly characterized by a straight and long sandy coast. The main coastal cities are Cotonou, Semé-Kpodji, and Grand-Popo. The area is characterized by low altitudes and the presence of Lake Nokoué behind Cotonou.

The climate of Benin's coastal zone is mainly humid subequatorial type under the influence of the Atlantic Ocean. It is characterized by an annual alternation of four distinct seasons and unequal duration (De Sutter et al. 2017):

- a long, rainy season from April to July that starts with thunderstorms and wet winds blowing from the Southwest. Humidity is very high this season;
- a short, dry season suddenly occurs in August. Humidity is always high this season;
- a short, rainy season occurs due to reduced winds south of the eighth parallel and the weakening of the Beninese currents between September and November. Humidity always remains high this season;
- a long, dry season from December to March characterized by breezes and wind from Harmattan from the Libyan anticyclone. The wind is weak and the humidity is relatively low this season.

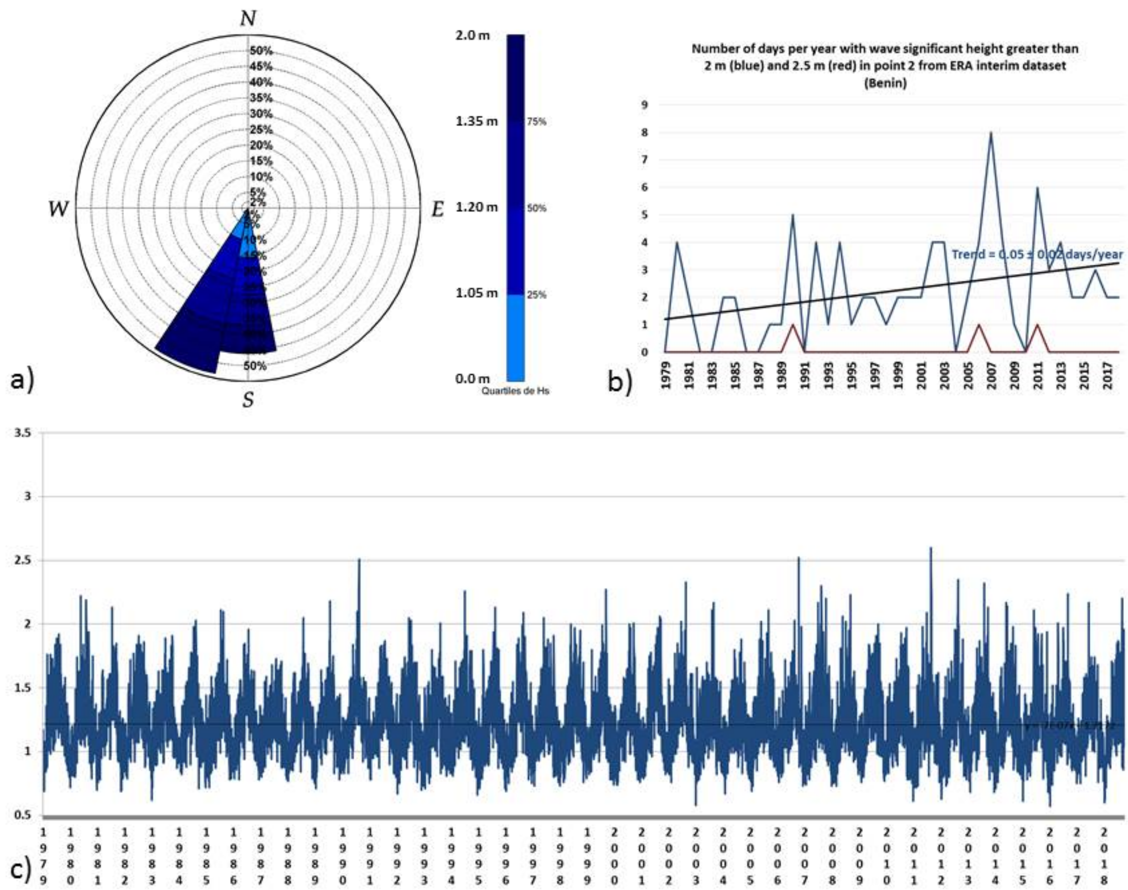
The thermal variations in the coastal zone of Benin are weak with temperature being around 27° C during the year. Throughout the year, average rainfall varies between 700 mm (extreme North) to 1,500 mm (extreme Southeast). Over the last two decades, rainfall patterns occasionally fluctuate in the peak of the seasons. Rainfall follows a steady decreasing gradient from West to East (1500 mm/year at Sèmè, 1,300 mm/year at Cotonou, 1,100 mm/year at Ouidah and 900 mm/year at

Grand-Popo). In addition, the Benino-Togolese coast is abnormally dry (800-1,500 mm/year), which explains the absence of dense forests at these latitudes, unlike Côte d'Ivoire and Nigeria located at the same latitudes (Dahomey Gap) (De Sutter et al. 2017).

The winds blowing on the Beninese coast come on average from the south-west directions. These winds define two seasons according to their directions and speeds (Laïbi 2011): a great wind season during which the wind speeds are quite high (average of the minima of the order of 3.6 m/s in May and average of nearby maxima of 5.12 m/s in August), then a shorter wind season in which wind speeds are lower (mean minima: 3.15 m/s in December; mean maxima: 4.55 m/s in March) (Laïbi 2011).

At the littoral zone, swells and winds are the main forces that drive the sedimentary transport and seasonal erosions (natural causes). Benin's coastline is exposed to waves from south-southwest and south directions with the first being the predominant direction characterized by more powerful waves. Wave height rarely reaches 2.5 m (Figure 28). The analysis of the intra-annual evolution of the waves' significant heights (Hs) averaged between 1958 and 2011 shows two swell seasons (DG-Eau 2015): the first characterized by strong swells (Hs>1.3 m) from April to October and the second characterized by moderate swells (Hs<1-3 m) from October to April. Longshore currents (coastal drift) dominate the processes structuring the Beninese coast with velocities up to 1 m/s. In breaking waves, the skew of the swell in relation to the shore varies between 4° and 9° with an average around 6-7° (De Sutter et al. 2017). It causes a shoreline drift directed from west to east and whose velocity measured in Cotonou is of the order of 0.3 to 1 m/s (DG-Eau 2015). This current is responsible for the annual transit of 1.2 to 1.5 million cubic meters of sand along the coast of the Gulf of Guinea (LCHF 1984). The tide cycle is approximately 12 hours and the amplitude range generally around one meter (MEHU 1998).

Figure 26: Oceanographic data from ERA-Interim in grid point 4 (6.0°N, 2.25°E). a) Direction of waves, b) Number of days per year with significant wave height greater than 2 and 2.5 m with linear trend. c) Daily significant wave height time series from January



Observed climate change in the coastal area and hotspots

Temperature

Historical series of precipitation, temperature, and sea level are similar to those shown for Togo. Mean annual temperature data series in Benin (Figure 29d) shows a positive trend of +0.013 ± 0.005 C°/year from 1979 to 2016, confirming the increasing temperature trend. However, when ERA data are taken into consideration to analyze the change of temperature in the last ten years (2008-2017) compared to the baseline period 1986-2005, a high variability of data is shown. As presented in Table 16a, the positive trend is confirmed with a higher increase of +0.18°C observed during the summer months in comparison to winter months in which an increase of +0.12°C has been observed.

However, both data for Togo show high variability. Therefore, the values should be considered with caution.

Precipitation

A reduction of precipitation is measured in the reanalysis data collected from ERA Interim in the last ten years (2008 to 2017) compared with 1986-2005 period data in coastal grid point 4. While in the winter months the decrease registered was -0.34 mm/month with a variability of ±0.38 in the summer months it reached -0.89 mm/month although the variability for this data is rather high (±1.14), making the observation of precipitation less certain for Benin. As shown in Figure 29c, annual mean precipitation at Porto Novo station for the two analyzed periods (1950-2016; 1979-2016) show significant variabilities. Therefore, clear trends are not discernible and annual precipitation from this station is extremely irregular with time.

Sea Level Rise

Data for sea level rise is not available from CCKP for Benin. Therefore, in Figure 29b and Table 16a, observed sea level data for Togo is used. For the 1992-2007 period, a positive trend of 0.25 ± 0.04 cm/year is obtained. Assuming that this annual trend remains constant in the whole 15 years' period from 1992 to 2007, the total sea level change is 3.7 ± 0.9 cm. These numbers are obtained from the regression line (y = 0.37·x - 2.4) shown in Figure 29b with mathematical propagation of slope (trend) uncertainty (±0.04 cm/year) and offset uncertainty (±0.3 cm) as explained in the methodology section.

Table 15:
a) Change and variability of the last 2008-2017 period compared to the 1986-2005 period using the ERA grid point 4 (6.0°N, 2.25°E) data series located in the coast of Benin

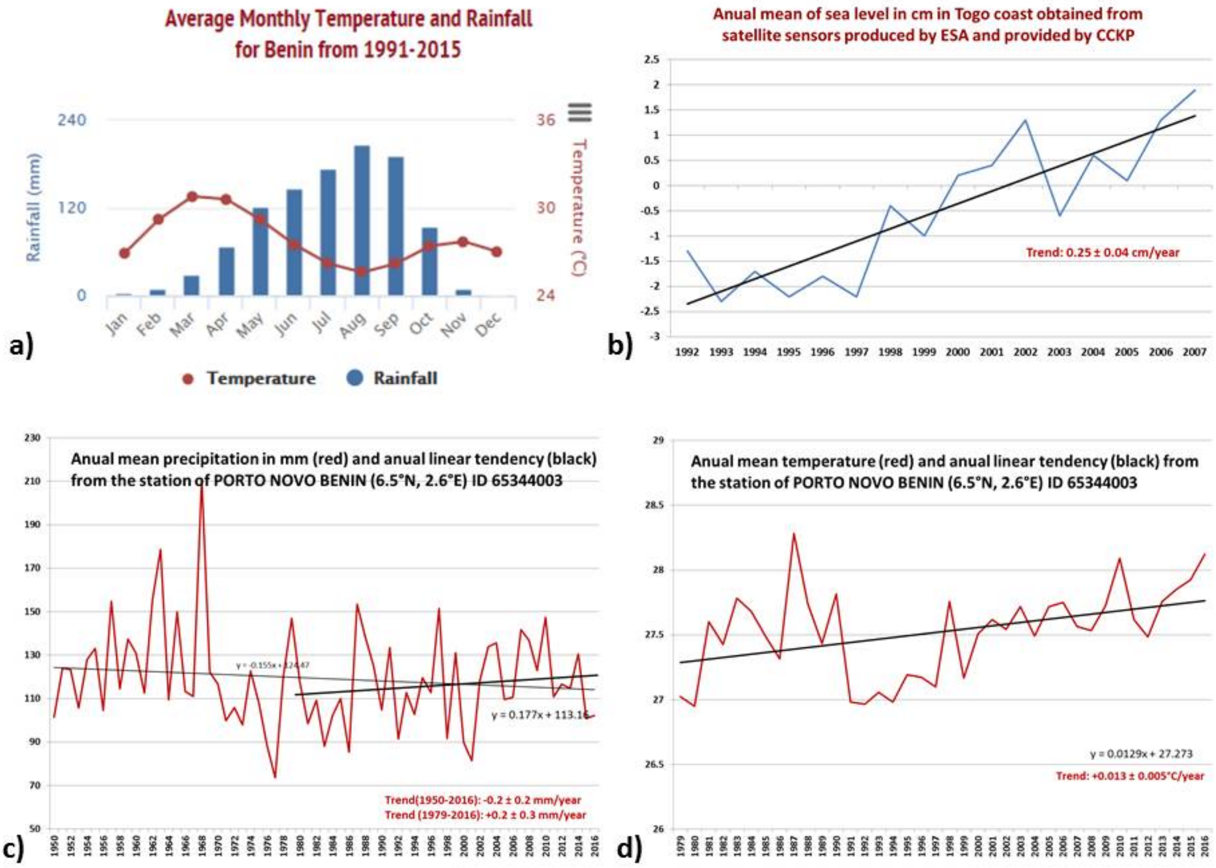
Parameter	Source data and used data period range	Dec-Feb		Jun-Aug	
		Change	Variability	Change	Variability
Temperature (C°/month)*	ERA-Interim 1986-2017	0.12	±0.14	0.18	±0.22
Precipitation (mm/month)*	ERA-Interim 1986-2017	-0.34	±0.38	-0.89	±1.14

b) Annual series trend and variability using ESA Satellite altimeter and temperature and precipitation trends using data from meteorological station in Porto Novo city

Parameter	Source data and used data period range	Trend	Trend uncertainty
Sea level rise (cm/year)**	ESA satellite altimeters **1992-2007**	0.25	±0.04
Temperature (C°/year)**	PORTO NOVO station (ID 65344003) **1979-2016**	0.013	±0.005
Precipitation (mm/year)**	PORTO NOVO station (ID 65344003) **1979-2016**	0.2	±0.3
	PORTO NOVO station (ID 65344003) **1950-2016**	-0.2	±0.2

* Based on monthly averages from initial daily ERA dataset. Changes and variabilities between the two periods are obtained each month and later averaged for 3 winter or 3 summer months.
** Based on monthly measurements that are annually averaged.

Figure 27*:* a) Country Mean monthly temperature and precipitation climatology from 1991 to 2015 obtained from CCKP web page. b) Country Annual mean sea level time series from 1992 to 2007 and trend. c) Mean annual precipitation time series from 1950 to 2016 with trends for different periods on a station location*.* d) Mean annual temperature time series from 1979 to 2016 with trend on a station location



Future climate change projections

Temperature

Temperature projections indicate an increase in all regions of Benin by 2100 (DCN 2011). The greatest thermal increase would be +3.9°C compared to the 1986-2005 reference period, while the lowest value would be +0.89°C (Table 17). A substantial temperature increase is expected to occur over the century with greater increases in the winter months compared to summer months. In 2030, the temperature is expected to increase up to +1°C for both scenarios RCP 4.5 and RCP 8.5 with the extreme values ranging between +0.51°/+1.3°C and +0.51°/+1.5°C respectively. For the time horizon 2040-2059, temperature will increase +1.3° under RCP 4.5 (with a range of +0.72°/+2°C) and +1.8° under RCP 8.5 (with values ranging between +1.1° and +2.73°C). At the end of the century, an increase of +1.8° is expected to occur under RCP 4.5 and of 3.7° under RCP 8.5, although a high variability is shown for both projections (values are expected to range between +1.1°/+3°C and +2.40°/+5.69°C respectively).

Precipitation

Future projections for precipitation show a significant decrease over the century only during the summer months, while during the winter months a slight increase is expected to occur (Table

17). Nevertheless, the variability of data remains high, weakening the consistency of predictions. At the seasonal scale, variations in rainfall in the March-April-May period when farmers are planting crops would be practically negligible in southern Benin by 2050 (De Sutter et al. 2017). For the time horizon 2020-2039, a decrease of -1.56 mm is projected under RCP 4.5 with a range of -15.78 to +21.45 mm while a slight increase of +0.04 mm is expected to occur under RCP 8.5 (with a range of -14.6 to +19 mm).

In mid-century (time horizon 2040-2059), an increase of +0.54 mm is expected in the winter months with values ranging from -4.44 to +5.55 mm and a decrease of -2.17 mm with a range of values of -37.17 to +37.73 mm under RCP 4.5. Under RCP 8.5, an average increase of +0.58 mm is expected to occur with a range of -23 to +25 mm. Regarding the time horizon 2080-2099, a decrease of -2.06 mm is expected under RCP 4.5 and -4.17 mm under RCP 8.5 (extreme values ranging between - 23.91 and +25.43 for the former scenario and between -31.89 and +35.53 mm for the latter). For both scenarios, a very high uncertainty is shown during the summer months rather than in winter months, therefore making long-term trends difficult to pinpoint, especially between June and August.

Sea Level Rise

Based on climate and non-climate scenarios established for the future evolution of the littoral zone, and according to indications provided by the DIVA software (DCN 2011), sea level could rise continuously, up to about +0.81 m over the period 2000-2100, therefore confirming IPCC projections. This rise in sea level could, among other things, have direct effects of coastal floods and saline intrusion in the courses and water tables. These effects may affect human settlements, public infrastructure, fishing activities, and other economic activities along the coast, the physicochemical characteristics of inland waters (rivers Ouémé and Mono, Lake Nokoué, etc.), and the biodiversity of coastal ecosystems (De Sutter et al. 2017).

Under RCP 8.5, an increase of +9.76 cm is expected to occur in the period 2020-2039 with a range of +7.34/+13.4 cm. Under the same scenario, sea level rise is projected to increase around +30 cm with the data showing a range of +23.3/+39 cm. At the end of the century, sea level rise is expected to reach +95 cm with a high range of values between +75.85/+120 cm under RCP 4.5 and +115 cm under RCP 8.5 with projections' data ranging between +87/+152 cm (Republique Togolaise 2016 and CCKP).

Table 16: Climate change projections in Benin.

Key Climate Variable	Representative Concentration Pathways	2020-2039		2040-2059		2080-2099		Projection data source	Publication source
		Change	Range	Change	Range	Change	Range		
Sea Level Rise (cm)	RCP 4.5	*	*	+20	*	(2090-2099) +95	(2090-2099) +75/+120 cm (DIVA (DCN, 2011))	Projected total SLR for 4 components combined (OD, MGIC, GIS, AIS)	Perrette et al. 2012
	RCP 8.5	+9.76	+7.3/+13.4	+30	+23.3/+39	(2090-2099) +115	(2090-2099) +87/+152		
Precipitation (mm)**	RCP 4.5	Dec-Feb +0.4	-2.5/+4	Dec-Feb +0.3	-2.8/+4	Dec-Feb +0.3	-4.2/+3.5	Results from 16 global circulation models (GCMs) are available for the African ensemble using the CCKP	CCKP
		Jun-Aug -2.8	-29/+29	Jun-Aug -1.5	- 42.5/+34.9	Jun-Aug -4.4	-46.9/+49.8		
	RCP 8.5	Dec-Feb +1	-3/+3	Dec-Feb +1	-4/+4	Dec-Feb +0.7	-4.1/+9.1		
		Jun-Aug -2	-25/+30	Jun-Aug -3	-47/+50	Jun-Aug -7.3	-68.2/+53.7		
Temperature (°C)**	RCP 4.5	Dec-Feb +1	+0.4/+1.5	Dec-Feb +1.5	+0.7/+2.2	Dec-Feb +1.95	+1.1/+3.2		
		Jun-Aug +0.9	+0.5/+1.3	Jun-Aug +1.3	+0.8/+2.1	+	+1.5/+3.03		
	RCP 8.5	Dec-Feb +1	+0.5/+1.7	Dec-Feb +2.1	+1.3/+2.8	Dec-Feb +3.9	+2.8/+5.9		
		Jun-Aug +0.9	+0.6/+1.4	Jun-Aug +1.75	+1.2/+2.5	Jun-Aug +3.5	+2.5/+5		

The data are presented according to two RCP scenarios and for three time horizons that are compared to the reference period (1986-2005). Temperature and precipitation changes and variabilities are provided by the CCKP. The change is the multimodel median (50th-percentile) and variability is represented by multimodel 10th-percentile and 90th-percentile percentile respectively

* No projection change or variability is available.

** Based on monthly measurements averaged for winter or summer seasons.

Climate change and natural hazards in Benin

Benin is very vulnerable to extreme weather events. Its coasts are witnessing one of the highest erosion rates in the world with the coastline moving back between 12 to 30 m per year (Antea Group *a* 2017). At the same time, the area is subject to inundations that provoke strong damage.

Erosion

On the whole, the shoreline of Benin is retreating due to the erosive effect of waves. Over the last 40 years, the coast has eroded more than 400 m in certain areas causing severe damage to the environment and sweeping away homes and infrastructure. The data collected from various sources (Perrette et al. 2012, DCN 2011) report that over the period 2040-2059, sea level will rise to +20 cm under RCP 4.5 and +39 cm under RCP 8.5 (see Table 17).

Projections about sea level rise for the period 2080-2099 show a high variability of data, foreseeing an increase between +75 and 120 cm under RCP 4.5 and +87 to 152 cm under RCP 8.5. According to Agbahoungba M. et al. (2001), a retreat of 50 m will occur for 2025, and 100 meters by the year 2050 if no protective sea-wall is envisaged. As for Togo, future sea level rise projections should be considered in relation to other factors such as tides and extreme climate events (storm surges and extreme precipitation events).

In the following chapter, a more extensive analysis of the hotspots identified along the coastline of Benin will be provided. For now, the most exposed areas to erosion is the sector between the border with Togo and Grand Popo where an area of about 7.51 km^2 is expected to be eroded by 2100. The lagoons of Mono and Kouffo and the area located at the east of Cotonou which suffered high erosion 1984-2015 (see Table 17) an area of 12.9 km^2 might disappear due to sea level rise.

Table 17: Main areas affected by erosion in Benin and projections for three time horizons and two RCP scenarios				
Name of affected place (INC: Increment, ERO: erosion)	**1984 - 2015**	**1984 - 2030**	**1984 - 2050**	**1984 - 2100**
	Satellite observed	Sat observed + Dynamical evolution (RCP 4.5 and RCP 8.5)	RCP 4.5-8.5	RCP 4.5-8.5
Grand Popo (6.261097°N, 6.261097°W)	-2.42 km²	-2.92 km²	-4.27 km²	-7.51 km²
AzizacoueE-Aboute (6.319531°N, 2.078991°W)	-0.89 km²	-1.23 km²	-1.72 km²	-2.91 km²
Djomehountin (6.343077°N, 2.399014°W)	+1.22 km²	+1.22 km²	+1.22 km²	+1.22 km²
Cotonú (6.357585°N, 2.513127°W)	-3.64 km²	-5.12 km²	-7.38 km²	-12.9 km²
Cotonú (border with Nigeria) (6.374028°N, 2.702191°W)	-0.16 km²	-0.23 km²	-0.33 km²	-0.58 km²

Flooding

Floods are expected to become more frequent and intense, posing challenges to agricultural productivity and cropping techniques, all of which threaten food security and economic vitality, as seen in the floods of 2010 and 2012. The coastal zone of Benin is exposed to two types of flood risk: river floods and marine (or coastal) floods. The risk of fluvial flooding is very high along the whole littoral zone because of the waterproofing nature of the ground, inadequacy of the sanitation network, uncontrolled urbanization, poor waste management, etc. The risk of marine flooding has always been constant but with minor damage.

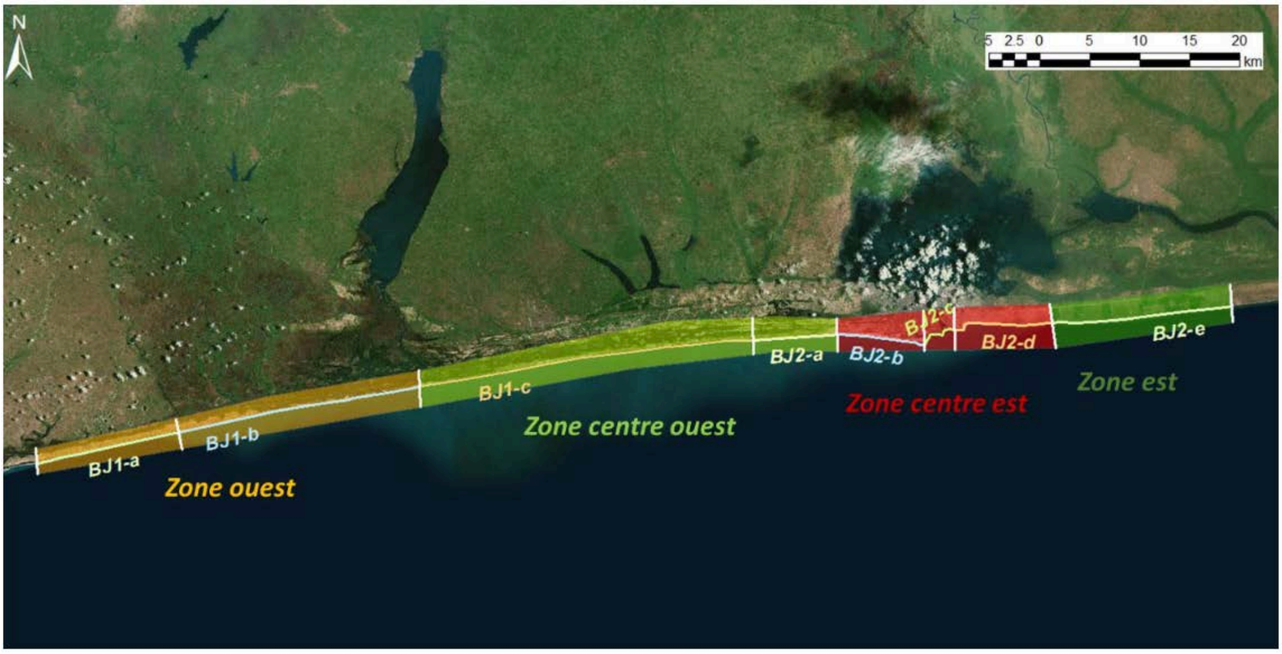
However, coastal flooding has become more frequent with one or two events per year registered in the previous decade (Antea Group a 2017). The estimations displayed in the aforementioned Table 4 about sea level rise and its combination with other natural elements indicate that two to three times per month sea level rise will combine with maximum high tide and reach up to +90 cm in 2050 under RCP 4.5 and +1.01 m under RCP 8.5. In 2100, the figures would become +1.65 m and +1.60 m respectively. In case of storm surge, sea level rise would reach up to +1.70 m in 2050 under RCP 4.5 and +1.81 m under RCP 8.5, while in 2100 it would increase +2.45 m for RCP 4.5 and +2.40 for RCP 8.5.

While this phenomenon may occur once every two years, the frequency of occurrence of extreme precipitation would be significantly lower, yet with more threatening consequences. Due to their position and morphological features, the most exposed area to inundations would be the area surrounding the lagoons of Mono and Kouffo. The exposure of the rest of the coastline is considered low (Antea group 2017a) as shown in Figure 30. Finally, to estimate the coastal areas exposed to inundation under different circumstances related to sea level rise, tides, and extreme events, tables were generated (see Annex I).

Hotspots

To analyze vulnerable areas, Figure 30 shows a sectoral division of the coastline of Benin proposed to identify four different areas that experience coastal erosion and flooding in various degrees and intensity (Antea Group a 2017). By taking into consideration this sectoral division of the coastline, a punctual analysis of the risk of natural hazards can be proposed as follows:

Figure 28: Division of the coastal area of Benin and correspondence with the 8 sectors identified by Mission d'Observation du Littoral Ouest Africain (MOLOA)



Source: Antea Group a 2017.

Western Area

The area is characterized by continuous events of erosion that provoke the submersion and destruction of natural habitats and infrastructure. The risk of erosion is very high in the city of Hillacondji, along the inter-state route and the border with Togo, and in the city of Grand-Popo. The risk of inundation in this area is high with adverse consequences for the population that cause the swallowing of beaches, the destruction of fishermen's homes, and farm animals taken away.

Center-West Area

The area is mapped as a moderate intervention priority with regular monitoring of the shoreline. Within the area, four coastal sections can be distinguished. The sections of Djondji-Mèko, Mèko-Agouin, and Avlékété-Adjahédji are characterized by a low risk of erosion, while the section of Adounjo-Bah presents a higher risk due to natural and anthropogenic factors. This section of the coastline is frequently subject to flooding caused by storms that inundate beaches and pose a threat to fishing boats. The risk level in this area is moderate.

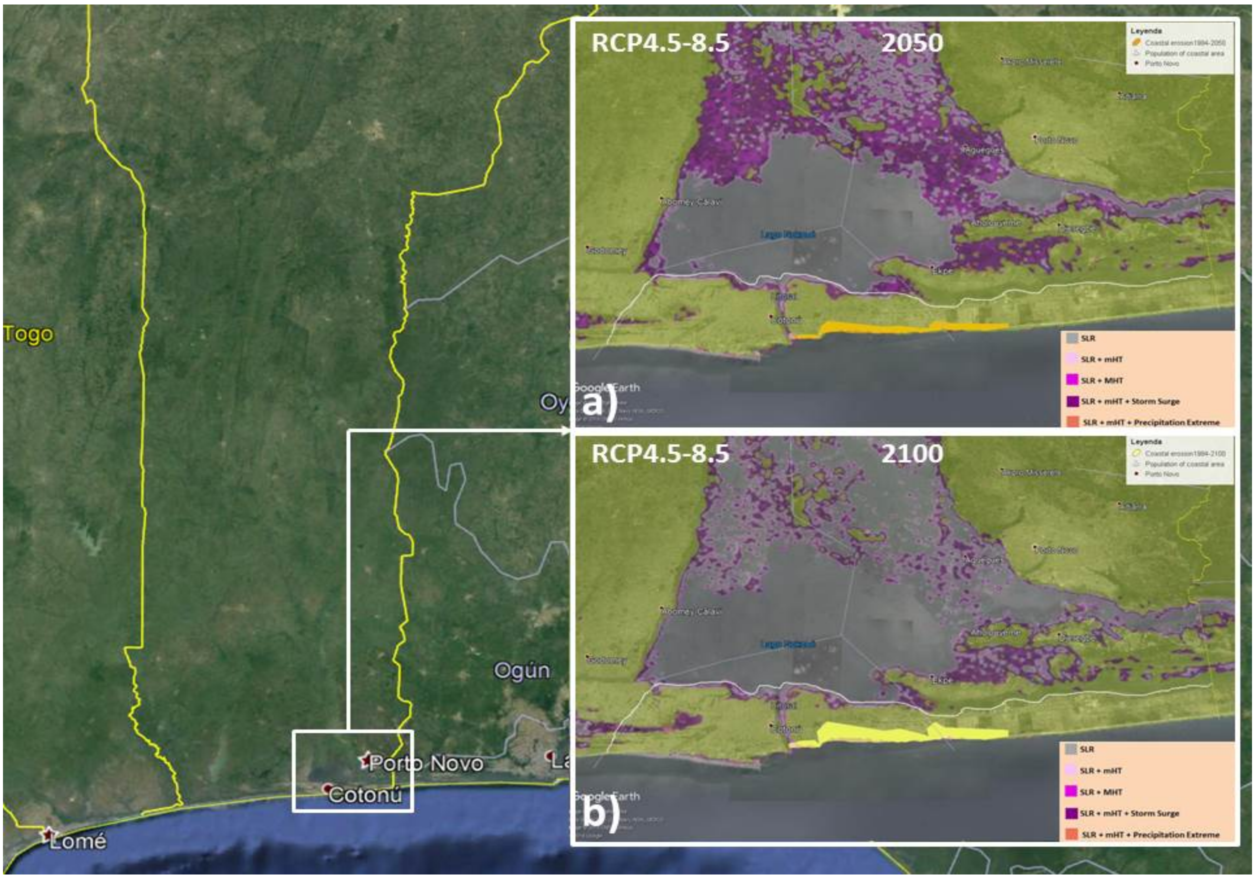
Center-East Area

The area is identified as a high priority area of intervention with some exceptions along the multiple sections. In the section of Fidjrossè – port de Cotonou, for example, the risk of erosion has been reduced due to the construction of an artificial barrier. Heading towards the East, the rest of the coastline is subjected to a high level of erosion. The risk of flooding is very low in the first part of this section. The risk is high in the section corresponding to BJ2-d due to exposure to storms and to the presence of valuable infrastructure near the coastline.

Eastern Area

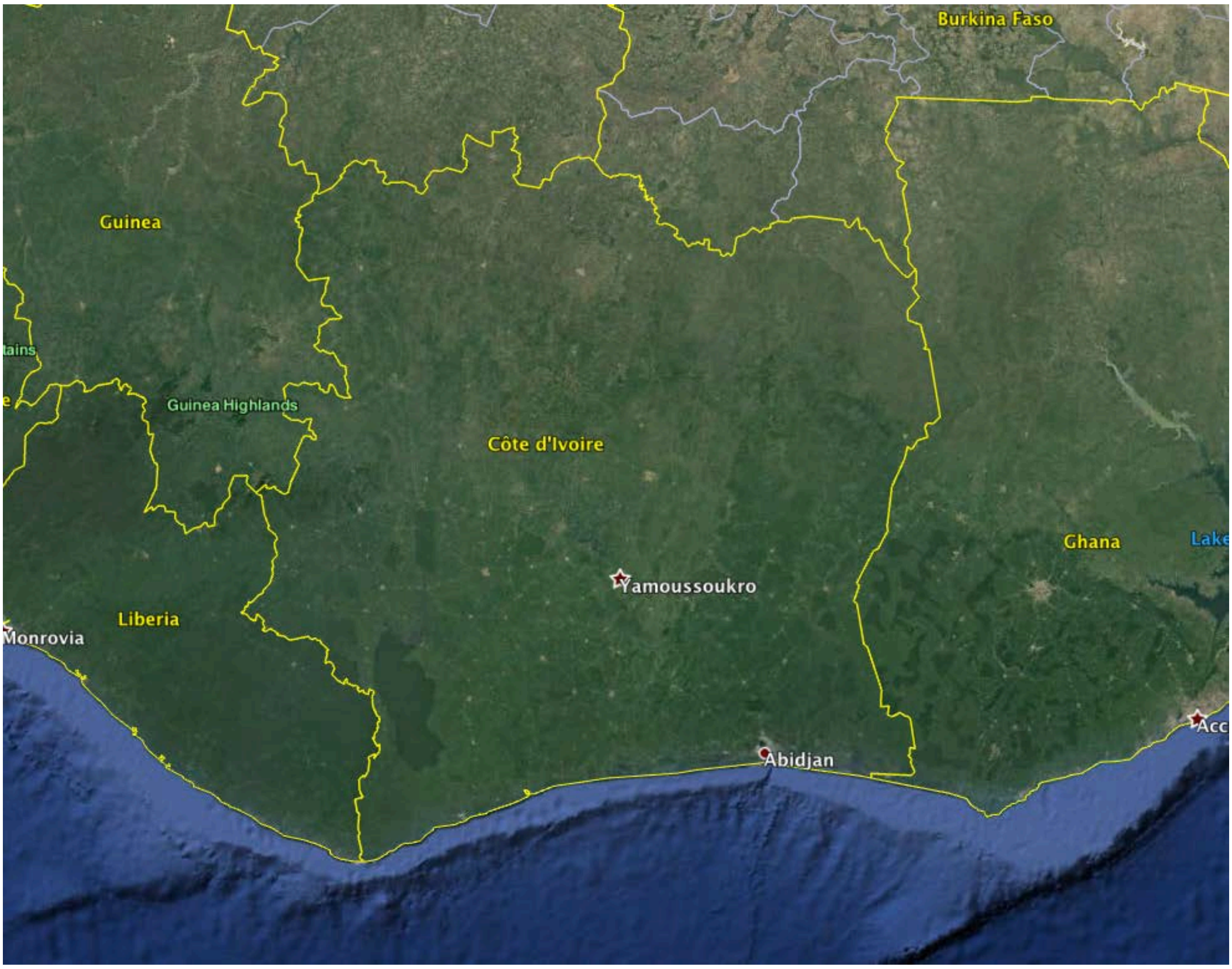
This small area can be divided into two sections from West to East. In the first section, the risk of erosion is negligible, while in the second section the risk of erosion is considered higher but not alarming. In this area, the risk of flooding is moderate.

Figure 29: Inundation and erosion exposed areas in the surroundings of Porto Novo city for both RCPs and time horizons. The main urban areas are located between the white line and the coast.



COTE D’IVOIRE

Figure 32: Map of Côte d'Ivoire



Source: Google Earth.

General climate characteristics of Côte d'Ivoire

The shoreline of Côte d'Ivoire is 566 km long and is characterized by sandy beaches forming a wide arch facing the Atlantic Ocean. Starting from the western border with Liberia towards the eastern border with Ghana, the coastline of Côte d'Ivoire is characterized by pocket beaches separated by rocky outcrops up until 25 km to the east of Sassandra. Continuing towards the east the coastline is characterized by a long sandy stretch until Ghana (Giardino et al. 2016).

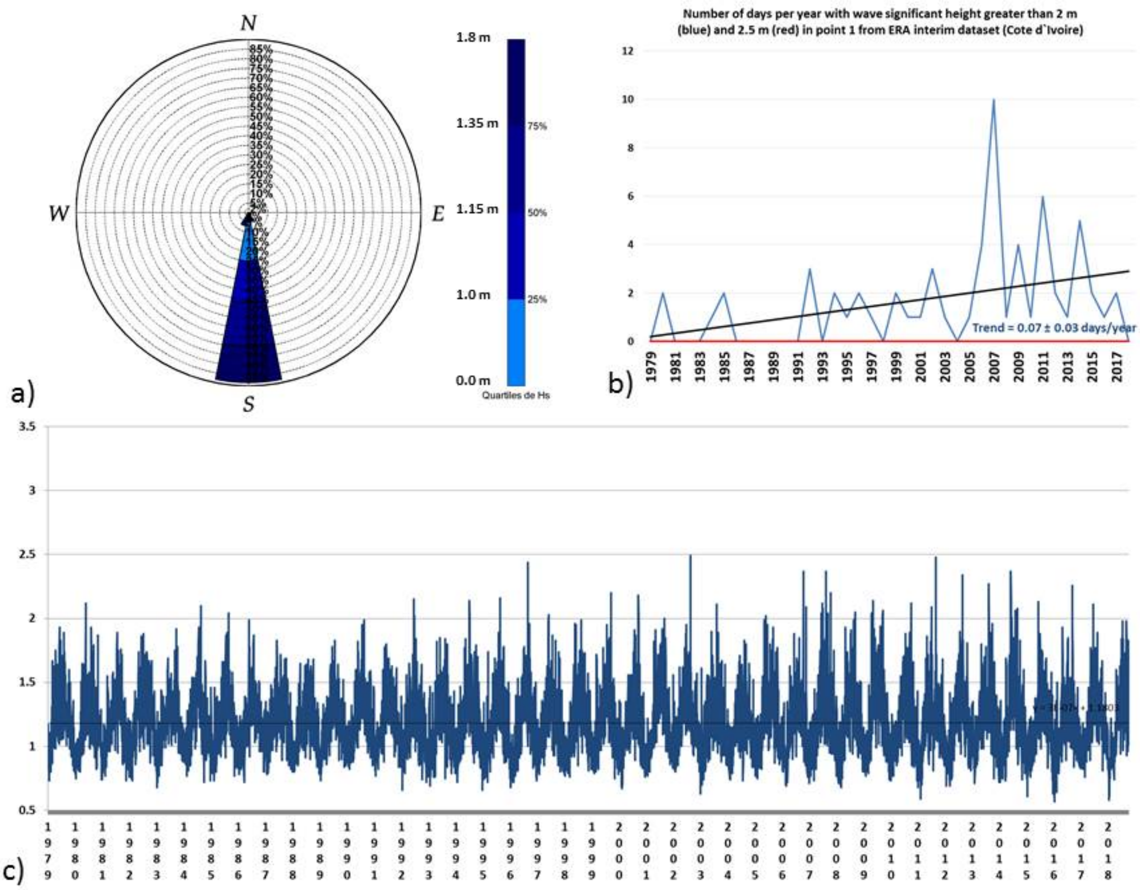
There are four major river systems that cross the country from north to south and that drain into the Gulf Guinea: the Cavally, the Sassandra, the Bandama, and the Comoé. At the climatic level, the country is influenced by two air masses: the monsoon, moist equatorial air mass and the harmattan, a dry tropical air mass with its desiccating wind.

Four main climatic zones can be distinguished, depending on the latitudes: mountain, Attiean, Baoulian, and Sudano-Guinean climates. The geographical situation of Côte d'Ivoire gives it a varied climate, a humid tropical climate in the south, and a dry tropical climate in the north. The coastline of Cote d'Ivoire generally experiences four seasons: from May to June heavy rains are registered; during August and September shorter rains occur; during October to November a shorter dry season occurs; and from December to April the main dry season occurs.

Precipitation in this area is around 1,000 to 1,200 mm/year. The subequatorial climate occupies the southern third of the country (average temperature is 25°C to 33°C, precipitation at 1,400 to 2,500 mm/year), it is very humid with an average rate of around 80 to 90 percent over the year and two rainy seasons interrupted by two dry seasons of unequal duration (MEEF 2000). The humid tropical climate occupies a belt that surrounds the subequatorial zone in the north (14°C to 33°C) with precipitation ranging from 1300 to 1750 mm/year and a humidity level of 60 to 70 percent.

The major climate processes are determined by the West African Monsoon and by the Intertropical Convergence Zone while prevailing winds bring either moist air from the Atlantic Ocean or hot, dusty air from the Sahara ('Harmattan' winds). The oceanographic data from ERA-Interim presented in Figure 33 show the waves come exclusively from the South. The height of the waves is rather limited with no waves being registered higher than 2.5 m. However, frequency of waves higher than 2 m has increased in 0.7 days each ten years as observed in Figure 33b.

Figure 30: Oceanographic data from ERA-Interim in grid point 3 (4.5°N, 5.25°W) in front of the Côte d’Ivoire. a) Direction of waves, b) Number of days per year with significant wave height greater than 2 and 2.5 m with linear trend. c) Daily significant wave height time series from January 1979 to September 2018



Observed climate change in the coastal area and hotspots

Temperature

The data collected from ERA Interim in Côte d'Ivoire is shown in Table 19a. For the 2008-2017 period, registered temperatures in the coastal grid point 3 have increased compared to the 1986-2005 period with a slightly higher increase of +0.19 C° during the winter months (December to February). Temperatures are higher from November to June and decrease during the summer months in accordance with higher precipitation levels registered (Figure 34a). In Figure 34d, a 38-year annual data series (1979-2016) of temperature is obtained from Abidjan Aero meteorological station with a clear positive trend of 0.017 ± 0.003 C°/year.

Precipitation

According to the World Bank’s country profile for Côte d'Ivoire, the Northeastern, Central, and Southwestern regions saw a decrease in rainfall between 1990 and 2000 and data from stations[7] located throughout the country exhibit decreasing trends in precipitation during the main rainy season of June-October over the 1951-2000 period (CCKP, Côte d’Ivoire).

This agrees with ERA reanalysis results from the last ten years (2008-2017) compared to the 1986-2005 period on coastal grid point 3 with a negative mean rainfall anomaly of -1.5 mm in summer (June

[7] The stations are located in Aboisso, Agboville, Bondoukou, Bouafle, Bouna, Dabakala, Daloa Aero, Gagnoa Idessa, Guiglo, Man Aero, Mankono, Odienne, Sassandra, and Soubre.

to August) and -1.8 mm in winter (December to February). The data obtained by the Abidjan Aero station in figure 34c from 1950 to 2016 show a general decrease of precipitation of -0.5 ±0.1 mm/year that continues during the latest 38 years with a lower trend of -0.1 mm/year. However, there is a very high trend of uncertainty of ±0.3 mm/year.

Sea Level Rise

As shown in Figure 34b, annual sea level series from 1992 to 2007 computed from ESA satellites altimeter data on Côte d'Ivoire's coastal area obtained a positive trend of +0.32 ± 0.05 cm/year. Assuming that this annual trend remains constant in the 15 year period from 1992 to 2007, the total sea level change is 4.8 ± 1.1 cm. These numbers are obtained from the regression line ($y = 0.32 \cdot x - 0.5$) shown in Figure 23b with mathematical propagation of slope (trend) uncertainty (±0.05 cm/year) and offset uncertainty (±0.4 cm) as explained in the methodology section.

Table 18:

a) Change and variability of the last 2008-2017 period compared to the 1986-2005 period using the ERA grid point 3 (4.5°N, 5.25°W) data series located in the Côte d'Ivoire

Parameter	**Source data and used data period range**	**Dec-Feb**		**Jun-Aug**	
		Change	Variability	Change	Variability
Temperature (C°/month)*	ERA-Interim **1986-2017**	0.19	±0.18	0.03	±0.07
Precipitation (mm/month)*	ERA-Interim **1986-2017**	-1.80	±0.63	-1.52	±1.18

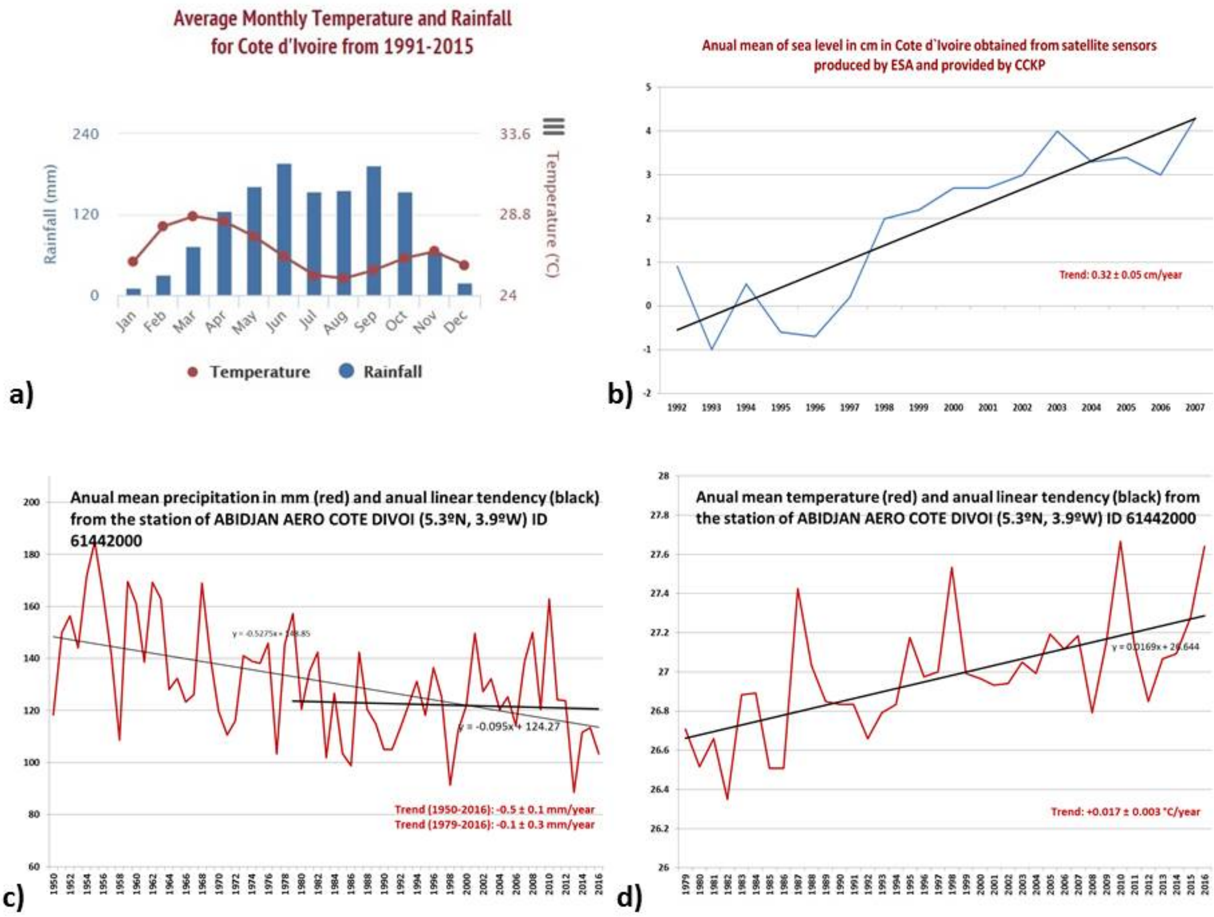
b) Annual series trend and variability using ESA Satellite altimeter and temperature and precipitation trends using data from meteorological station in Abidjan city

Parameter	**Source data and used data period range**	**Trend**	**Trend variability**
Sea level rise (cm/year)**	ESA satellite altimeters **1992-2007**	0.32	±0.05
Temperature (C°/year)**	ABIDJAN AERO station (ID 65578000) **1979-2016**	0.017	±0.003
Precipitation (mm/year)**	ABIDJAN AERO station (ID 65578000) **1979-2016**	-0.1	±0.3
	ABIDJAN AERO station (ID 65578000) **1950-2016**	-0.5	±0.1

* Based on monthly averages from initial daily ERA dataset. Changes and variabilities between the two periods are obtained each month and later averaged for 3 winter or 3 summer months.

** Based on monthly measurements that are annually averaged.

Figure 31*:* a) Country Mean monthly temperature and precipitation climatology from 1991 to 2015 obtained from CCKP web page. b) Country Annual mean sea level time series from 1992 to 2007 and trend. c) Mean annual precipitation time series from 1950 to 2016 with trends for different periods on a station location*.* d) Mean annual temperature time serie*s* from 1979 to 2016 with trend on a station location



Future climate change projections

Temperature

The future scenario in Côte d'Ivoire shows a temperature increase of more than +3°C by 2100 over most of the country from north to south. A greater increase is projected to occur during the winter months (December to February) for every time horizon and RCP scenarios. An increase of almost +1°C is projected for 2030 under RCP 4.5 with extreme values ranging between +0.4° and +1.5°C. Under RCP 8.5, the temperature is expected to increase up to the same level and with very similar variability (see Table 20). In 2050, temperatures are expected to increase an average of +1.2°C under RCP 4.5 and almost +1.6°C under RCP 8.5 with values ranging between +0.8°/+2.14°C and +1°/+2.50°C respectively. In 2100, the temperature is expected to increase up to +1.6°C for RCP 4.5, with a variability of +1.1°/+3.15°C, and more than +3.4°C for RCP 8.5 with a variability of +2.4°/+5.45°C.

Precipitation

Precipitation projections are highly diverse over the century. A clear trend that emerges from the data is an increase in rainfall in the winter months and a decrease expected in the summer months. In 2030, monthly precipitation is expected to increase up to almost +1 mm in winter and decrease -0.04 mm during summer months for RCP 4.5. An increase of +1 mm and a decrease of -3 mm are projected to occur in winter and summer months respectively for RCP 8.5.

For both scenarios, a very high variability (with values ranging between -27.2 to +38.2 mm for RCP 4.5 and -34 to +40 mm for RCP 8.5) is registered for June to August. For the period 2040-2059, a similar trend is registered. Under RCP 4.5, a slight increase of precipitation is registered in the winter months while a significant decrease is registered in summer months. Under RCP 8.5, a small increase is projected to occur both during winter and summer months. In 2100, a precipitation increase is expected to occur during both winter and summer months and under both scenarios. However, the high variability shown in the data brings high uncertainty for future climate projections of precipitation.

Sea Level Rise

Sea level is expected to rise to +30 cm in 2070 and +95 cm in 2100 for RCP 4.5 with the extreme values ranging between +75 and +120 cm. Under RCP 8.5, sea level is expected to rise to +115 cm in 2100 with a value ranging between +87 and +152 cm.

Table 19: Climate change projections in Côte d'Ivoire.

Key Climate Variable	Representative concentration Pathways	2020-2039		2040-2059		2080-2099		Projection data source	Publication source
		Change	Range	Change	Range	Change	Range		
Sea Level Rise (cm)	RCP 4.5	*	*	Whole coast (2070) + 30 (Giardino et al. 2016)	*	(2090-2099) +95	(2090-2099) +75/+120 (DIVA (DCN, 2011))	Projected total SLR for 4 components combined (OD, MGIC, GIS, AIS)	Perrette et al. 2012
	RCP 8.5	*	*	*	*	(2090-2099) +115	(2090-2099) +87/+152		
Precipitation (mm) **	RCP 4.5	Dec-Feb +0.95	-5.5/+8.7	Dec-Feb +1.38	-5.2/+11.3	Dec-Feb +1.2	-7.3/+9.9	Results from 16 global circulation models (GCMs) are available for the African ensemble using the CCKP.	CCKP
		Jun-Aug -0.04	-27.2/+38.2	Jun-Aug -3.57	-37.5/+49.4	Jun-Aug +0.9	-41.5/+53.3		
	RCP 8.5	Dec-Feb +1	-7/+7	Dec-Feb -0.5	-5/+7	Dec-Feb +2.3	-8.8/+18.5		
		Jun-Aug -3	-34/+40	Jun-Aug -0.7	-43/+47	Jun-Aug +0.8	-58.8/+61.7		
Temperature (°C) **	RCP 4.5	Dec-Feb +0.9	+0.4/+1.7	Dec-Feb +1.4	+0.8/+2.4	Dec-Feb +1.8	+1.1/+3.5		
		Jun-Aug +0.7	+0.5/+1.3	Jun-Aug +1.1	+0.9/+1.9	Jun-Aug +1.5	+1.1/+2.8		
	RCP 8.5	Dec-Feb +1	+0.6/+1.7	Dec-Feb +1.8	+0.9/+3	Dec-Feb +3.7	+2.4/+5.9		
		Jun-Aug +0.9	+0.6/+1.3	Jun-Aug +1.5	+1/+2	Jun-Aug +3.2	+2.4/+5		

The data are presented according to two RCP scenarios and for three time horizons that are compared to the reference period (1986-2005). Temperature and precipitation changes and variabilities are provided by the CCKP. The change is the multimodel median (50th-percentile) and variability is represented by multimodel 10th-percentile and 90th-percentile percentile respectively.
* No projection change or variability is available.
** Based on monthly measurements averaged for winter or summer seasons.

Climate change natural hazards in Côte d'Ivoire

Erosion

Coastal erosion is generated by the combination of climate change and certain socio-economic factors caused by the population. Among these factors is immigration towards coastal urban areas (especially Abidjan and San Pedro), the disappearance of mangrove forests in favor of domestic firewood, the installation of dams and barriers, and the extraction of sea sand for construction purposes. Regarding climate change, sea level rise represents the main source of coastal erosion, especially if combined with other natural factors such as storm surges and extreme precipitation events. Climate projections displayed in Table 20 show that in 2070 sea level will rise to +30 cm under RCP 4.5 while in 2100 it will increase by +95 cm for RCP 4.5 and around +1.15 m under RCP 8.5.

When these data are combined with other natural factors (high tides, storm surges, and extreme precipitation events), it is possible to calculate sea level rise during exceptional events and assess the risk of the country's coastal areas.

As shown in Figure 35, the most exposed sectors are in the eastern part of the coastline. However, in the western part there are areas that present high vulnerability due to population and the economic infrastructure (see Table 21). The coastline of San Pedro, for example, is expected to decrease about -0.23 km^{2}. by 2050 and -0.39 km^{2} in 2100, therefore threatening human settlements in the area. In Abidjan, a land loss of -1.60 km^{2} is expected to occur by 2050 and of -2.83 km^{2} by the end of the century.

These parts of the coastline present a dynamic that is part of a significant regressive evolutionary trend, thus defining critical points or hotspots distributed over three sectors of the coast that will be described in the following chapter.

Table 20: Main areas affected by erosion in Mauritania and projections for three time horizons and two RCP scenarios

Name of affected place (INC: Increment, ERO: erosion)	1984 - 2015	1984 - 2030	1984 - 2050	1984 - 2100
	Satellite observed	Sat observed + Dynamical evolution (RCP 45 and RCP 85)	RCP 4.5-8.5	RCP 4.5-8.5
San Pedro (4.737498°N, -6.631531°W)	-0.1 km^{2}	-0.1 km^{2}	-0.23 km^{2}	-0.39 km^{2}
Lagune of Popo (4.776824°N, -6.518894°W)	-0.71 km^{2}	-1 km^{2}	-1.46 km^{2}	-2.63 km^{2}
Sassandra (Brodje - Coco Plage) (4.965702°N, -6.047588°W)	-0.22 km^{2}	-0.30 km^{2}	-0.44 km^{2}	-0.93 km^{2}
Grand Lahou (5.134668°N, -5.023133°W)	-0.38 km^{2}	-0.49 km^{2}	-0.65 km^{2}	-0.87 km^{2}
Abidjan (5.247241°N,-3.939564°W)	-0.79 km^{2}	-1.12 km^{2}	-1.60 km^{2}	-2.83 km^{2}

Flooding
Riverine floods repeatedly hit Côte d'Ivoire, especially in the southern part of the country where the highest amount of rainfall occurs. The city of Abidjan is very prone to flooding and poor sanitation systems within urban areas, including clogged drains and sewers, which lead to flooding during the rainy season. Coastal flooding, on the other side, will mainly depend on sea level rise and its combined effects with extreme phenomena, as well as on the altitude of the coastal area. Projections presented in Table 4 show the increase in sea level rise in case high tides or extreme events occur. As already discussed for Togo and Benin, the highest increases would result from a storm surge or extreme precipitation events. If the former event occurs, sea level rise would increase up to +1.70 m under RCP 4.5 and +1.80 m under RCP 8.5 in 2050 and +2.45 m for RCP 4.5 and +2.40 m for RCP 8.5 at the end of the century.

In case of extreme precipitation events, sea level would increase by +2.10 m under RCP 4.5 and +2.21 m under RCP 8.5 in 2050 and +2.95 m for RCP 4.5 and +2.80 m for RCP 8.5 in 2100. Apart from three sectors in the west of the country – in proximity of the cities of San Pedro and Sassandra – the rest of the country's coastline is not considered to be highly exposed. The highest indicator of coastal flooding is calculated in the area of Port Bouet Est (IMDC 2017). In this sector, located on the eastern part of the coast and characterized by a very dense occupation and population, damage was reported during the storm surges of August 2011 and end of May 2014. An estimation of other coastal areas exposed to coastal flooding is provided in Tables A1-10, A1-11, and A1-12 in Annex 1.

Hotspots

With a rise in sea level the impacts will be increase erosion of the coast, aggravate floods in coastal areas, flood swamps, mangroves, and other lands and coastal vegetation, increase salinity in estuaries and aquifers, change the hydrological regimes of rivers, and increase sedimentary transit and modification of the intertidal zones. Natural factors combine with human interventions in the natural environment such as the construction of artificial structures on the shore, extraction of sand on beaches, construction of river dams which previously assured the sedimentary supply of the littoral, uncontrolled extraction of water in the deposits and coastal reservoirs, and the destruction of mangroves.

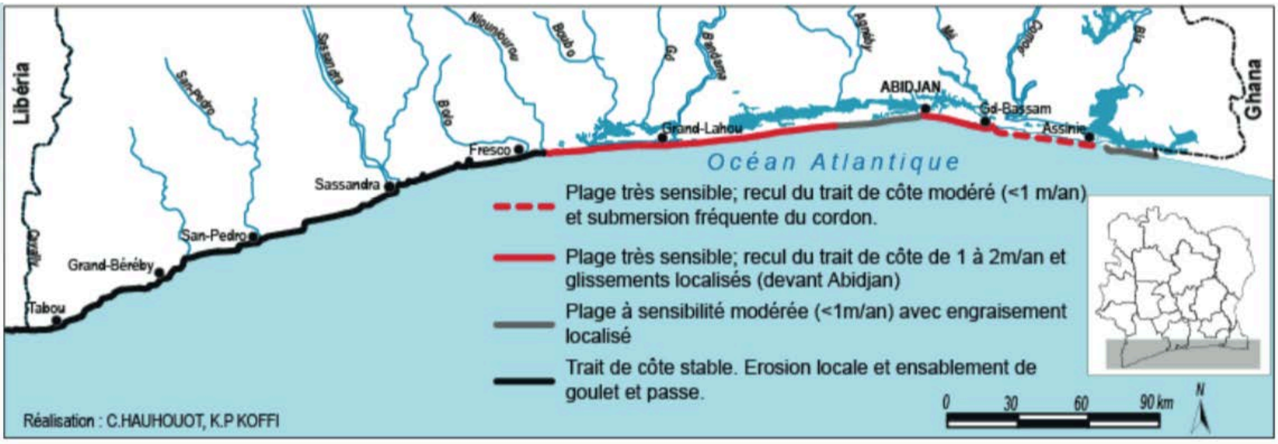
The sensitivity of the country's coastal areas varies based on geological and morphological characteristics. Figure 35 shows three areas that can be distinguished along the coastline of Côte d'Ivoire (MINSEDD 2017):

Cap des Palmes-Sassandra
The coast in this area is considered stable due to the nature of the ground characterized by rock formation. Critical areas of erosion are located along the coastal perimeter of the Port of San Pedro. The coastline of San Pedro has been affected by anthropogenic pressure from the construction of the Port in 1970 and extraction of beach sand for construction from the city (Cédric et al. 2017).

Sassandra-Abidjan
This section is characterized by a dynamic formation of sand, although the angle of incidence of waves (27°) is less favorable for sediment transit. However, the coast does not present the same trend everywhere with the most vulnerable areas in the West. The coastal area of Abidjan and Grand Bassam is a vulnerable area with strong environmental, socio-economic, tourist, and cultural issues.

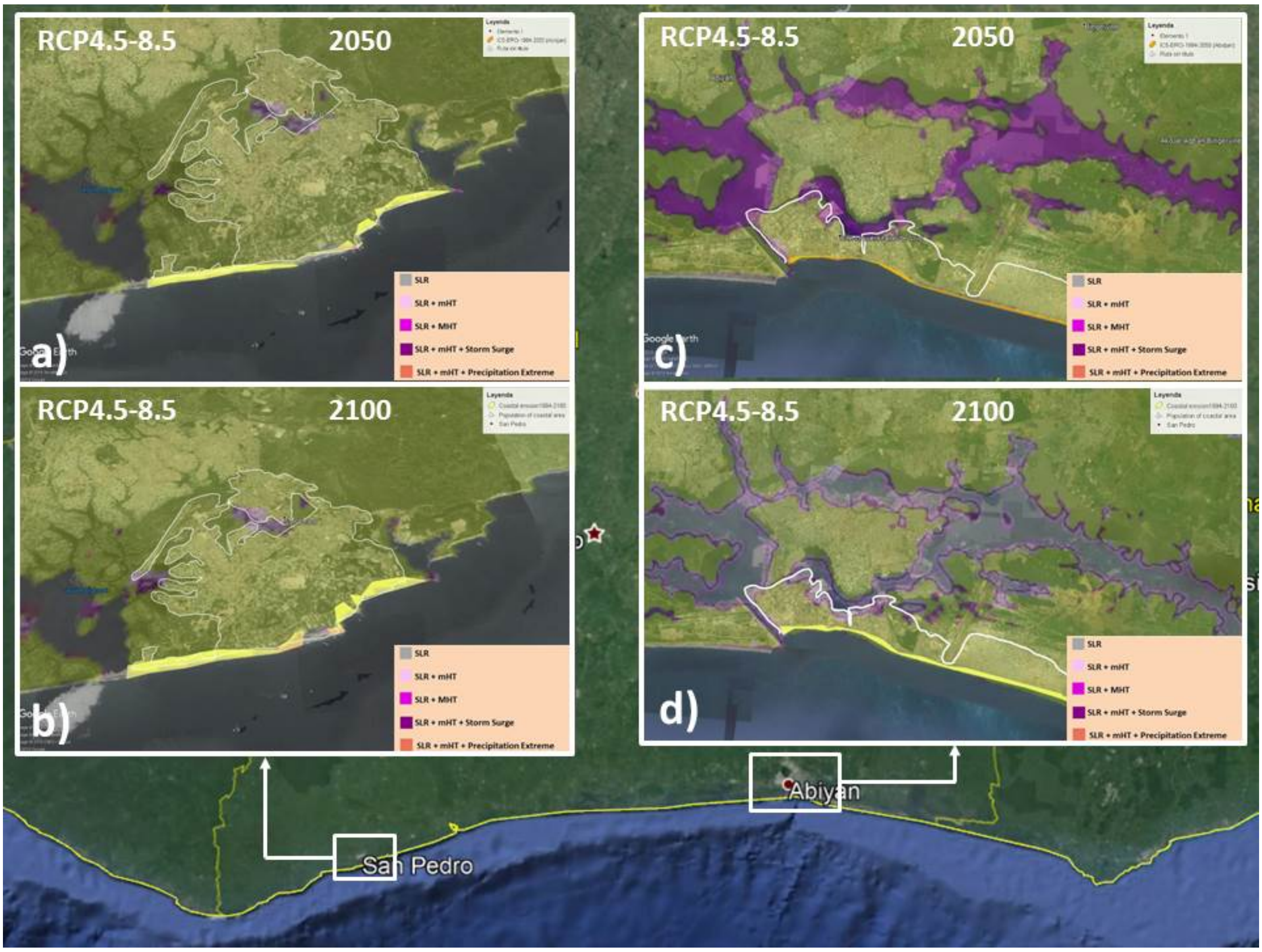
Abidjan-border with Ghana
The coastal area suffers from a sedimentary deficit caused by anthropic origin (interruption of the sedimentary transit by the protection structures of the Vridi canal). These disturbances induce an average retreat of the shoreline of the order of 1 to 3 m / year. Between Abidjan and Bassam, the coastline remains more or less stable apart from the disturbances of stormy tides. In Grand-Bassam, the definitive closure of the outlet of the Comoé River resulted in eutrophication of the lagoon environment and deprived the sandy cordon sedimentary inputs from the river, favoring an erosive phenomenon that threatens this city.

Figure 32. Map of the sensibility of the coastline of Côte d'Ivoire



Source: MINSEDD 2017.

Figure 33. Inundation and erosion exposed areas in the surroundings of San Pedro and Abidyan city, for both RCPs and time horizons. The main urban areas are located betwen the white line and the coast.



CONCLUSION

Climate change poses a serious threat to the coastline of West Africa. People, ecosystems, and assets in coastal zones are exposed to a variety of natural hazards, including floods, coastal erosion, cyclones, sea surges, and extreme precipitation events. In this study, current and future impacts of climate change and the major biophysical hazards were discussed for five West African countries.

Historical climate data for precipitation and sea level rise were generated through ERA Interim data series for each country. Observations on temperature show a general increase in the coastal areas of the five countries. The analysis performed using ERA Interim data series compared the last ten years (2008-2017) with the reference climate period (1986-2005) showing a mean monthly temperature anomaly of around +0.15 C° in summer (June-August) and winter (December-February) except for Mauritania and Senegal that show a negative anomaly of around -0.20 C° during winter months.

The analyzed annual temperature data series recorded from stations situated near the most important coastal cities generally show trends of temperature increase up to +0.20 C° per 10 years, with a maximum increase in Nouakchott (Mauritania) of +0.25C° per 10 years, and a minimum in Porto Novo (Benin) and Lomé Aero (Togo) with an increase of +0.13C° per 10 years. Mean monthly precipitation anomalies from ERA interim data series comparing the last 10 years (2008-2017) to the reference period (1986-2005) show high variability in the five countries. However, some conclusions can be drawn:

- In Senegal, a positive anomaly of +0.77 mm for the rainy season (June-August).
- In Togo, Benin and general negative anomalies around -1.10 mm in summer (June-August) and winter months (December-February).

Precipitation annual trends obtained from city stations mostly present negative trends (-0.4 mm/year) in long periods (1950-2016) with high variability. In three countries, Mauritania, Senegal, and Togo positive precipitation trends have been registered (around +0.6 mm/year) in the last forty years (1979-2016).

Sea level rise of +0.25 cm/year in Senegal, Togo, and Benin and of +0.32 cm/year in Mauritania and Côte d'Ivoire was observed between 1992-2007 using ESA satellite data. The observation is consistent with the literature (Jet Propulsion Laboratory, Beckley et al. 2017), that shows trends of +2.5 to +3.5 mm/year (1992 to 2018).

In the present work, 40 years (1979-2018) of three hourly significant wave height data series from the ERA Interim were downloaded, daily averaged, and analyzed for the closest grid point to each country's coastal area. While the observation data show that the frequency of days with waves greater than 2 meters is generally increasing in the whole region at a rate of one day every ten years, in Senegal this trend has been decreasing. However, the data show high uncertainty and should be considered with caution.

A general warming is estimated in the whole area of study with temperature increasing up to 3°C (up to 4.6°C in Mauritania) at the end of the century under the higher greenhouse gas emission pathway RCP 8.5. Except for Mauritania, winter months are expected to be warmer than summer months. While climate projections of temperature present a consistency in the results, precipitation is characterized by high variability in the data, which impedes the establishment of clear trends and certainty of forecasting events. In the analysis proposed above, a general decrease in future precipitation (except for Côte d'Ivoire) can be noticed for each country, as well as a shortening of rainy seasons during the year. Although precipitation will probably occur less frequently, it is possible that extreme precipitation events will happen more often.

Projections of sea level rise highlight a clear increase over the century with similar results for the countries analyzed and small variabilities in the data. Compared to the reference period 1980-2005, sea level rise is expected to reach +90 to +110 cm at the end of the century for RCP 8.5. Sea level rise is well defined by IPCC reports at a global scale but poorly defined at local scale, especially in specific

African countries. Limited research studies and government reports were used to obtain information on projected sea level rise in the countries. There is still a lack of information about future occurrence and intensity of storm surges and other extreme phenomena. Although many reports underline that these events will happen more often and with more intensity, there is no detailed evidence on the exact magnitude and on the return period that these phenomena will have in the future.

Future climate projections have been considered for two climate scenarios (RCP 4.5 and RCP 8.5) to show the degree of change between two most commonly referenced pathways. In the Fifth IPCC Report, a new set of scenarios, the so-called Representative Concentration Pathways (RCP), was used for new climate model simulations. These scenarios are identified by their approximate radiative forcing for the year 2100 relative to 1750: 2.6 W m-2 for RCP 2.6, 4.5 W m-2 for RCP 4.5, 6.0 W m-2 for RCP 6.0, and 8.5 W m-2 (IPCC 2013). The four RCP trajectories include a scenario in which the efforts in mitigation lead to a very low level of forcing (RCP 2.6), two stabilization scenarios (RCP 4.5 and RCP 6.0), and a scenario with a very high level of GHG emissions (RCP 8.5).

While RCP 4.5 represents a scenario in which changes have been undertaken to reduce emissions, RCP 8.5 represents the “if no action is taken” scenario and corresponds to the pathway with the highest greenhouse gas emissions. Establishing which future emission scenario we are following today is a difficult task, especially because most of the RCPs show a similar pathway in terms of global emission until about 2025 or 2030 (IPCC 2019). There may be good reasons to be skeptical of RCP 8.5's late-century values since this pathway combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements (Riahi et al. 2011). However, observations to-date do not give us grounds to exclude it. Considering it as a potential outcome is thus very useful as an example of why action is needed.

The projections mentioned above show a clear change in climate parameters and suggest that adverse consequences will occur if these trends are not taken into consideration. As discussed, the effects of these changes are already happening. The coastline of West Africa is exposed to a variety of natural and potentially damaging events. Erosion and flooding are the most visible evidence of climate change. Erosion has caused severe damage and represents a threat to both humans and the ecosystem. Human settlements and infrastructure have been destroyed, agricultural land has disappeared, and beaches have been lost. Flooding has threatened coastal environments, especially low-lying areas, and caused damage to people and assets. In the following table, a list of the most vulnerable areas is presented for each country analyzed in this study. Each area has been described in detail in the previous chapters.

Table 21: Coast areas exposed to erosion and flooding						
Benin	Western Area (BJ1-a, BJ1)	Center West Area (BJ1-c, BJ2-a)	Center East Area (BJ2-b, BJ2-c, BJ2-d)	Eastern Area (BJ2-e)		
Côte d'Ivoire	Cap des Palmes-Sassandra	Sassandra-Abidjan	Abidjan-border with Ghana			
Mauritania	Nouakchott	Nouadhibou				
Senegal	Rufisque-Bargny	Saint Louis	Saly Portudal	Casamance		
Togo	First Zone (TG1-a, TG-1b)	Lomé	Second Zone (TG1-c)	Third Zone (TG1-d)	Fourth Zone (TG1-e)	Fifth Zone (TG1-e Benin border)

Key findings, gaps, and future studies

Table 22 below summarizes the key findings for all the countries. Information gaps that were identified during the development of this work and potential ways to address them are summarized in Table 24.

Table 22: Task 1. Summary of key findings

	Observed Climate Change			Future Climate Change Projections			Climate Change related Hazards	
	Temperature	Precipitation	Sea Level Rise	Temperature	Precipitation	Sea Level Rise	Erosion	Flooding
Benin	Mean annual temperature increased by almost +0.5°C between 1979-2016.	General decrease in precipitation of -0.2 mm/year in 1950-2016 period in Porto Novo station. From 1979, a +0.2 mm/year increase with strong uncertainty of ±0.3 mm/year was observed.	A +0.25 cm/year increase in 1992-2017 period as registered by ESA satellites.	Mean annual temperature expected to rise +1.3° C under RCP 4.5 and +2.1° C under RCP 8.5 by mid-century. Warming in winter months is higher than summer months.	Future projections show decrease over the century in summer months. In winter months, a slight increase is expected.	By end of century, sea level is expected to increase to +81 cm in a range between +75 and +152 cm.	Areas identified to be most affected are western area of the coastline, especially cities of Hillacondji and Grand-Popo. The section of Azizacoue-Abouta, Djomehountin, Cotonoú, and border area with Nigeria are also at risk.	More frequent and intense floods expected. Most exposed sections of coastline are the western and the central western areas. In this report, the surrounding area of Cotonoú has been analyzed.

Côte d'Ivoire	Mean annual temperature increased by almost +0.7°C in 1979-2016 period.	A decrease of -0.5 mm/year in 1950-2016 period in Abidjan airport station. The 1979-2016 period shows a decrease by -0.1 mm/year. This data shows higher trend variability and uncertainty.	Increased about +0.32 cm/year in 1992-2017 period measured by ESA satellites.	Mean annual temperature projected to rise +1.9°C by 2050 in high emission under RCP 8.5.	Mean annual precipitation could decrease by -1.38 to -3.57mm in 2050 under RCP 4.5 and -0.5 to -0.7mm under RCP 8.5.	Sea level is expected to increase to +30 cm in 2070 and +95 cm in 2100 for RCP 4.5. Sea level is expected to increase to +115 cm in 2100 under RCP 8.5.	From west to east, the first section of coastline is stable. From Sassandra to Abidjan, coastline is significantly exposed to erosion. Other areas exposed to erosion are Grand Lahou, Lagune of Popo, and San Pedro.	Heavy precipitation along coastline and sea level rise generate frequent flooding events especially between Abidjan and border with Ghana.
Mauritania	Mean annual temperature increased by almost +0.9°C in 1979-2016 period.	No clear precipitation trend observed. While a decrease of -0.04 mm/year is registered in 1950-2016 period, a positive trend of +0.5 mm/year is observed in 1979-2016 period.	According to ESA data, an increase of +0.32 cm/year in1992-2007 period is measured.	Temperatures are projected to increase by +2.3°C by 2050 and +4.6°C by 2100 under RCP 8.5.	Precipitation is expected to fall by -2 mm in 2050 under RCP 8.5.	Sea level rise is expected to increase up to +60 cm at mid-century under RCP 8.5.	Sandy and low-lying coastline is expected to be severely affected, mainly area in south of port of Nouakchott, area of Jreida, and coastline of Nouadhibou.	Coast is constantly at risk of inundation as extreme weather events will occur more frequently. Urban areas like Nouakchott and Nouadhibou are exposed to coastal flooding.

Senegal	Mean annual temperature increased by almost +0.8°C in 1979-2016 period.	A general decrease from the Dakar station observed in 1950-2016 period (-0.8 mm/year). From 1979, an increase of +0.9 mm/year registered.	An increase of +0.25 cm/year registered by ESA satellites in 1992-2017 period.	Temperatures are projected to increase by +1.3/+2.7°C by 2050s and up to +4.3°C by 2100 under RCP 8.5.	A general decreasing trend in precipitation is likely. However, robust conclusions are difficult to make.	Projections for sea level rise show an increase of more than +1 m by the end of the 21st century.	Most exposed areas are N'Dar Toute-Saint Louis, Fas Boue, Boro Deunde, Kayar, M'Bour-Saly Portudal, Kafoutine-Casamance, Ngalou Sam Sam, Palmarin, and Dijffer.	Relatively low altitudes areas. The most exposed areas are cities of Saint-Louis, Dakar, and Casamance region.
Togo	Mean annual temperature increased by about +0.5°C in 1979-2016 period.	A decrease of -0.1 mm/year in 1950-2016 period. Positive trend in 1979-2016 period, registering a +0.3 mm/year increase.	Sea level increased by about +0.25 cm/year in 1992-2017 period as measured by ESA satellites.	Temperatures projected to increase by +1.1/+2.8°C by end of 2050 and by +2.5°C /+5.6°C by end of century under RCP 8.5.	Projections of change in rainfall present high variability and uncertainty. An increase during winter months and decrease during summer month is shown.	Sea level is estimated to increase about +31 cm by 2050 under RCP 8.5.	Coastline is almost entirely affected by erosion. Most vulnerable areas include sector TG1-c, TG1-d, and TG1-e. Main affected areas identified in south of Lomé and at border with Benin.	Risk of flooding is high along whole coastline, mainly in lower region of city of Lomé and in sector TG1-c.

Table 23: Gaps and recommendations				
	Key Findings	**Gaps and Limitations**	**Main Contribution**	**Recommendations for Future Studies**
General Climate Characteristics	Mauritania and Senegal have a long dry season (Nov-May) with mild and high temperatures (22-32°C) and a short, wet season in summer (Jul-Sep). Waves of 1.2 to 1.7 m come mostly from Northwest. The other three countries have a long rainy season (Apr-Oct) with hot temperatures the entire year (24-32 °C) and waves of 1.2 m coming mostly from the south.	Information about wind and swell directions and magnitude, tides, and currents were usually poorly detailed so was information on storm surge and extreme precipitation events.	A description of the main climate characteristics, e.g., temperature and precipitation patterns, coastal geomorphology, winds regime, and oceanic conditions, are provided at a regional level and analyzed for each country. Directional waves rose were generated for each country to show the frequency and significant height of waves coming from various directions using ERA interim dataset.	Further studies on extreme climatic events such as storm surges and extreme precipitation rainfall are needed.
Observed Climate Change	A general increase of temperature and sea level rise has been observed at a regional level and for each country. With higher data variability, a general decrease of precipitation was also detected in the area of study.	The high variability observed in historical data for precipitation represents a significant limitation when analyzing evolution of rainfall over the decades. Studies on storm surges and precipitation extreme events were also missing.	Observed data on temperature and precipitation were collected and processed from ERA Interim data series and main coastal city weather stations. Sea level data were obtained from CCKP, and transformed to yearly trends, and analyzed. Return periods and sea level anomalies related to storm surges and precipitation extreme were collected from risk data platforms.	Future studies on past extreme climate events and interpretation of high variability of precipitation and wave events are needed.

Future Climate Change	Temperature and sea level rise are expected to increase, while future projections of precipitation that are expected to decrease in the future show high variability. This does not allow the drawing of accurate conclusions.	Although many studies are available on sea level rise at a global level, a significant data gap has been detected at the regional and at national levels. Information is missing for various time horizons and scenarios (especially RCP4.5). Research on projections of extreme events like storm surges and precipitation are getting initiated. Therefore, reliable results for specific places are difficult to find.	Projection data of main climate parameters were gathered mostly from the World Bank CCKP Portal, but also from scientific reports and national and international documents. The information was summarized in tables and the results were analyzed for each climate parameter.	To understand how sea level rise, storm surges, and extreme climate events will change in the future, further studies will have to be undertaken at regional and national levels.
Climate Change Natural Hazards	Sea level rise, temperature increase, and increase in frequency and intensity of extreme climate events will amplify the phenomenon of erosion and generate more flooding events along the coastline of all countries analyzed. Human intervention on coastal areas will intensify these effects.	Lack of updated studies on the influence of extreme climate events such as storm surges, extreme winds, and precipitation on erosion and coastal flooding in the region.	Description of erosion and coastal flooding issues at a regional level and their further analysis at the national level was completed. For each country, the most exposed areas were identified, and an analysis of the effects were provided. Maps of erosion (for Mauritania and Senegal) and coastal flooding (for each country) were generated to show the effects of erosion and flooding over the three-time horizons and two climate scenarios.	More studies will be useful to assess the effects that extreme climate hazard may have on coastal erosion and flooding.

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Annex 1
Table of coastal areas exposed to inundation

Figure A1-1 shows the analysed sectors of the coastline of Mauritania and Senegal and Figure A1-2 illustrates the same of Togo, Benin, and Côte d'Ivoire. These sectors were selected and downloaded through SRTM-DEMs (Shuttle Radar Topographic Mission Digital Elevation Maps) for the purpose of this study but are not related to any geomorphological feature of the countries coastlines. For this reason, some sectors may also cover some areas of another country's coastline. For example, **MAUR2** sector (Figure A1-1) contains inundation areas of the southern part of Mauritania but also of the northern area of the coastline of Senegal, as well as **TOBE** sector (Figure A1-2) which contains all the inundation areas of Togo and Benin. The numbers displayed in the following tables correspond to potential inundation areas in km² for each RCP and time horizon and are generated by simulating the increasing sea level from the most frequent issue to lowest using sea level heights shown in Task 1 report Table 3 (for Mauritania and Senegal) and Table 4 (for Togo, Benin, and Côte d'Ivoire).

Figure A1-1: Studied sectors based on STRM DEMs on Mauritania and Senegal

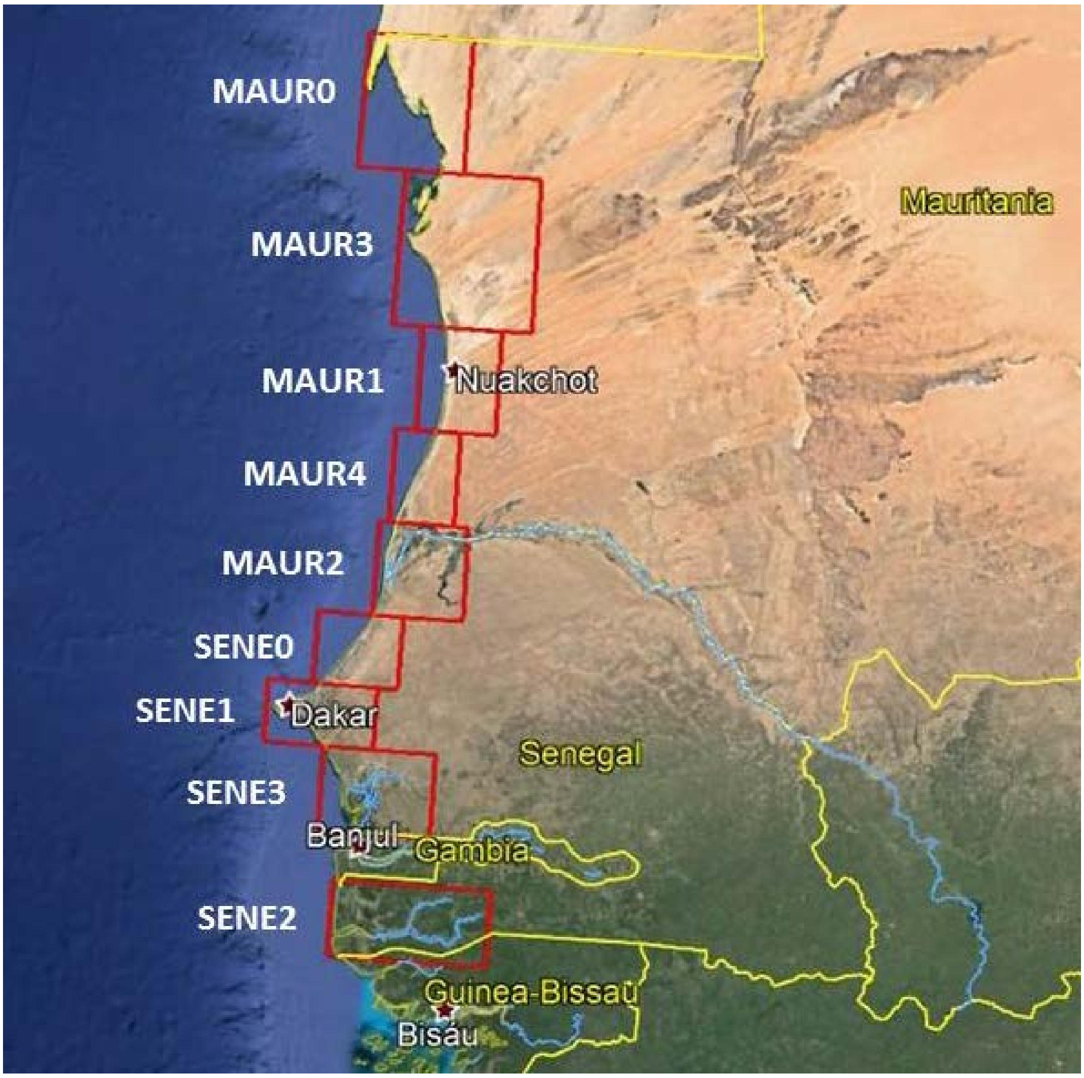

Figure A1-2: Studied sectors based on STRM DEMs on Togo, Benin and Côte d'Ivoire

Table A1-1: Potential inundation area in km² in MAUR0 sector (Country: Mauritania. Largest coastal city: Nouadhibou)

Upper left coord: 21.3°N, 17°W Lower right coord: 20°N, 16°W Total sector area: 16823 km²	**RCP 4.5**		**RCP 8.5**		**Frequency of inundation occurrence**
	2050	**2100**	**2050**	**2100**	
SLR	15.3	129.4	248.0	352.0	Continuous
SLR + mHT	271.4	481.5	632.3	729.7	Semi-diurnal tide two times per day
SLR + m**HT**	481.4	703.5	833.9	929.2	Two or three times per month
SLR + mHT + SS (Storm Surge)	809.6	988.6	1106.7	1247.7	One time every two years
SLR+ mHT +PE (Precipitation Extreme)	988.5	1156.9	1247.7	1317.1	25 years return period

Table A1-2: Potential inundation area in km² in MAUR1 sector (Country: Mauritania. Largest coastal city: Nouakchott)					
Upper left coord: 18.5°N, 16.3°W **Lower right coord: 17.5°N, 15.5°W** **Total sector area: 9452 km²**	**RCP 4.5**		**RCP 8.5**		**Frequency of inundation occurrence**
	2050	**2100**	**2050**	**2100**	
SLR	78.2	316.7	436.5	523.3	Continuous
SLR + mHT	459.3	621.4	747.1	814.8	Semi-diurnal tide two times per day
SLR + mHT	621.4	801.6	911.6	1012.9	Two or three times per month
SLR + mHT + SS (Storm Surge)	900.3	1067.8	1209.1	1349.6	One time every two years
SLR+ mHT +PE (Precipitation Extreme)	1067.8	1258.7	1349.6	1427.3	25 years return period

Table A1-3: Potential inundation area in km² in MAUR2 sector (Country: Mauritania, Senegal. Largest coastal city: Sant Louis)					
Upper left coord: 16.6°N, 16.6°W **Lower right coord: 15.7°N, 15.7°W** **Total sector area: 9705 km²**	**RCP 4.5**		**RCP 8.5**		**Frequency of inundation occurrence**
	2050	**2100**	**2050**	**2100**	
SLR	74.6	95.7	109.2	128.8	Continuous
SLR + mHT	116.1	152.4	200.2	229.0	Semi-diurnal tide two times per day
SLR + mHT	152.4	225.6	292.6	582.2	Two or three times per month
SLR + mHT + SS (Storm Surge)	288.5	645.1	882.5	1189.9	One time every two years
SLR+ mHT +PE (Precipitation Extreme)	645.1	980.2	1189.9	1406.1	25 years return period

Table A1-4: Potential inundation area in km² in MAUR3 sector (Country: Mauritania. Largest coastal city: Nouamghar)					
Upper left coord: 20°N, 16.6°W Lower right coord: 18.5°N, 15.2°W Total sector area: 25570 km²	**RCP 4.5**		**RCP 8.5**		**Frequency of inundation occurrence**
	2050	**2100**	**2050**	**2100**	
SLR	1094.1	2949.6	3419.6	3703.8	Continuous
SLR + mHT	3502.9	3985.8	4292.1	4457.0	Semi-diurnal tide two times per day
SLR + mHT	3985.8	4418.5	4654.1	4842.1	Two or three times per month
SLR + mHT + SS (Storm Surge)	4620.8	4948.0	5190.2	5453.4	One time every two years
SLR+ mHT +PE (Precipitation Extreme)	4948.0	5282.0	5453.4	5594.1	25 years return period

Table A1-5: Potential inundation area in km² in MAUR4 sector (Country: Mauritania. Largest coastal city: Tiguent)					
Upper left coord: 17.5°N, 16.5°W Lower right coord: 16.6°N, 15.8°W Total sector area: 6920 km²	**RCP 4.5**		**RCP 8.5**		**Frequency of inundation occurrence**
	2050	**2100**	**2050**	**2100**	
SLR	17.8	90.1	142.3	185.6	Continuous
SLR + mHT	155.0	236.1	305.3	341.3	Semi-diurnal tide two times per day
SLR + mHT	236.1	335.4	394.3	450.8	Two or three times per month
SLR + mHT + SS (Storm Surge)	389.5	482.0	566.2	651.1	One time every two years
SLR+ mHT +PE (Precipitation Extreme)	482.0	595.9	651.1	700.0	25 years return period

Table A1-6: Potential inundation area in km² in SENE0 sector (Country: Senegal. Largest coastal city: Mboro)					
Upper left coord: 15.7°N, 17.1°W Lower right coord: 15°N, 16.3°W Total sector area: 7100 km²	**RCP 4.5**		**RCP 8.5**		**Frequency of inundation occurrence**
	2050	**2100**	**2050**	**2100**	
SLR	0.0	0.0	0.0	0.0	Continuous
SLR + mHT	0.0	0.0	0.0	0.1	Semi-diurnal tide two times per day
SLR + mHT	0.0	0.1	0.2	0.3	Two or three times per month
SLR + mHT + SS (Storm Surge)	0.2	0.4	0.9	1.3	One time every two years
SLR+ mHT +PE (Precipitation Extreme)	0.4	1.0	1.3	1.7	25 years return period

Table A1-7: Potential inundation area in km² in SENE1 sector (Country: Senegal. Largest coastal city: Dakar)					
Upper left coord: 15.0°N. 17.6°W Lower right coord: 14.4°N. 16.5°W Total sector area: 7935 km²	**RCP 4.5**		**RCP 8.5**		**Frequency of inundation occurrence**
	2050	**2100**	**2050**	**2100**	
SLR	0.4	4.1	9.8	16.4	Continuous
SLR + mHT	11.9	23.9	33.1	37.4	Semi-diurnal tide two times per day
SLR + mHT	23.9	36.8	43.4	49.7	Two or three times per month
SLR + mHT + SS (Storm Surge)	42.9	53.0	62.4	73.1	One time every two years
SLR+ mHT +PE (Precipitation Extreme)	53.0	65.9	73.1	80.2	25 years return period

Table A1-8: Potential inundation area in km² in SENE2 sector (Country: Senegal. Largest coastal city: Ziguinchor)					
Upper left coord: 13.1°N. 16.8°W Lower right coord: 12.4°N. 15.3°W Total sector area: 14514 km²	**RCP 4.5**		**RCP 8.5**		**Frequency of inundation occurrence**
	2050	**2100**	**2050**	**2100**	
SLR	397.9	428.4	450.0	504.0	Continuous
SLR + mHT	461.0	544.8	631.1	681.8	Semi-diurnal tide two times per day
SLR + mHT	544.8	675.7	784.7	932.6	Two or three times per month
SLR + mHT + SS (Storm Surge)	778.2	1016.5	1289.5	1617.4	One time every two years
SLR+ mHT +PE (Precipitation Extreme)	1016.5	1394.8	1617.4	1842.0	25 years return period

Table A1-9: Potential inundation area in km² in SENE3 sector (Country: Senegal. Largest coastal city: Palmarin)					
Upper left coord: 14.4°N. 17.0°W Lower right coord: 13.6°N. 15.9°W Total sector area: 11054 km²	**RCP 4.5**		**RCP 8.5**		**Frequency of inundation occurrence**
	2050	**2100**	**2050**	**2100**	
SLR	152.1	221.5	278.1	347.8	Continuous
SLR + mHT	299.1	438.7	575.6	651.8	Semi-diurnal tide two times per day
SLR + mHT	438.7	636.6	767.8	894.3	Two or three times per month
SLR + mHT + SS (Storm Surge)	753.7	968.0	1179.4	1428.6	One time every two years
SLR+ mHT +PE (Precipitation Extreme)	968.0	1262.3	1428.6	1587.9	25 years return period

Table A1-10: Potential inundation area in km² in CDM1 sector (Country: Côte d'Ivoire. Largest coastal city: Abidjan)					
Upper left coord: 5.7°N. 4.9°W Lower right coord: 5°N. 2.7°W Total sector area: 20000 km²	**RCP 4.5**		**RCP 8.5**		**Frequency of inundation occurrence**
	2050	**2100**	**2050**	**2100**	
SLR	372.0	785.4	372.0	785.4	Continuous
SLR + mHT	392.4	856.4	392.4	856.4	Semi-diurnal tide two times per day
SLR + mHT	805.6	887.9	805.6	887.9	Two or three times per month
SLR + mHT + SS (Storm Surge)	900.1	974.7	900.1	974.7	One time every two years
SLR+ mHT +PE (Precipitation Extreme)	942.6	1016.0	942.6	1016.0	25 years return period

Table A1-11: Potential inundation area in km² in CDM2 sector (Country: Côte d'Ivoire. Largest coastal city: Grand Lahou)					
Upper left coord: 5.7°N. 6.6°W Lower right coord: 5°N. 5°W Total sector area: 13730 km²	**RCP 4.5**		**RCP 8.5**		**Frequency of inundation occurrence**
	2050	**2100**	**2050**	**2100**	
SLR	0.0	0.0	0.0	0.0	Continuous
SLR + mHT	0.0	0.1	0.0	0.1	Semi-diurnal tide two times per day
SLR + mHT	0.0	0.3	0.0	0.3	Two or three times per month
SLR + mHT + SS (Storm Surge)	0.7	2.3	0.7	2.3	One time every two years
SLR+ mHT +PE (Precipitation Extreme)	1.4	128.7	1.4	128.7	25 years return period

Table A1-12: Potential inundation area in km² in CDM3 sector (Country: Côte d'Ivoire. Largest coastal city: San Pedro)					
Upper left coord: 5°N. 7.6°W Lower right coord: 4.3°N. 5.8°W Total sector area: 15560 km²	**RCP 4.5**		**RCP 8.5**		**Frequency of inundation occurrence**
	2050	**2100**	**2050**	**2100**	
SLR	3.9	6.1	3.9	6.1	Continuous
SLR + mHT	4.7	7.2	4.7	7.2	Semi-diurnal tide two times per day
SLR + mHT	6.3	8.1	6.3	8.1	Two or three times per month
SLR + mHT + SS (Storm Surge)	8.6	11.5	8.6	11.5	One time every two years
SLR+ mHT +PE (Precipitation Extreme)	10.0	13.2	10.0	13.2	25 years return period

Table A1-13: Potential inundation area in km² in TOBE sector (Country: Togo, Benin. Largest coastal city: Lomé (Togo) and Porto Novo (Benin)					
Upper left coord: 5°N. 7.6°W Lower right coord: 4.3°N. 5.8°W Total sector area: 15560 km²	**RCP 4.5**		**RCP 8.5**		**Frequency of inundation occurrence**
	2050	**2100**	**2050**	**2100**	
SLR	334.2	585.7	334.2	585.7	Continuous
SLR + mHT	477.3	785.4	477.3	785.4	Semi-diurnal tide two times per day
SLR + mHT	632.2	895.2	632.2	895.2	Two or three times per month
SLR + mHT + SS (Storm Surge)	946.0	1181.3	946.0	1181.3	One time every two years
SLR+ mHT +PE (Precipitation Extreme)	1084.0	1290.5	1084.0	1290.5	25 years return period