UNIVERSIDADE DE LISBOA
FACULDADE DE CIÊNCIAS

Faculdade de Ciências
Faculdade de Letras
Instituto de Ciências Sociais
Instituto Superior de Agronomia
Instituto Superior Técnico

Faculdade de Ciências Sociais e Humanas
Faculdade de Ciências e Tecnologia

Climate change impacts on island coastal evolution: the case of Boa Vista (Cabo Verde)

" Documento Definitivo"

Doutoramento em Alterações Climáticas e Políticas de Desenvolvimento Sustentável

Especialidade em Ciências do Ambiente

Cesária da Conceição Baessa Moreira Gomes

Tese Orientada por:
Professor Doutor Filipe Duarte Santos
Professor Doutor Rui Pires de Matos Taborda

Documento especialmente elaborado para a obtenção do grau de Doutor

2019

UNIVERSIDADE DE LISBOA
FACULDADE DE CIÊNCIAS

Faculdade de Ciências
Faculdade de Letras
Instituto de Ciências Sociais
Instituto Superior de Agronomia
Instituto Superior Técnico

Faculdade de Ciências Sociais e Humanas
Faculdade de Ciências e Tecnologia

Climate change impacts on island coastal evolution: the case of Boa Vista (Cabo Verde)

Doutoramento em Alterações Climáticas e Políticas de Desenvolvimento Sustentável

Especialidade em Ciências do Ambiente

Cesária da Conceição Baessa Moreira Gomes

Tese Orientada por:

Professor Doutor Filipe Duarte Santos

Professor Doutor Rui Pires de Matos Taborda

Júri:

Presidente:

- Doutor Rui Manuel dos Santos Malhó, Professor Catedrático da Faculdade de Ciências da Universidade de Lisboa.

Vogais:

- Doutora Iva Miranda Pires, Professora Associada
  Faculdade de Ciências Sociais e Humanas da Universidade Nova de Lisboa;
- Doutor Paulo Renato Enes Baganha Baptista, Investigador Auxiliar
  Centro de Estudos do Ambiente e do Mar (CESAM) da Universidade de Aveiro;
- Doutora Susana Costas Otero, Investigadora Auxiliar Convidada
  Centro de Investigação Marinha e Ambiental (CIMA) da Universidade do Algarve;
- Doutora Sílvia Osório Martins Fonseca da Nave, Investigadora Auxiliar
  Laboratório Nacional de Engenharia e Geologia (LNEG);
- Doutor César Augusto Canelhas Freire de Andrade, Professor Catedrático
  Faculdade de Ciências da Universidade de Lisboa;
- Doutor Rui Pires de Matos Taborda, Professor Associado com Agregação
  Faculdade de Ciências da Universidade de Lisboa (Orientador).

Documento especialmente elaborado para a obtenção do grau de Doutor

Fundação para a Ciência e Tecnologia no âmbito da Bolsa de Doutoramento PD/BD/113931/2015

2019

This thesis should be cited as Gomes, C. (2019). Climate change impacts on island coastal evolution: the case of Boa Vista (Cabo Verde). PhD thesis. University of Lisbon, Portugal, 131p.

Dedicated to my children: **César Gomes and Leonel Gomes**

" ***We ourselves feel that what we are doing is just a drop in the ocean. But the ocean would be less because of that missing drop.***" Mother Teresa of Calcutta.

Acknowledgements

Without the generous and good-humoured support and advice of some people during this wonderful journey, none of this would have been possible. This thesis is a result of long a journey that began by the end of 2015. A lot of work, many learnings, adventures, joys and sorrows were experienced during this time. However, beside personal motivation to building this doctoral thesis, it was supplied by the precious collaboration of many people, which I would like to express my sincere and deep gratitude to all of them:

I would like to thank my supervisors Professor Filipe Duarte Santos and Professor Rui Taborda for their expert guidance, objectivity and scientific rigour, namely for them contribution as co-author on the published papers that stem from this thesis and in clarifying my doubts, which made me feel very honoured to be able to work with them during this time. Professor Rui Taborda is passion, enthusiasm and patience have been inspirational and it was an privilege to be supervised by him.

My sincere thanks also go to Ana Nobre Silva, for the professionalism, scientific rigour, inexhaustible patience, attention and availability given during the preparation of this work, namely for her contribution as co-author on the published papers that stem from this thesis. Additionally, in the fieldwork, office work, revision, correction and feedback in each chapter of this thesis.

My gratitude to FCT for awarding me a doctoral grant (PD/BD/113931/2015) that enabled this research to be carried out.

I would like to thanks Professors César Andrade (FCUL, UL) and Julia Seixas (FCT, UNL) to facilitate that I improved my knowledges about coastal process and SIG, at Faculdade de Ciências, Universidade de Lisboa (FCUL, UL) and Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa (FCT, UNL), respectively.

My thanks are extended to Raquel Brito, for all help that she gave me, namely logistic support during this time. My thanks to Raquel Brito become special, for the serenity she always transmitted to me in the most anxious moments. I also wish to thank Goretti Matias (ICS) for her encouraging words to me for all time that we meet.

My gratitude to Centre for Ecology, Evolution and Environmental Changes (CE3C) and Geology Department, all from Faculdade de Ciências, Universidade de Lisboa, the institutions that hosted me, for the logistical support their gave me during the execution of this work.

My sincere and deep thanks to Direcção Nacional do Ambiente (DNA) of Cabo Verde, for stimulating in me the interest in improving my knowledges about climate change impacts on islands, namely on islands coastal areas. For all my DNA colleagues many thanks.

Additionally my thanks to Rita Caldeira and Cristina Costa (both LNEG) for providing and digitalized help the 1968 and 1983 aerial photos. Thanks to Euda Miranda and Wagner Nogueira (both INGT) for providing 1991 aerial photo, 2003 and 2010 Orthophoto maps, Digital Terrain Model (DTM) and Laws about Management Cabo Verde Territory.

I would like to thanks Pedro Costa, João Cascalho, Vera Costa, for their precious support at laboratory work and contribution as co-author on the published paper that stem from this thesis. My thanks are extended to Luis Rebelo and Aníbal Medina for their contribution as co-author on the published paper that stem from this thesis.

I would like to thanks Ricardo Ramalho, for his precious support about Boa Vista island is geology, geomorphology and others important informations.

Additionally acknowledgements are due to the editors and reviewers from the Earth Surface Processes and Landforms, and World Scientific for their time spent to reviewing and assessing the manuscript that were submitted to their journals.

My special thanks to Cristina Lira for good feedback about many things and sharing good times, but specially to present me LATEX software and her all patience in support me about LATEX domain, which facilitate my life in terms of thesis formatting.

My thanks are extended to Ana Bastos, Tanya Silveira, Carlos Nogueira, Andreia Ferreira, Soraia Romão, Mariana Andrade, Fátima Valverde, Daniela Rato, Ivana Bosnic and Stephanie Dumont for their support and sharing good times.

A special and heartfelt thanks to my world: Agnelo Gomes, César Gomes and Leonel Gomes. Agnelo Gomes whom together we embrace this adventure since first time with an inexhaustible patience, unwavering and unconditional support demonstrate throughout my academic formation, for his love, the complicity, understanding, friendship, companionship, love and all that we still have to live together. César Gomes and Leonel Gomes, my motivation and reason to want learn and acquire more and more skills that contribute for un sustainable world.

A special and heartfelt thanks to my father, Cesário Moreira and my mother Maria de Fátima Baessa (in memoriam) my great source of inspiration, my model of courage, joy and strength to live.

My deep thanks to my friends Ana Borges, Aleida Borges, Rita Moreira, Celestina Lopes, Cristalina Rodrigues, her mother Maria Mendes and her sister Diana Rodrigues, Neusa Tavares, Miguel Lourenço, Natacha Magalhães, Karen James, Luzia Oliveira, Dudene Lima, Ana Martins, Maria de Fátima Oliveira, Cândida Oliveira, Emanuela da Veiga, Odete Rocha, Olinda Gamboa and Sara Almeida for all encouraging words that they said to me every time.

My thanks are extended to my mother-in-law, Maria Madalena Baessa, my father-in-law, Jesuíno Gomes (in memoriam), his brother Francisco Gomes and my sisters-in-law Luisa Gomes, Andradina Baessa and Judite Gomes for their constant concern to follow the evolution of my formation.

I am grateful to my brother Nilton Moreira and my sisters Niltina Moreira, Amilcedina Moreira, Hélida Moreira for the encouragement and support.

For all, many thanks.

Abstract

Boa Vista is the easternmost island of the ten volcanic islands of Cabo Verde archipelago, being in the group of Windward islands between the latitudes 15°58'N and 16°14'N and longitudes 22°40'W and 22°58'W.

This work presents a coastal evolution analysis of Boa Vista island, in the present (1968 to 2010) and in the future scenarios (2019 to 2100), taking into account the climate change impacts, in particular the sea level rise. Subsequently, this work investigates the low-lying sandy coast evolution of Boa Vista through an integrated characterization of coastline and shoreline indicators (over the past four decades) based on aerial imagery and orthophoto maps. This analysis indicate that between 1968 and 2010 the coast was relatively stable, although some spatial variability was recognized. The largest changes were observed at the tips of embayed beaches and a clear coastal progradation was found at the southern (downwind) coastal sectors. Findings show that understanding coastal evolution at low-lying islands should be supported on island-scale observations, being the only scale capable to capture the sedimentary connections between beach systems, that often control coastal evolution.

The factors responsible for coastal evolution were also evaluated. It is concluded that the sedimentary balance is mainly responsible for the recent coastal evolution. Therefore, sediment dynamics characterization was conducted with the purpose to identify sediment source, transport processes and sediment sink. Thus, this work confirms the existence of a net north to south sand transport but with considerable differences between the sediment transport processes and paths around the island. On the Western side sediment transport is dominated by overpass (wind action) while on the Eastern side headland bypass (wave action) prevails. At the western side of the island the estimated magnitude of overpass transport closely matches the sedimentary sink related with coastal progradation, thus this offers the possibility for a first quantitative assessment of Boa Vista sedimentary budget. This analysis, was materialised on a conceptual semi-quantitative model of sediment transport at Boa Vista island.

Although rising sea level have played a minor role in recent coastal evolution of Boa Vista Island, the scenario is likely to change with expected medium and long term climate change. In this sense, coastal evolution was projected for 2100 based on NOAA representative scenarios of sea level rise (SLR) until the end of the 21^{st} century (2100). The results show that except Ponta Varandinha to Ponta Pesqueiro Grande stretch, variations associated with SLR exceed the sedimentary balance in all coastal areas, in all NOAA scenarios. In Ponta Varandinha to Ponta Pesqueiro Grande stretch, SLR induce a coastline retreat that exceed the sedimentary balance only in the NOAA extreme scenario. Based on these results, coastal areas are projected that could be more susceptible to flooding with SLR based on NOAA extreme scenario (2.5 m). The results indicate that Sal Rei City could be probably the most flooded coastal area.

According to the results mentioned above, coastal assets at Boa Vista coastal area were analysed, including coastal vulnerability key factors. In this regard, some climate change adaptation strategies were discussed and could be implemented.

This thesis show that coastline evolution in Boa Vista island is the result of natural process (sedimentary budget) with poor anthropogenic disturbance. In that sense, having in consideration the results obtained and taking into account the relevance of Boa Vista island sun and beach tourism in terms of economic revenue, it is necessary to highlight the vulnerability of the sedimentary links between coastal and dune systems, and therefore the absolute need to avoid the creation of any obstacles to sediment transport that can put in peril the delicate coastal equilibrium. Methodologies used here may be replicated or extended to other island systems.

Keywords: climate change, coastline evolution, vulnerability, Boa Vista island.

Resumo

Boa Vista é a ilha mais oriental de Cabo Verde, encontrando-se no grupo de ilhas de Barlavento entre as latitudes 15°58'N and 16°14'N and longitudes 22°40'W and 22°58'W.

Este trabalho apresenta uma análise sobre a evolução da linha de costa da ilha da Boa Vista, no presente (1968 a 2010) e em cenários futuros (2019 a 2100), tendo em conta os impactos das alterações climáticas, em particular a subida do nível do mar. Consequentemente, este trabalho examinou a evolução integrada da costa arenosa de baixa altitude da ilha, com base nos indicadores linha de costa e seco-molhado (nas últimas quatro décadas) em fotografias aéreas e ortofotomapas. Esta análise integrada indica que, entre 1968 e 2010, a costa apresenta-se relativamente estável, embora evidencia alguma variabilidade espacial. As maiores alterações foram observadas em praias encaixadas e existe uma clara progradação costeira nos sectores costeiros situados ao sul da ilha. Os resultados mostram que a compreensão da evolução da linha de costa em ilhas baixas deve ser apoiada em observações à escala da ilha, sendo a única escala capaz de permitir a percepção das ligações sedimentares entre os sistemas de praia, que frequentemente controlam a evolução da linha de costa.

Avaliaram-se ainda, os factores responsáveis pela evolução da linha de costa. Conclui-se que o balanço sedimentar é o principal responsável pela evolução recente. Assim, procedeu-se à caracterização da dinâmica sedimentar da ilha em questão, identificando a fonte, os processos de transporte e sumidouro sedimentar. Este trabalho confirma a existência do transporte sedimentar no sentido norte-sul, com diferenças consideráveis entre os processos e vias de transporte sedimentar ao longo da ilha. No sector Oeste, o transporte sedimentar é dominado pelo processo de *overpass* (induzido pela acção do vento), enquanto que no sector Este, o processo dominante é o *headland bypass* (induzido pela acção das ondas). Ainda, no lado oeste da ilha, estimou-se a magnitude do transporte sedimentar relacionada com a progradação costeira, permitindo uma primeira avaliação quantitativa do balanço sedimentar da ilha da Boa Vista. Esta análise foi materializada através de um modelo conceptual semi-quantitativo de transporte sedimentar da ilha da Boa Vista.

Apesar do aumento do nível do mar ter vindo a desempenhar um papel secundário na evolução recente da linha de costa da ilha da Boa Vista, o cenário provavelmente irá mudar com as mudanças climáticas previstas para médio e longo prazo. Neste sentido, fez-se a projecção da evolução da linha de costa relativamente à subida do nível do mar com base nos cenários representativos da NOAA até ao final do Século XXI. Os resultados mostram que com excepção do troço Ponta Varandinha a Ponta Pesqueiro Grande, as variações associadas à elevação do nível do mar excedem o balanço sedimentar em todas as áreas costeiras, em todos os cenários da NOAA. No troço Ponta Varandinha - Ponta Pesqueiro Grande, a subida do nível do mar induz um recuo da linha de costa que excede o balanço sedimentar apenas no cenário extremo da NOAA. Com base nestes resultados, fez-se a projecção das áreas costeiras que poderão ser mais susceptíveis a fenómenos de inundação com a subida do nível do mar com base no cenário extremo da NOAA (2.5 m). Os resultados indicam que a Cidade de Sal Rei será uma das áreas costeiras mais afectada.

De acordo com os resultados anteriores, analisou-se os bens existentes na área costeira da ilha da Boa Vista, incluindo os factores-chave de vulnerabilidade costeira. Deste modo, foram mencionadas algumas estratégias de adaptação às alterações climáticas que poderão ser implementadas.

Esta tese mostra que a evolução da linha de costa na ilha da Boa Vista é resultado de um processo natural (balanço sedimentar) e com pouca perturbação antropogénica. Porém, tendo em consideração os resultados obtidos e a relevância da ilha em termos do turismo de sol e praia e o peso desta contribuição relativamente ao crescimento económico a nível nacional (Cabo Verde), é necessário destacar a vulnerabilidade das conexões sedimentares existentes entre sistemas costeiros e dunares. Por conseguinte, é fundamental evitar a existência de quaisquer obstáculos ao transporte sedimentar que possam colocar em perigo o delicado equilíbrio costeiro. Metodologias aqui utilizadas poderão ser replicadas ou estendidas a outros sistemas insulares.

Palavras-chave: alterações climáticas, evolução da linha de costa, vulnerabilidade, ilha da Boa Vista.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Motivation

Climate change affects relevant society sectors. There are real evidence that demonstrate cause-and-effect relationships between these changes (e.g. temperature variation) and disturbances in biophysical systems in several locals of the world (e.g. IPCC, 2001; Santos *et al.*, 2002).

The Earth's climate is determined by a number of complex interconnected physical, chemical and biological processes occurring in the atmosphere, land and ocean (Denman *et al.*, 2007). Nowadays, these systems are strongly affected by human activities with serious consequences in the climate system. Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia (IPCC, 2013a). The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased (IPCC, 2013a).

The atmospheric concentration of CO_2 (the major player among the greenhouse gases) constitute one of the most relevant drivers regarding global climate change (Bijlsma *et al.*, 1996). Daily averages went above 400 ppm (413.55 ppm) for the first time at Mauna Loa (Havai island, USA) station in June 2019 (Scripps, 2019), has increased by about 49% over the pre industrial concentration about 277 ppm in 1750 (Joos and Spahni, 2008). According Bijlsma *et al.* (1996) it will continue to increase in the future, even if rather stringent policies on CO_2 emissions are adopted.

Coastal zones are characterized by highly diverse ecosystems, where takes place in a great number of functions, performed over a relatively small area. These functions, together with their spatial location, makes coastal zones highly attractive areas for people to live and work in (Bijlsma *et al.*, 1996). The world's human population that lives on coastal zone are estimated about 50 to 70%, although there are several variations between countries (Bijlsma *et al.*, 1996).

According to Bijlsma *et al.* (1996) there are several attempts to define the coastal zones, as well as their terrestrial and maritime limits: a) some definitions are based on the physiographic characteristics (e.g. influence of the extension of the tide, geomorphology of the continental shelf); b) others simply use the fixed distance from the coastline. In small islands, the coastal zone may include the whole island (Bijlsma *et al.*, 1996; Mimura *et al.*, 2007). Consequently, coastal areas of small islands are extensive comparatively to the island area (Mimura *et al.*, 2007). These environments are constantly under threats induced by natural and anthropogenic actions. Small islands constitute very heterogeneous group in terms of climate change exposition and sensitivity, due the majority of climate change elements that are not evenly distributed spatially, because islands have different topographies and bio-physical environments, and their populations have different livelihoods and economic bases (Mimura *et al.*, 2007).

Study and understanding climate change impacts on small islands and their coastal area constitute a concern that have been increasing significantly in recent years. Thus, since the Fourth Assessment Report, the literature on small islands and climate change has increased substantially (Nurse *et al.*, 2014). Although, it has been recognized that greenhouse gas (GHG) emissions from small islands are negligible (less than 1%) in relation to global emissions (Mimura *et al.*, 2007), small islands will most probably be highly impacted by climate change (Srinivasan, 2010), namely sea level rise (SLR), which in small islands environment can be very real (Nurse *et al.*, 2014). With sea level rising projected throughout the 21st century and beyond (e.g. Vermeer and Rahmstorf, 2009; Jevrejeva *et al.*, 2012; IPCC, 2013a; NOAA, 2017; IPCC, 2019), coastal systems, low-lying areas of developing countries and small islands will increasingly experience adverse impacts such as submersion, coastal flooding and coastal erosion (IPCC, 2014a), although impacts may be reduced through effective adaptation measures (Nurse *et al.*, 2014).

The consequences of extreme climate change impacts such as SLR, wave regime, wind, temperature, ocean acidification and storms are being considered as major threats for coastal regions and small islands until the end of the 21st century (Bijlsma *et al.*, 1996; Santos and Miranda, 2006). In coastal areas of small islands, consequences will be even more serious due their size and fragile nature. Furthermore, climate change impacts on islands depend on their location, level of coastal development and infrastructure, diversification of the economy, type of tourism (international versus national, exclusively seaside, biodiversity etc.), health of ecosystems (coral reefs, beach, mangroves, etc.) and their responses to climate change (Sauter *et al.*, 2013). Many small islands in the last two or three decades have experienced substantial changes in human settlement patterns with rapid urbanization in coastal areas, affecting the socio-economic and environmental resources (Wong, 2014; Nurse *et al.*, 2014). Thus, sometimes those changes may make increasingly difficult to detect the clear evidence of past and recent climate change effects, especially in the constrained environments of small islands, due the presence of other anthropogenic drivers (Nurse *et al.*, 2014). Studies from islands in the Pacific, Indian, Atlantic Oceans and the Caribbean have shown that human impacts play an important role in coastal islands (e.g. Nurse *et al.*, 2014; Parker and Miller, 2012). Therefore, given the range of natural and anthropogenic impacts on the small islands coast in a medium-long term, without a good monitoring, the climate change effects in this environment will continue to be difficult to identify and quantify (Nurse *et al.*, 2014).

An integrated assessment and analysis of coastline evolution on island-scale are essential to understand the interaction between all drivers, that often control coastal evolution at medium-long term. Here, this assessment was applied along the entire Boa Vista coastline. In that sense, this approach constitutes a pertinent and innovative contribution of this work, which a detailed analysis of sedimentary dynamic characterization, including transports processes, source and sink was conducted.

In addition, this thesis is also routed to a personal motivation. In my professional life (Technician of *Direcção Nacional do Ambiente de Cabo Verde*) I felt the urgent need to improve my knowledge and experience, in order to better contribute for a sustainable environmental actions and practices, namely on coastal areas, using tools that allow better intervention, which minimize the climate change harmful effects in my country, Cabo Verde. The relevance of this issue, is justified by its timeliness in international fora and its strong impact on the environment in general and on fragile ecosystems such as island regions, which need to be apprehended, due to their complexity, with purpose to establish urgent and adequate measures to mitigate the adverse effects and draw policies that increase climate change adaptation capacity.

1.2 Research Objectives

The main objective of this thesis is to study the climate change impacts in Boa Vista coastal evolution. The following complementary objectives were also pursue:

1. To characterize and describe the recent Boa Vista coastal evolution on decadal time scale (1968 to 2010);

2. To understanding present coastal evolution and establishing a model of sedimentary budget for Boa Vista coastal area, and establishing of sedimentary sources and sinks;

3. To identify the main forcing drivers of Boa Vista coastline evolution in a climate change context;

4. To contribute to a Boa Vista coastal risk assessment in a Climate Change scenarios, particularly with is related to sea level rise;

5. To establish strategies for coastal adaptation.

1.3 Thesis Outline

This work is structured as follows:

1. Following this introduction that corresponds to **Chapter 1**, is the **Chapter 2**, the Recent Coastal Evolution, which explore the coastal evolution at a decadal-time-scale (1968 until 2010) at Boa Vista island.

2. **Chapter 3** presents the Drivers of Coastal Change. Here, the main drivers (namely sedimentary budget, sea level rise and wind) that influence coastal change were identified.

3. **Chapter 4**, presents the Scenarios of Coastal Change in a climate change context, highlighting the role of sea level rise.

4. **Chapter 5**, describes the Coastal Risk under a Climate Change Scenario. Here, risk assessment in a climate change context was explored, and the strategies for coastal adaptation discussed.

5. **Chapter 6** contains the key Conclusions, summarizes the major achievements of the aforementioned chapters and add suggests for future work.

A wide overview related to the framework of this thesis was outlined in a flowchart, showed in Figure 1.1.

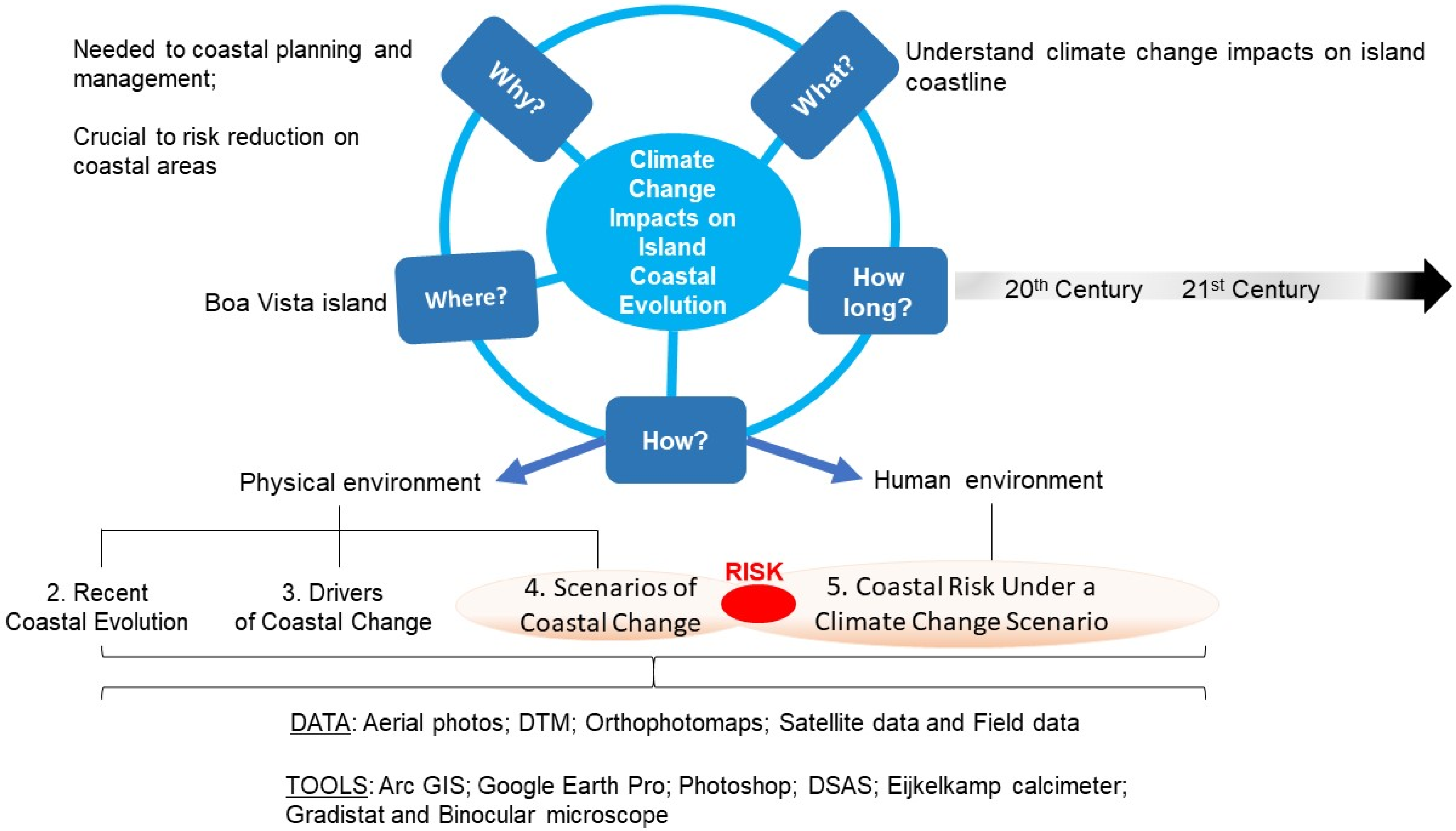


Figure 1.1: Graphical thesis outline.

1.4 Study Area

1.4.1 Geographical, geomorphological and geological setting

Boa Vista is the easternmost island of the ten volcanic islands of Cabo Verde archipelago, being in the Windward group islands between the latitudes 15°58'N and 16°14'N and longitudes 22°40 'W and 22°58'W. Cabo Verde is located between the Equator and the Tropic of Cancer, among the latitudes of 14°28'N and 17°12'N and longitudes of 22°40'W and 25°22'W, approximately 500 km from the West African coast near Senegal (Figure 1.2). Boa Vista is the third largest island in the archipelago (after Santiago and Santo Antão), with an area of 620 km^2 (RCM, 2016), and a population of 16.620 inhabitants (IMC, 2017). Nowadays, the Boa Vista island is the second most important island in terms of sun and sand tourism, with a strong increase in the last two decades (Eusébio *et al.*, 2018; Sánchez-Cañizares and Castillo-Canalejo, 2014) with about 36% of total Cabo Verde tourists after the Sal island (54.8%) (INE-CV, 2017). The tourism assumes critical relevance in Cabo Verde, as it generates about 44,9% of the Gross Domestic Product - GDP (direct, indirect, and induced effects) (WTTC, 2018).

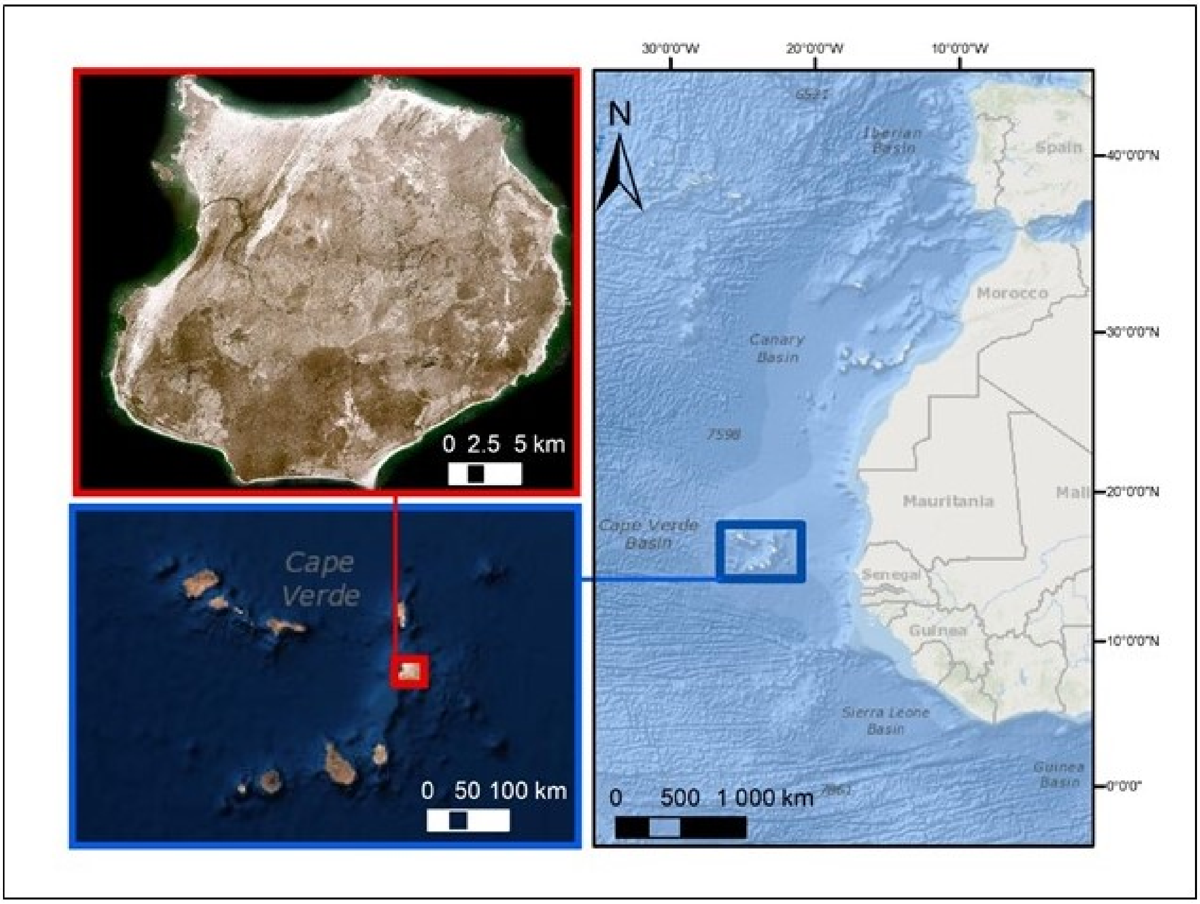


Figure 1.2: Location map of Boa Vista island (Imagery Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

Boa Vista has a relatively planar morphology, without young volcanic forms (Serralheiro *et al.*, 1974) and its flat morphology is only interrupted by some residual prominences, whose highest point is 380 m above sea level (Ramalho *et al.*, 2010a). Thus, is considered one of the most vulnerable islands of Cabo Verde to climate change effects (Governo de Cabo Verde, 2007).

The island is composed of volcanic rocks (basalts, phonolites and trachytes) deposited at different stages in the formation of the island (Hernández and Suárez, 2006). Carbonate sedimentary formations of continental and marine facies, of Pliocene to Holocene ages, are widely represented in Boa Vista occupying vast areas of littoral and raised platforms (Cabo Verde Natura, 2000; Hernández and Suárez, 2006). The ancient beaches, represented by compact calcareous and calcareous fossils, are associated with marine facies. These sedimentary deposits are distributed throughout the coastal strip (Cabo Verde Natura, 2000; Ramalho *et al.*, 2010a). The main source of Boa Vista's sand is biogenic and is located in the northern insular shelf (Cabo Verde Natura, 2000; Hernández and Suárez, 2006). Sediment transport at Boa Vista is dominated by a unidirectional (or strongly asymmetrical) NE-SW wind field (Calvento *et al.*, 2017) related with trade winds (Hernández and Suárez, 2006). The sediment transport pathways links the north and south coasts of the island by overpass (western side) and headland bypass (eastern side) (Hernández and Suárez, 2006).

Boa Vista, like the nearby islands of Sal and Maio, exhibits evidences for complex long-term uplift subsidence histories. During the Quaternary these islands experienced a slow uplift trend, which is attested by the presence of multiple and wide erosional and depositional raised marine terraces, arranged in a staircase morphology that extends up to approximately 100 m above present-day sea level (Serralheiro *et al.*, 1974 ; Ramalho *et al.*, 2010a,b). The quaternary uplift trend, however, was probably preceded by subsidence of a similar magnitude, as suggested by the present-day position of older Pliocene and Miocene sea-level markers (Ramalho *et al.*, 2010a). This complex succession of subsidence followed by uplift is probably responsible for significant morphological and sedimentary regime changes along these islands coastlines starting with the formation of wide insular shelves that were subsequently gradually exposed by means of uplift, favouring sediment accumulation along the coast, either from recycling of previous marine terraces or simply from the exposure of available mobile shelf sediment (Ramalho *et al.*, 2013).

1.4.2 Climatic and Oceanographic settings

Cabo Verde is characterized by stable temperatures with extreme aridity (Marques *et al.*, 2016). The archipelago is affected by the two-season (wet and dry) nature of the inter-tropical convergence zone (ITCZ). Precipitation levels are unpredictable, depending on how the ITCZ progresses and how much tropical moisture it carries (Marques *et al.*, 2016). The climate is permanently hot (average temperature between 21 and 28 ºC) and windy (mean velocity of 24 km/h.), with irregular and scarce precipitation (about 120 mm year^{-1}) concentrated in a few days with torrential nature (RCM, 2016; Costa *et al.*, 2011).

In terms of oceanographic setting, Boa Vista has a tidal amplitude between high and low tide (not exceeding 1.15 m). The predominant direction of waves is from NE quadrant. This quadrant presents the greater wave height. The maximum height reached is 4.1 m from NE direction, although the height of the most frequent significant wave is 1.5 and 1.9 m (RCM, 2016). In this work, the wave forcing offshore Cabo Verde was characterized based on hindcast wave data at a position located northward of the archipelago (Lat:17° 15'N; Long: 22° 45' W) from 2005 to 2017 (c.f.http://polar.ncep.noaa.gov/waves/hindcasts/). The average offshore wave regime has a significant wave height of 2.1 m, peak period of 10 s and waves typically approaching from N (mean wave direction of 2°).

1.4.3 Coastal Environments

Along Boa Vista island coastal, it possible to identifying a combination of some coastal environment, namely dunes, beaches, cliff and rocky platform. To allow an overall perception of coastal environments, identification of many coastal types was performed. Classification was based on the visual analysis of orthophoto maps of 2010 and presence of natural elements. Coastal areas was classified according to Decreto-Lei nº 14/2016 (2016), which established the elaboration and implementation of regulation on coastal planning and adjacent sea (POOC-M, portuguese acronym) of Cabo Verde:

(a) in relation to its land side, an area referred as Terrestrial Zone (TZ), that corresponds to a width of 1.500 m (one thousand and five hundred meters) from the high tide line measured horizontally to the land side;

(b) regarding, an area referred as Adjacent Sea Zone (ASZ), which corresponds to a width of 3 (three) nautical miles, counted from topographic zero, measured horizontally to the sea side.

Coastline and shoreline positions were used to classify the following elements: dunes, structures (e.g. port or road infrastructures and houses) and cliffs from TZ, and subtidal beach and rocky platforms from ASZ, respectively (Figure 1.3, Figure 1.4 and Table 1.1).

Results show that Boa Vista coastline, that extends for about 123 km, the landward side is composed by cliffs (51%), dunes (48%) and structures (1.5%). The seaward side is dominated by a rocky platform, sometimes covered by an intertidal beach or by a beach that extents seaward (subtidal beach) (60%) and subtidal beach (40%) (Table 1.1). It possible to identifying several combination of these environments (**ENV**), namely (Figure 1.3):

1. dune and subtidal beach ($\mathbf{ENV_1}$);

2. dune and rocky platform (with or without intertidal beach)($\mathbf{ENV_2}$);

3. cliff/structure and subtidal beach($\mathbf{ENV_3}$);

4. cliff/structure and rocky platform (with or without intertidal beach)($\mathbf{ENV_4}$).

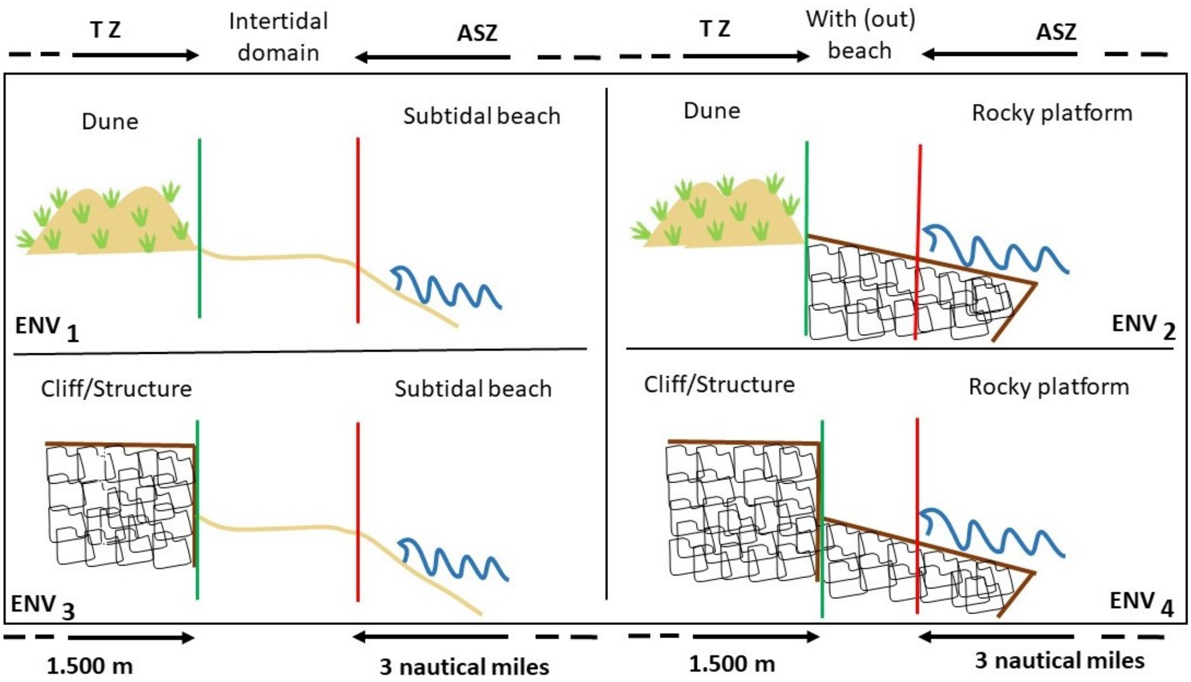


Figure 1.3: Coastal classification related to the geomorphological content at the landward and seaward sides of coastline and shoreline. Dune, Cliff or Structure in the TL; and Subtidal beach on rocky platform along ASZ. Coastline (green line) and Shoreline (red line).

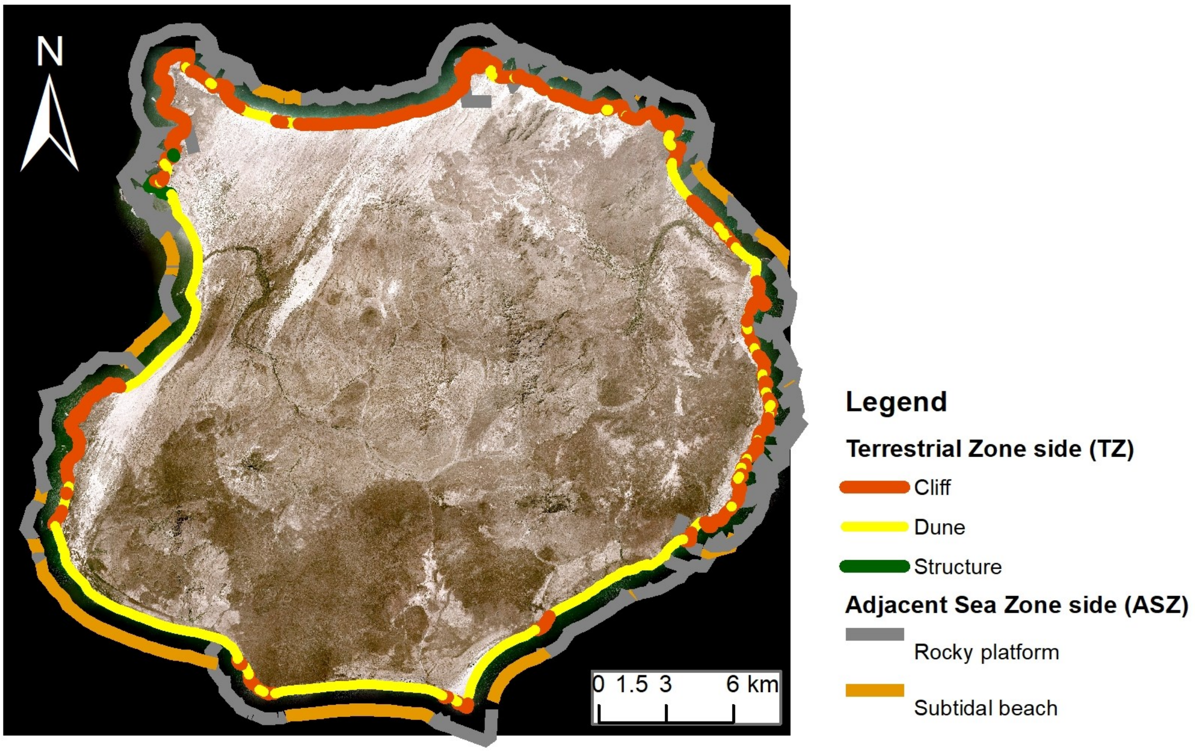


Figure 1.4: Coastal environments classification based on orthophoto map 2010.

Table 1.1: Boa Vista coastal classification

Terrestrial Zone side (TZ)			Adjacent Sea Zone side (ASZ)		
	Length (m)	Percentage (%)		Length (m)	Percentage (%)
Dune	58907	48%	Subtidal Beach	48969	40%
Cliff	62588	51%	Rocky platform	74419	60%
Structure	1892	1.5%			
Total	123387		Total	123387	

Taking into account that this classification was based on the orthophoto map from 2010 (Figure 1.4) and that the presence of natural elements is influenced by temporal and spatial variability, without field validation, this results should be regarded as rough estimates.

Chapter 2

Recent Coastal Evolution

This chapter is partially based on the work:

Gomes, C., Silva, A.N., Taborda, R., Santos, F., Rebelo, L. and Medina, A. (2019). Drivers of island beach evolution: insights from an island-scale study at Boa Vista (Cabo Verde). *Earth Surface Processes and Landforms*, 44, 2810-2822. doi: 10.1002/esp.4709. https://doi.org/10.1002/esp.4709.

2.1 Introduction

Insular coastal zones are areas of exceptional environmental, economic and social importance. In most cases, small islands economies are also highly dependent on coastal attractiveness typically grounded on the concept of stable and pristine beaches. However, this setting is increasingly being threatened by a combination of human and environmental pressures (Mimura *et al.*, 2007). Thus, it is of scientific, economic and social relevance to understand the processes that control coastal evolution, such as erosion and recovery, (Hapke *et al.*, 2016). In this context, the assessment of past coastline changes is critical (Alesheikh *et al.*, 2007; Crowell *et al.*, 1991) as knowledge will support the understanding of the main drivers of change and contribute to a sustainable coastal environmental planning (Di *et al.*, 2003; Alesheikh *et al.*, 2007; Ahmad and Lakhan, 2012; Ford, 2013; Carapuço *et al.*, 2016). Despite the unquestionable importance of these studies most of the works that have dealt with this theme generally have a local character (e.g. Adnan, 2016; Ford, 2013; Hapke *et al.*, 2016) and do not give a perspective on an island-scale, which is fundamental to understand the links between different beach systems. This problem is particularly relevant at insular systems where over- and by- pass sedimentary processes frequently connect the entire sandy coastal system. An example of such systems is represented by Boa Vista island (Cabo Verde), a relatively flat island, highly dependent on sun and beach touristic activities. Here, human pressure on the coast is increasing by the day and the poorly planned development of the coastal zone can put in peril the long-term island sustainability. The main goal of this chapter is to perform an assessment of Boa Vista island coastal evolution at island-scale and understand the main drivers of change. The work focuses on the coastal evolution at decadal time scale and is supported by historic aerial photographs and orthophoto maps.

2.2 Methods

2.2.1 Data sources and imagery processing

The present study uses aerial photographs of Boa Vista island from different dates and different sources: 1968 and 1983 from *the Laboratório Nacional de Energia e Geologia* (LNEG) and 1991, from *Instituto Nacional de Gestão do Território de Cabo Verde* (INGT-CV). Additionally, official orthophoto maps of 2003 and 2010, from INGT, were also used (Table 2.1).

Table 2.1: Characteristics of aerial photographs and ortophoto maps used in this study

Dataset	Date	Source	Scale (approx.)	Type	Image resolution (m)	Number of mosaics Created	Average Georeferencing RMS Error (m)
Aerial photographs	1968*	LNEG	1:20 000	Black and white	approximately 1	13	7.13
	1983**					11	5.65
	1991***	INGT-CV	1:15 000			8	1.9
Orthophoto maps	2003	INGT-CV	1:14 450	Colour	0.5	N/A	N/A
	2010		1:6 000		0.4		

Missing imagery coverage:

∗ part of the coastal stretch Ponta Varandinha - Ponta Manga Larga;

∗∗ coastal stretch between Ponta de Praia de Cabral and Cruz do Morto;

∗∗∗ coastal stretch between Carlota beach and Ponta Varandinha (see Figure 2.2 for locations).

The aerial photographs, with about 60% of overlap, were digitized and mosaicked using Adobe Photoshop ® CS5, to create wider images and increase the spatial continuity, thus minimizing the misalignments in contiguous images. The mosaicking process can be performed by different methods which generally include radiometric normalizations and blending processes (c.f. Chon *et al*., 2010; Du *et al*., 2008; Wan *et al*., 2013; Wang *et al*., 2008) that, with respect to coastal studies, allows the coastline location in long coastal sections where is frequently difficult to identify control points (Verhoeven *et al*., 2012).

The mosaics were georeferenced in a GIS environment (ArcGIS® 10.6) based on noticeable matching features (or control points), against the oldest orthophoto map (2003), and georeferencing transformation based on the Spline algorithm. According to Verhoeven *et al.* (2012) georeferencing using Spline algorithms is often used when relief induced deformations are moderate. In this sense, and given the low-relief geomorphology of Boa Vista coast, this algorithm was considered adequate and was applied.

The uncertainty of mosaics georeferencing was estimated by cross-validation using multiple independent test samples. In each test, random 10% of the control points used in georeferencing were removed and used as test-points (Table 2.1). For statistical relevance at least 50 test-points were considered for the computation of the georeferencing errors (root mean square - RMS) at each mosaic, thus whenever 10% of the control points represented less than 50 test-points, testing was duplicated. The average georeferencing RMS error for each aerial photograph dataset is presented at Table 2.1.The imagery processing tasks, as well as the other processes performed in this work are synthetized at the workflow in Figure 2.1.

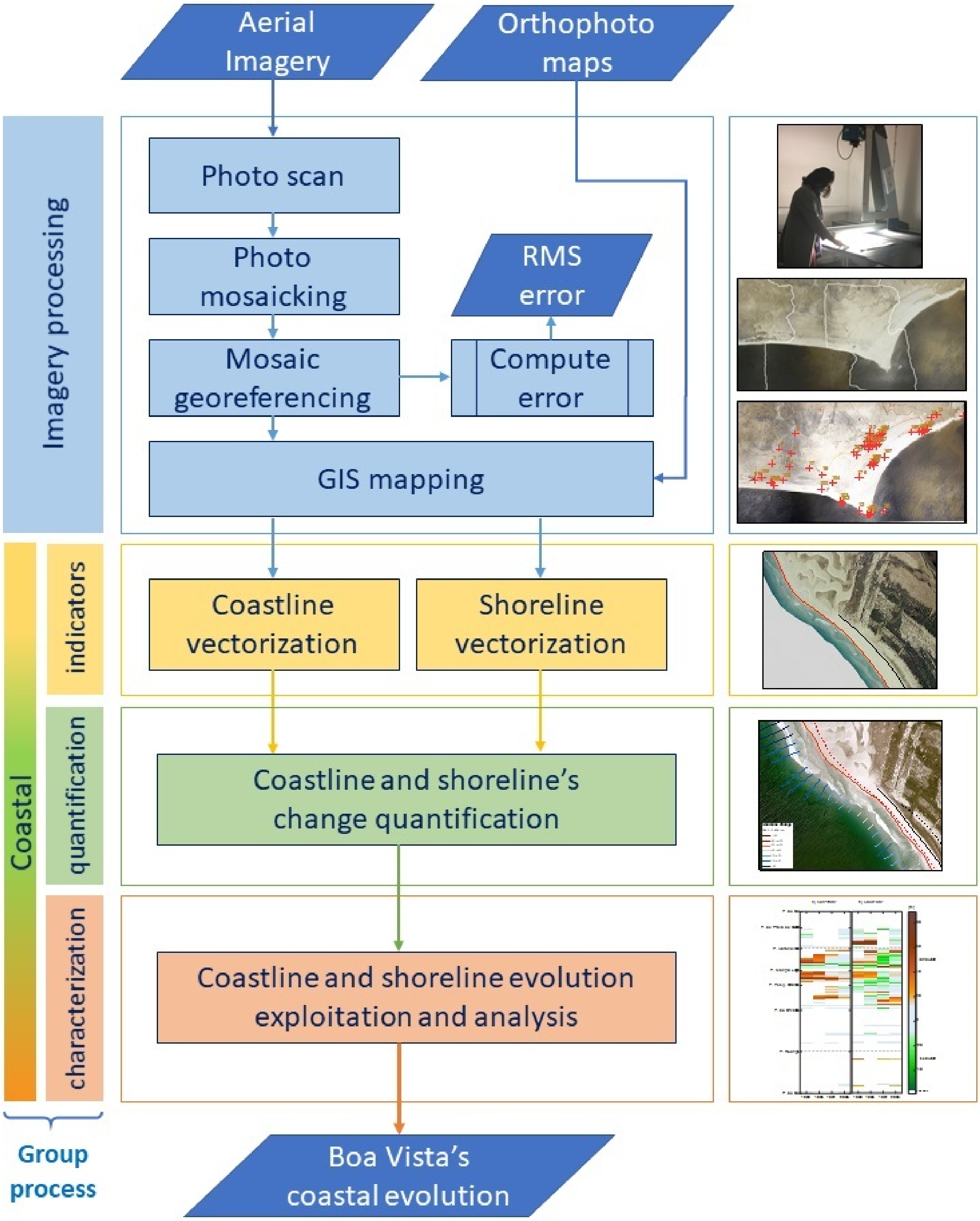


Figure 2.1: Workflow of processes and tasks performed in the scope of this work.

2.2.2 Coastline and shoreline indicators

Most of the studies on coastal evolution base their analysis on the assessment of coastline (*senso lato*) changes (Pajak and Leatherman, 2002 ; Alesheikh *et al.*, 2004, 2007), where the term coastline represents the physical boundary between land and ocean, however, the term shoreline is sometimes used to represent the same concept (Ford, 2012, 2013; Rooney and Fletcher, 2005; Ekercin, 2007; Hapke *et al.*, 2016). Both coastline and shoreline definitions have been debated over time and there are challenges in adopting single and objective definitions due to the dynamic nature of coasts (c.f. Boak and Turner, 2005; Alves, 2007) and efforts have been made towards establishing a common framework as proposed by Carapuço *et al.* (2016).
This work analyses the changes of two different coastal indicators, perceptible in aerial imagery:

1. the coastline position (*stricto sensu*), a morphology-based concept representing the landward limit of the beach and materialized by the foredune toe or the seaward limit of the dune vegetation (Carapuço *et al.*, 2016; Webb and Kench, 2010 ; Ford, 2012; Adnan, 2016). From here, the term coastline refers to its *stricto senso*.

2. the shoreline position representing the physical interface of land and water (Carapuço *et al.*, 2016; Dolan *et al.*, 1980; Evadzi, 2017) by means of the imagery-based recognition of the high-water swash line, according to Boak and Turner (2005) the most frequent shoreline indicator.

Shoreline indicator, due to its high dynamic nature, is more affected by short-term (tidal and seasonal) morphological changes (Ponte Lira *et al.*, 2016 ; Ferreira, 2006; Del Río and Gracia, 2013) than the morphology-based coastline indicator, particularly used in long-term studies (Ponte Lira *et al.*, 2016) as there it is less influenced by high-frequency changes on the land-water interface (Coastal Indicators Vectorization process on Figure 2.1). Nevertheless, the coastline mapping is more restrictive as it depends on the presence of a dune system in the backshore, while the shoreline indicator mapping can be also recognised on beach systems backed by cliffs.

Uncertainties in indicator mapping

Aside the estimated georeferencing and resolution-related uncertainties, the recognition of the adopted indicators over aerial imagery has additional source of uncertainties, particularly over the oldest aerial photographs (1968 and 1983) due to its low spatial and spectral resolution. While on sectors where the dune vegetation can be clearly identified the coastline mapping can be straightforward, on sectors where dune mobility is larger, or the vegetation cover is too sparse the location of the coastline can be highly-uncertain. In the latter case, the coastline indicator was not mapped.

Shoreline-indicator mapping incorporates the uncertainties related with runup marks on the sand, that are associated to the tidal and wave characteristics when the images were produced. Considering that the high-water swash line corresponds to high tide water levels, tidal-related displacements $(E_{shore,tide})$ are of minor magnitude (Ruggiero and List, 2009). The shoreline variation uncertainty relates essentially with the horizontal excursion of the wave runup, estimates of this term $(E_{shore,runup})$ followed the parameterization of (Stockdon *et al.*, 2006), updating the procedures described in Hapke *et al.* (2006) and Ruggiero and List (2009) by considering that the variations of wave run-up on the beach in fair weather conditions are primarily related with differences in typical wave conditions (25th to 75th wave height percentiles). Considered the long-term 25th and 75th wave height percentiles (respectively 1.61 m and 2.64 m) and the long-term peak period (10 s) (hindcast wave data, from 2005 to 2017, at Lat:17°15'N; Lon:22°45'W position; c.f. `http://polar.ncep.noaa.gov/waves/hindcasts/`), runup magnitudes are 0.98 m and 1.19 m, respectively. These values result in a vertical runup difference of 0.21 m that over a beach face with an average slope of 3º (measured on the field) leads to a horizontal runup-related uncertainty of about 4 m.

The uncertainties related to the vectorization process $(E_{coast,vect}; E_{coast,img})$ of both coastline and shoreline indicators were estimated as a magnitude of error of 7 m, which is in agreement with the results obtained by Ponte Lira *et al.* (2016) where three different operators digitized the same indicator. The total error can be estimated by the square root of the sum of the squares (addition in quadrature) of independent errors (c.f. Hapke *et al.*, 2006) for each indicator at each date (Table 2.2). The coastline error (E_{coast}) includes the vectorization error $(E_{coast,vect})$ and the error related to the image positional quality $(E_{coast,img})$ which is represented by the image resolution on the orthophoto maps, or by the mosaic georeferencing errors on the aerial photographs (equation 2.1):

$$E_{coast} = \sqrt{E^2_{coast,vect} + E^2_{coast,img}} \tag{2.1}$$

The shoreline error (E_{shore}) adds in quadrature the respective vectorization error $(E_{shore,vect})$ the image position error $(E_{shore,img})$, tide-related error $(E_{shore,tide})$ and the runup-related error $(E_{shore,runup})$ (equation 2.2):

$$E_{shore} = \sqrt{E^2_{shore,vect} + E^2_{shore,img} + E^2_{shore,tide} + E^2_{shore,runup}} \tag{2.2}$$

For any given period, the uncertainty estimation (E_{period}) can be estimated through the add in quadrature of the errors of each date (t1 and t2), both for the shoreline and coastline indicators (equation 2.3 and Table 2.3):

$$E_{period} = \sqrt{E^2_{t1} + E^2_{t2}} \tag{2.3}$$

Table 2.2: Independent errors and total error of the coastline and shoreline indicators positioning.

		Coastline indicator errors (m)			Shoreline indicator errors (m)				
Dataset	Date	$E_{ct,vt}$	$E_{ct,img}$	E_{ct}	$E_{sh,vt}$	$E_{sh,img}$	$E_{sh,td}$	$E_{sh,rp}$	E_{sh}
Aerial photographs	1968	7.0	7.1	10.0	7.0	7.1	1.2	4.0	10.8
	1983	7.0	5.7	9.0	7.0	5.7	1.2	4.0	9.9
	1991	7.0	1.9	7.3	7.0	1.9	1.2	4.0	8.4
Orthophoto maps	2003	7.0	0.5	7.0	7.0	0.5	1.2	4.0	8.2
	2010	7.0	0.4	7.0	7.0	0.4	1.2	4.0	8.2

$E_{ct,vt}$ - coastline vectorization error; $E_{ct,img}$ - coastline image error; E_{ct} - coastline error; $E_{sh,vt}$ - shoreline vectorization error; $E_{sh,img}$ - shoreline image error; $E_{sh,td}$ - shoreline tide error; $E_{sh,rp}$ - shoreline run-up error; E_{sh} - shoreline error.

Table 2.3: Total errors for each period analysed.

	Errors (m)	
Period	Coastline	Shoreline
1968-1983	13.5	14.7
1983-1991	11.6	13.0
1991-2003	10.1	11.7
2003-2010	9.9	11.6
1968-2010	12.2	13.6

Assessment of coastal evolution

The coastal indicators, coastline and shoreline, were manually vectorized in GIS environment at visualization scales ranging from 1:2 000 to 1:10 000, for the complete data-sets of imagery (1968, 1983, 1991, 2003 and 2010) and along the entire low-lying sandy coast of Boa Vista. The vectorization procedures tended to smooth out the high-irregularities of both limits (vegetation and swash reach) into a linearized limit hence closer to their natural configuration. Coastline and shoreline evolution changes were quantified in GIS environment using the Digital Shoreline Analysis System ArcMap extension (Thieler *et al.*, 2017), based on transects perpendicular to the coast spaced by 50 m (Coastline Evolution Quantification process on Figure 2.1).

To ease results exploitation and analysis Boa Vista coast was segmented into 7 sections, bounded by headlands (*Pontas*) that represent natural discontinuities (Figure 2.2):

1. Ponta do Sol - Ponta de Praia de Cabral;
2. Ponta de Praia de Cabral - Ponta Varandinha;
3. Ponta Varandinha - Ponta Manga Larga;
4. Ponta Manga Larga - Ponta Pesqueiro Grande;
5. Ponta Pesqueiro Grande - Ponta Ervatão;
6. Ponta Ervatão - Ponta Rodrigo;
7. Ponta Rodrigo - Ponta do Sol

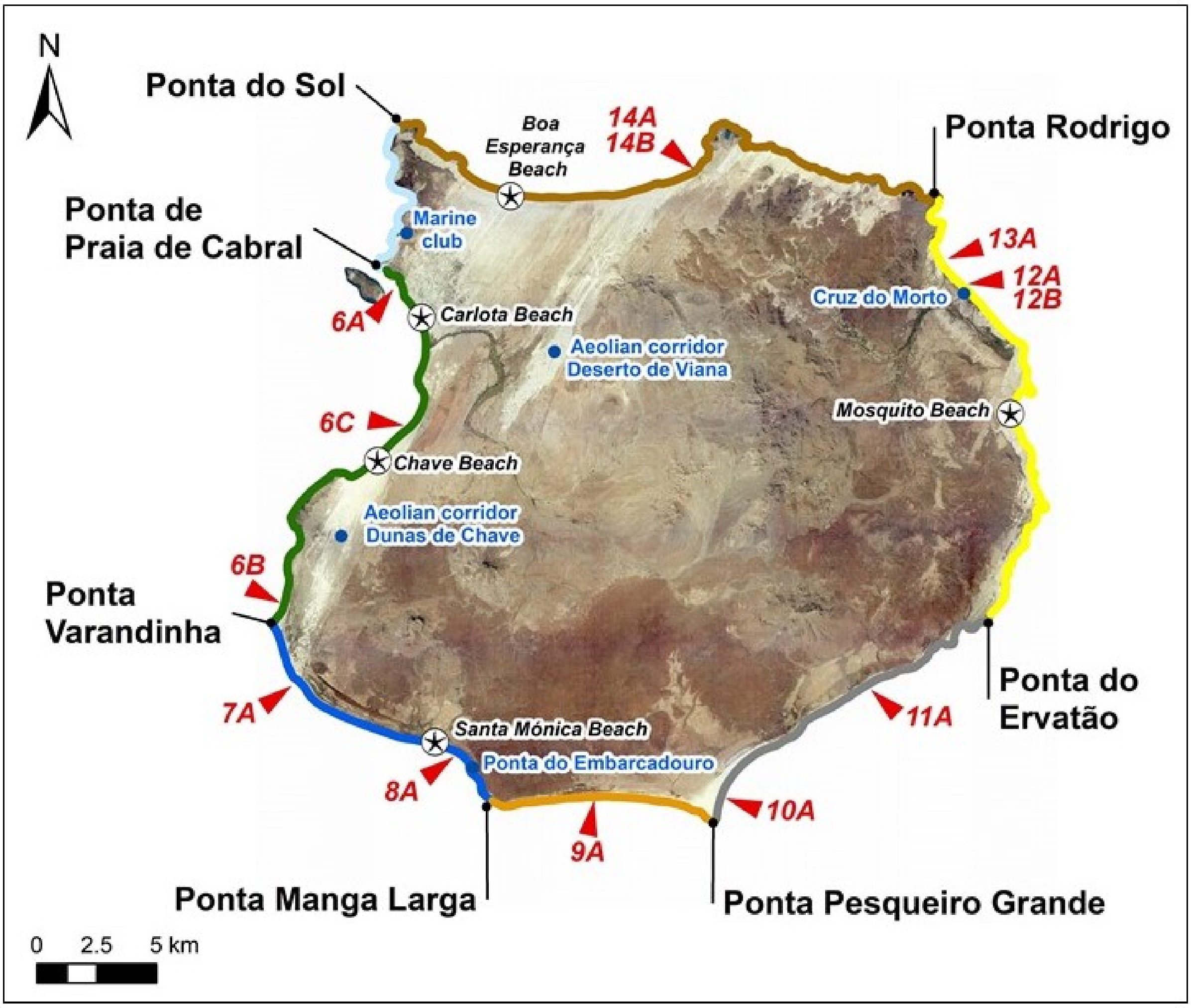


Figure 2.2: Boa Vista coastal sectors with the location of the images presented in the results section (red triangles).

2.3 Results

The spatio-temporal changes along the entire Boa Vista island, between 1968 and 2003, with respect to the latest date (2010) are represented in Figure 2.3. This image depicts coastal evolution across the entire island where the blank areas correspond to data gaps related to: 1) the impossibility to map the coastal indicator, which depends on either on the existence of a dune system or a sandy beach, for coastline and shoreline, respectively; 2) the lack of aerial photographs in some areas (please refer to information on Table 2.1); 3) the high-uncertainties in the recognition of the indicator on some images/dates that can be related to presence of dune corridors or sand sheets - without vegetation cover or a recognizable dune toe.

Coastline indicator results cover most of the southern sectors between Ponta Varandinha and Ponta do Ervatão, where a predominant coastline progradation is recognized. The shoreline has greater spatial coverage, though naturally restricted to beach environments, and represents greater spatio-temporal variability as the shoreline indicator also displays short-to long-term beach response.

Spatially integrated evolution along the sandy coastal stretches of Boa Vista island, between 1968 and 2010, was found to be 0.48 m/year and 0.18 m/year, for the coastline and the shoreline, respectively (Table 2.4 and Figure 2.5). This evolution corresponds to an average coastline progradation of about 20 m, a value that clearly exceeds the error estimate (12.2 m). The spatially integrated shoreline evolution also suggests a progradation but with a lower magnitude, of about 8 m. It is worth mentioning that the coastline and shoreline indicators do not represent exactly the same coastal domains as the coastline was only delimited in coastal stretches where the beach is backed by a dune system (about 400 transects) whereas the shoreline has greater coverage as it was also mapped in beaches backed by cliffs (more than 730 transects processed). Moreover, some coastal stretches are represented by a small number of transects and the results at these sections must be taken with caution, in this sense the coastal sectors where the number of transects with valid data were less than 10% of total coastal transects are represented by unfilled bars in Figure 2.5.

Coastal evolution shows a significant spatial and temporal variability for both indicators (Figures 2.3 and 2.5). The coastline evolution was dominated by the seaward progradation, or accretion, in two of the southern sectors the Ponta Varandinha - Ponta Manga Larga and the Ponta Manga Larga - Ponta Pesqueiro Grande, with a mean coastline progradation of 24 m and 39 m, respectively (Table 2.4 and Figure 2.5). The remaining Boa Vista's sandy coastal sectors show marginal retreat, less than 5 m, over the 42 years analysed. In the coastal sectors where the number of analysed transects is significant (filled bars in Figure 2.5), the shoreline indicator shows a similar trend but with a magnitude of signal that is generally within the uncertainty band. Shoreline was dominanted by accretion at Ponta de Praia de Cabral - Ponta Varandinha, Ponta Varandinha - Ponta Manga Larga and Ponta Manga Larga - Ponta Pesqueiro Grande. In contrast, at Ponta Pesqueiro Grande - Ponta do Ervatão a small to medium magnitude of shoreline retreat was detected (-11 m over 42 years). The accretion reported at Ponta Rodrigo-Ponta do Sol represents a very small coastal stretch, namely on Cabral beach.

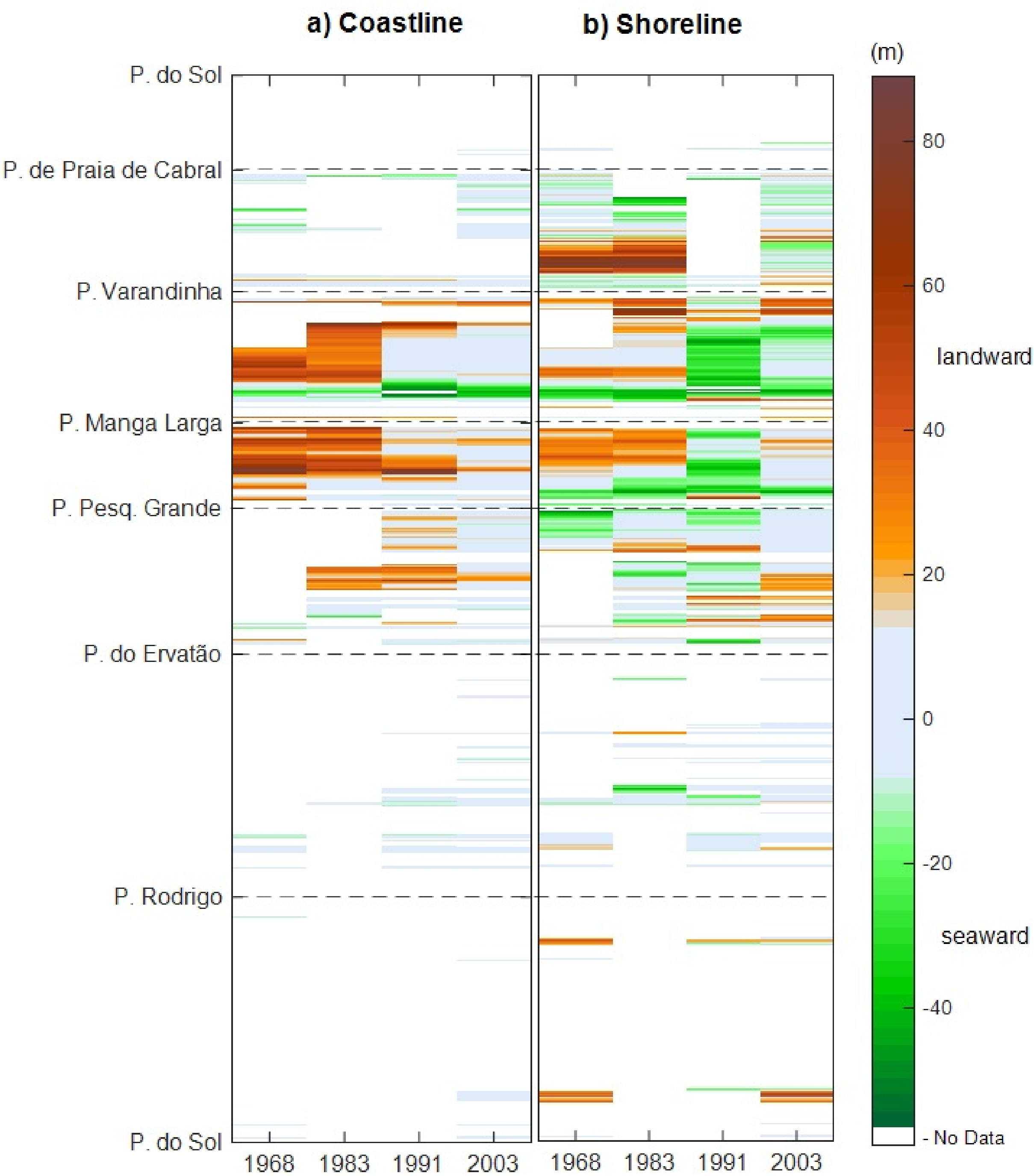


Figure 2.3: Time-series of Boa Vista coastline (a) and shoreline (b) positions relative to 2010 (P. refers to Ponta and Pesq. refers to Pesqueiro). Dark green to light green colours represent erosion (indicator was located seaward of reference line–coastline at 2010) while dark brown to orange colours represent accretion (indicator was located landward of reference line–shoreline at 2010) light blue colours represent values within the uncertainty margin.

Table 2.4: Coastal evolution at Boa Vista island from coastline (top) and shoreline (bottom) indicators: left – integrated from 1968 to 2010; right – for different time intervals. N – represent the number of transects; m represents changes in meters for accretion (positive values) and retreat (negative values).

Coastline evolution	1968–2010		1968–1983		1983–1991		1991–2003		2003–2010	
	(m)	N.	(m)	N.	(m)	N.	(m)	N.	(m)	N.
P. do Sol - P. de Praia de Cabral	n.a.	0	n.a.	0	n.a.	0	n.a.	0	2.5	7
P. de Praia de Cabral - P. Varandinha	-2.9	76	0.7	41	-1.2	28	-3.4	30	-1.4	125
P. Varandinha - P. Manga Larga	24.1	131	2.7	130	28.0	179	3.1	196	-2.1	195
P. Manga Larga - P. Pesqueiro Grande	38.8	143	7.8	143	13.6	141	8.4	149	8.2	150
P. Pesqueiro Grande - P. do Ervatão	-4.8	19	-16.7	7	3.9	88	9.6	199	3.3	188
P. do Ervatão - P. Rodrigo	-4.6	27	n.a.	0	-3.3	9	-3.5	66	1.2	98
P. Rodrigo - P. do Sol	-2.5	11	n.a.	0	n.a.	0	-19.5	1	3.0	38
Boa Vista island	20.2 ±12.2	407	4.3±13.5	321	16.2±11.6	445	5.3±10.1	641	1.9±9.9	801

Shoreline evolution	1968–2010		1968–1983		1983–1991		1991–2003		2003–2010	
	(m)	N.	(m)	N.	(m)	N.	(m)	N.	(m)	N.
P. do Sol - P. de Praia de Cabral	-1.9	6	n.a.	0	n.a.	0	-9.7	7	-3.0	12
P. de Praia de Cabral - P. Varandinha	12.6	223	1.6	171	-9.0	16	-14.0	29	0.3	220
P. Varandinha - P. Manga Larga	5.2	139	-3.3	144	32.5	213	-15.2	216	-4.2	218
P. Manga Larga - P. Pesqueiro Grande	12.4	153	7.6	154	21.7	149	-19.7	149	3.0	153
P. Pesqueiro Grande - P. do Ervatão	-10.7	104	-14.6	106	1.7	210	-12.0	204	9.8	210
P. do Ervatão - P. Rodrigo	2.0	63	-8.5	22	0.4	50	-6.8	100	2.8	112
P. Rodrigo - P. do Sol	24.1	47	n.a.	0	n.a.	0	-4.0	54	15.8	53
Boa Vista island	7.6 ±13.6	735	-1.3±14.7	597	16.3±13.0	638	-13.2±11.7	759	2.8±11.6	978

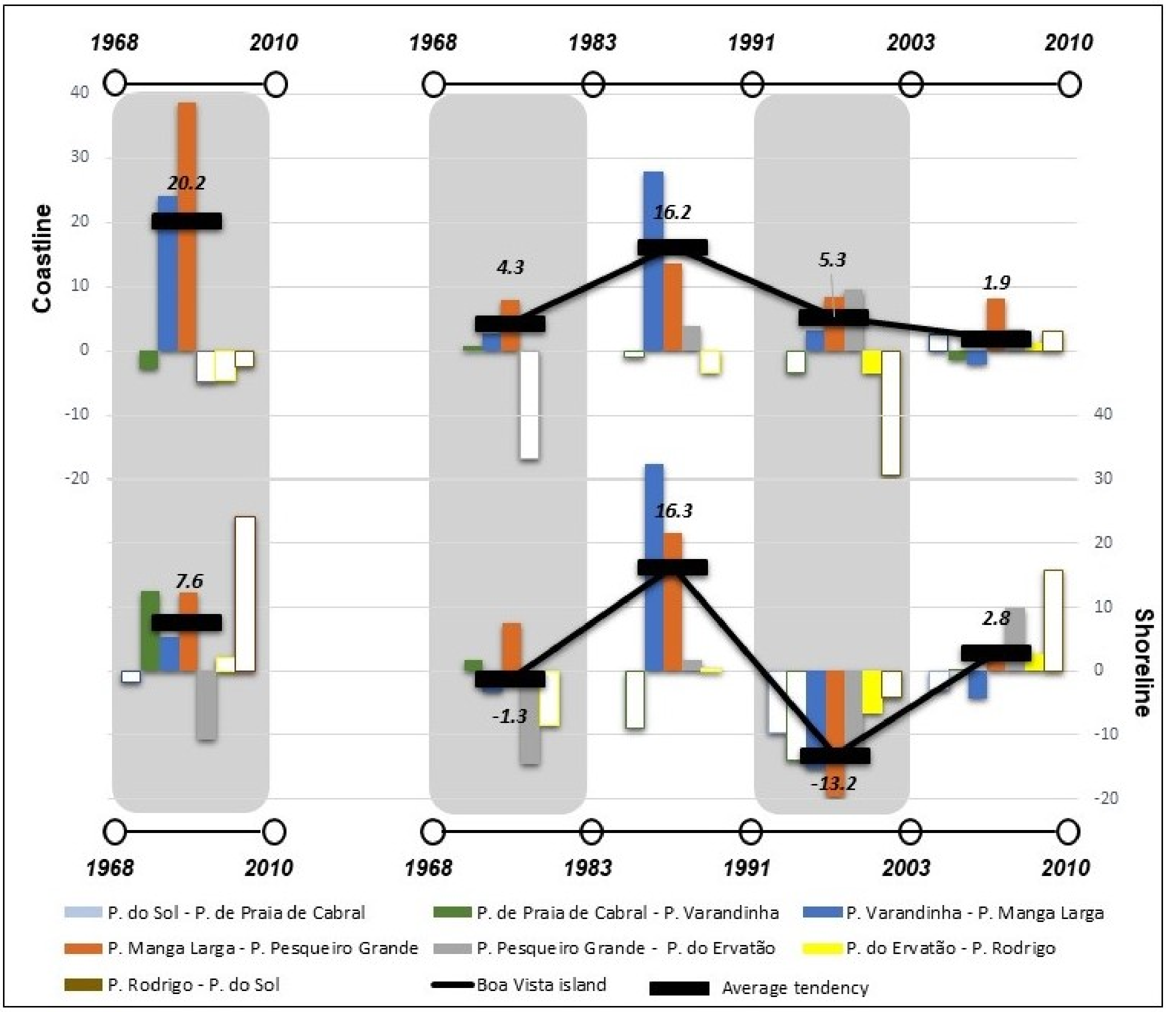


Figure 2.5: Coastal evolution (in meters) at Boa Vista island from coastline (top) and shoreline (bottom) indicators: left – integrated from 1968 to 2010; right – for different time intervals, along different coastal sectors. Only the sectors with transect data are represented; the coastal sectors where the number of transects with valid data were less than 10% of total coastal transects are represented by unfilled bars (refer to Table 2.4 for information on the processed transects at each coastal sectors).

2.3.1 Ponta do Sol to Ponta de Praia de Cabral sector

The coastal stretch between Ponta do Sol and Ponta de Cabral is dominated by a rocky shore, except for the meridional section, south of Marine Club hotel, where some small embayed sandy beaches develop (Figure 2.2). Due to light-overexposing and low resolution of the oldest aerial photographs, the vegetation landward limit could not be clearly recognized thus the coastline mapping was only completed on the 2003 and 2010 orthophoto maps. On the other hand, the shoreline could be mapped, on both orthophotos and on the 1968's imagery data-set.

Results suggests that both indicators are stable, with slight changes during the observation period. These changes were less than 5 m, except for the period between 1991 and 2003 when the shoreline retreated nearly 10 m. This retreat however seems time specific, as the longer-term evolution of the shoreline (between 1968 and 2010) was less expressive (less than 2 m retreat) (Figure 2.3, Table 2.4 and Figure 2.5).

2.3.2 Ponta de Praia de Cabral to Ponta Varandinha sector

Between Ponta Praia de Cabral and Ponta Varandinha the geomorphological content of the coast exhibits a larger variability, being dominated by beaches backed by dunes in most of the section and by some rocky low-height cliffs in the southern limit of this sector (Figure 2.2). This sector is particularly influenced by the aeolian corridors of Boa Vista island and thus is characterized by the high mobility of the dune systems. This coastal stretch comprises an expressive unvegetated barchan dune in the southern end of Praia de Chave (Figure 2.6-view 6C) that prevented the coastline indicator mapping.
Nevertheless, the changes in this sector can be characterized by small coastline retreat, up to 4 m (where the indicator was able to be mapped). The shoreline position evolution is characterized by alternating advances and retreats of the shoreline position though a mean 12.6 m progradation is recognized along this sector (Table 2.4 and Figure 2.6).

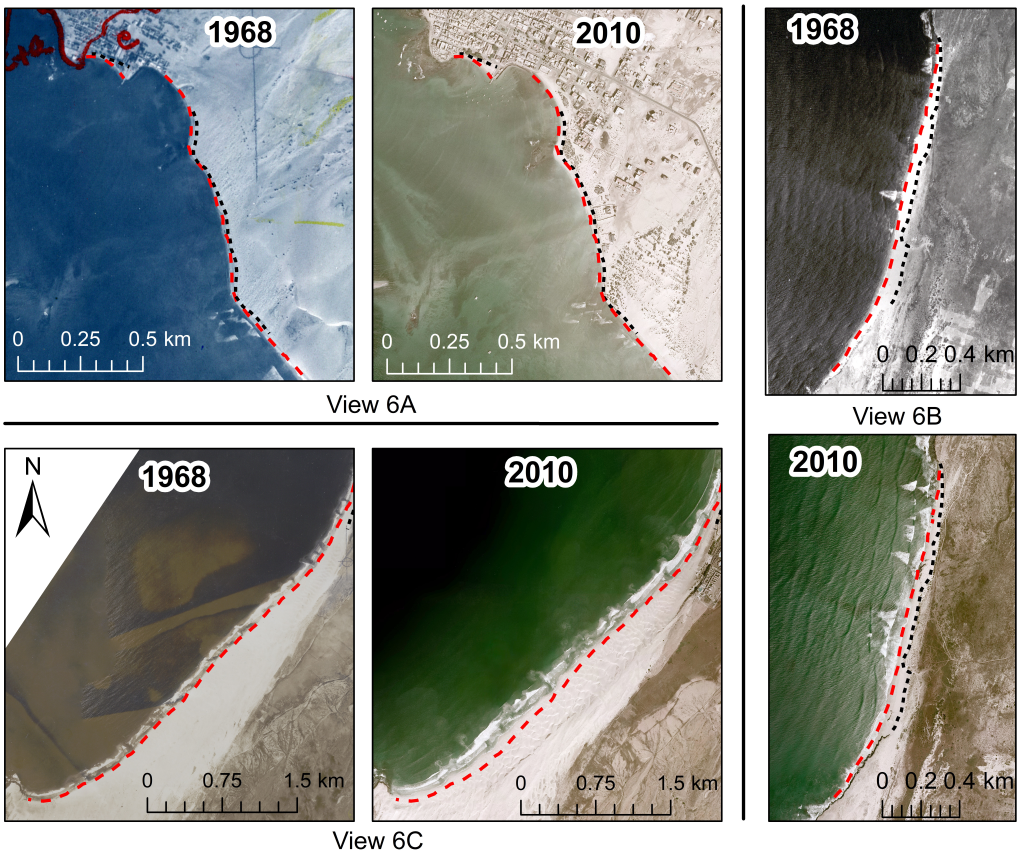


Figure 2.6: Beach evolution between 1968 and 2010 at coastal stretch Ponta Praia de Cabral and Ponta Varandinha (Views 6A, 6B and 6C, see Figure 2.2 for locations); reference lines represent 1968 coastline (black dot) and 1968 shoreline (red dash). The absence of coastline indicator in some images is related to difficulties in to recognizing the proxy.

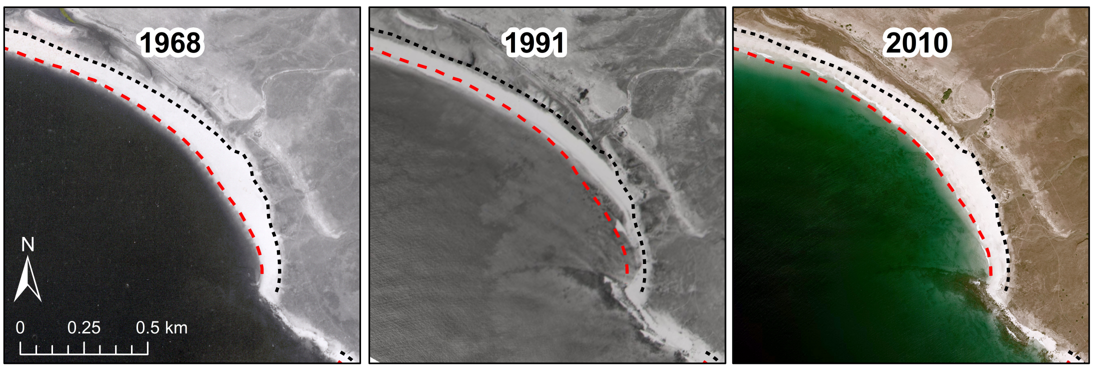
2.3.3 Ponta Varandinha to Ponta Manga Larga sector

The coastal sector between Ponta Varandinha and Ponta Manga Larga (Figure 2.2) is roughly a continuous wide beach backed by barchanoid dunes at the western section and shore-parallel beach ridges (Figure 2.7) and vegetated coastal plain (Figure 2.8) at the eastern section. At the eastern end of this sector a succession of small embayed beaches occurs. Again, at the western end of this segment, the coastline could not be mapped, as this area corresponds to the downwind edge of the dune corridor that starts at Praia de Chaves (Figure 2.7).

Coastal evolution, measured by either coastline and shoreline indicators, is characterized by strong spatial variability with the largest variations occurring at the eastern tip of Santa Mónica beach (near Ponta do Embarcadouro) (Table 2.4 and Figure 2.8). Long-term coastline evolution at this coastal stretch was dominated by accretion (coastline progradation of about 24 m), which occurred mainly between 1983 and 1991 (Table 2.4 and Figure 2.5). The long-term shoreline evolution presented similar accretional signal but with a smaller magnitude (progradation of the shoreline about 5 m; Table 2.4). The spatial pattern of coastal evolution, at this sector, reveals that the eastern section of Santa Mónica beach registered noticeable shoreline erosion from 1968 to 1991 (with a maximum close to 70 m) but experienced almost complete recovery in the subsequent years (up to 2010) (Figure 2.8).

View 7A

Figure 2.7: Beach evolution between 1983 and 2010 at Ponta Varandinha and Ponta Manga Larga section (View 7A, see Figure 2.2 for location); reference lines represent 1983 coastline (black dot) and 1983 shoreline (red dash). The coastline does not extend through the aeolian corridor because the absence of a recognizable proxy for the coastline position.



View 8A

Figure 2.8: Beach evolution between 1968 and 2010 at coastal stretch Ponta Varandinha and Ponta Manga Larga (View 8A, see Figure 2.2 for location); reference lines represent 1968 coastline (black dot) and 1968 shoreline (red dash).

2.3.4 Ponta Manga Larga to Ponta Pesqueiro Grande sector

The sector between Ponta Manga Larga and Ponta Pesqueiro Grande, is characterized by an arcuate sandy embayment. In the central section the beach develops as a sand barrier, made by a single ridge with low dunes. The sand barrier, backed by supratidal salt pans, has little vegetation cover and is punctuated by numerous overwash fans (Figure 2.2).

Between 1968 and 2010 the coastal evolution at Ponta Manga Larga - Ponta Pesqueiro Grande section has been consistently dominated by long-term accretion with magnitudes of progradation circa 39 m and 12 m, for the coastline and shoreline indicators, respectively. An episodic erosional behaviour was only detected in the shoreline position and during a single period (between 1991 and 2003) (Table 2.4 , Figure 2.3 and Figure 2.9).

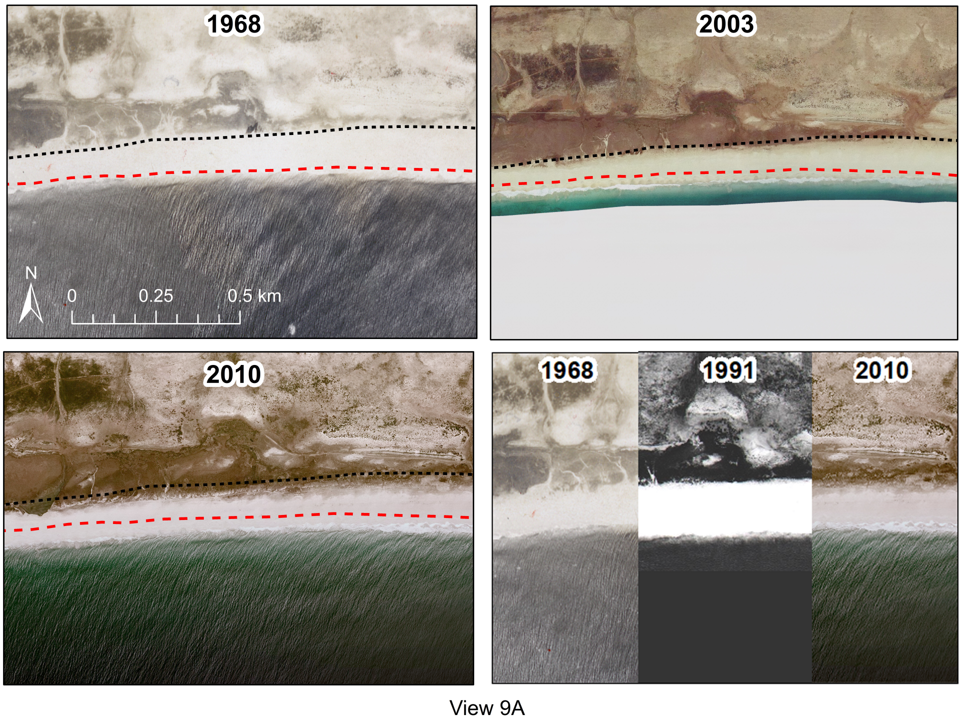


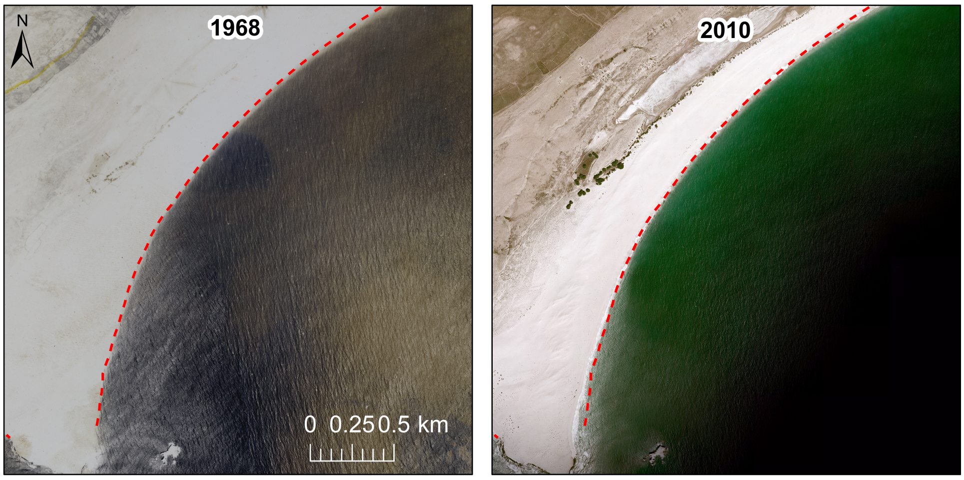
Figure 2.9: Beach evolution between 1968 and 2010 at coastal Ponta Manga Larga and Ponta Pesqueiro Grande (View 9A, see Figure 2.2 for location); reference lines represent 1968 coastline (black dot) and 1968 shoreline (red dash).

2.3.5 Ponta Pesqueiro Grande to Ponta do Ervatão sector

Between Ponta Pesqueiro Grande and Ponta do Ervatão, the coast is dominated by extensive beaches backed by sand sheets (at the western limit of this coastal sector; Figure 2.10) and nebkha dunes (at the central part of the sector; Figure 2.11). At the eastern section of this coastal sector the beach confines with low-lying cliffs that at some places encases small embayed beaches (Figure 2.2). It is worth mentioning that the coastline indicator could only be mapped on a fraction of this coastal stretch, namely along the beach backed by the nebkha; in places where the beach is backed by sand sheets it was not possible to recognize any coastline proxy (vegetation or foredune toe). Moreover, the imagery data-set of 1983 did not include part of this sector, thus the long-term analysis based on the 1968-2010 data-sets should consider these limitations.

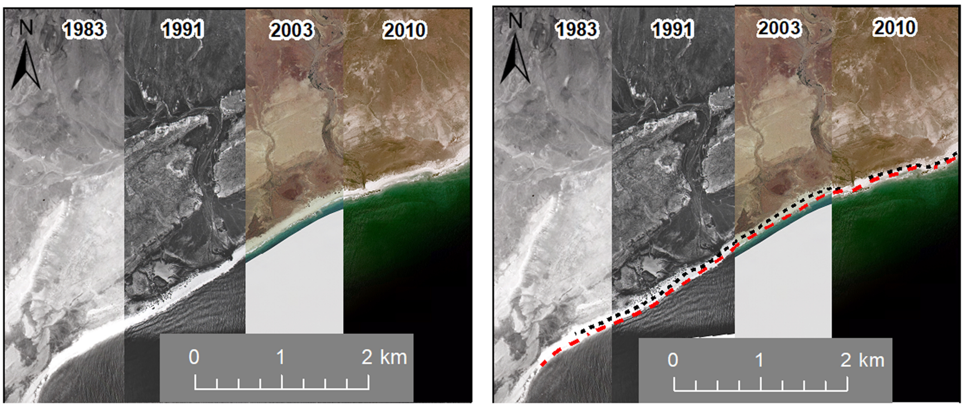
Between 1968 and 2010, coastal evolution was dominated by a retreat of both coastline (Figure 2.10) and the shoreline indicators, with a magnitude of 4.8 m and 10.7 m, respectively (Table 2.4 and Figure

2.5). Along the central section, an alternation of retreat and advances was recognized, mostly on the shoreline indicator (Figure 2.3 and Figure 2.11).



View 10A

Figure 2.10: Beach evolution between 1968 and 2010 at Ponta Pesqueiro Grande and Ponta Ervatão section (View 10A, see Figure 2.2 for location); reference lines represent 1968 shoreline (red dash).



View 11A

Figure 2.11: Beach evolution between 1983 and 2010 at Ponta Pesqueiro Grande and Ponta Ervatão (View 11A, see Figure 2.2 for location); reference lines represent 1983 coastline (black dot) and 1983 shoreline (red dash).

2.3.6 Ponta do Ervatão to Ponta Rodrigo sector

Ponta do Ervatão – Ponta Rodrigo section is a sector dominated by low-height cliffs where some beaches develop in relation to sand accumulation along rocky indentations (Figure 2.2). These embayments, particularly at the northern end of this sector, are related to cliff erosion (Figure 2.12) and might extend up to few hectometres. This sector also includes two long sandy beaches (more than 1 km), Mosquito Beach and the beach at Cruz do Morto (Figure 2.13), backed respectively, by a low-height dune field (predominantly nebkha) and an interdune depression.

Long-term coastline and shoreline evolution results, between 1968 and 2010, are characterized by small coastline retreat (-4.6 m) and marginal shoreline advance (2.0 m), though the shoreline has also retreated in the periods 1968 to 1983 and 1991 to 2003 (Figure 2.3, Table 2.4 and Figure 2.5). Still, is possible to verify in this section, evidences of cliff erosion with localized retreat that can occasionally exceed 30 meters, associated with the development of small bays which provide a geomorphology favourable area for sand accumulation and the formation of new pocket beaches (Figure 2.12).

Figure 2.12: Cliff erosion and localized beach development at coastal stretch Ponta do Ervatão and Ponta Rodrigo (Photograph views 12A and 12B looking SE, see Figure 2.2 for location).

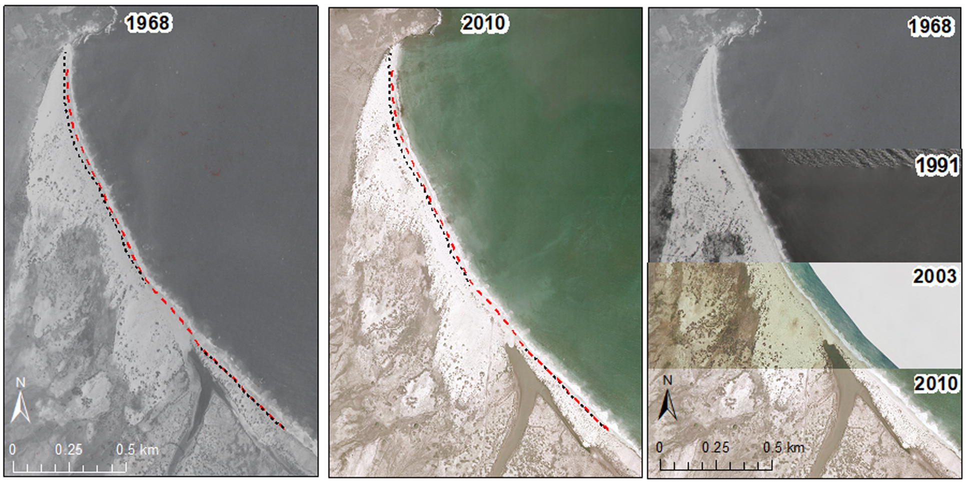


Figure 2.13: Beach evolution between 1968 and 2010 at Ponta do Ervatão and Ponta Rodrigo (View 13A, see Figure 2.2 for location); reference lines represent 1968 coastline (black dot) and 1968 shoreline (red dash).

2.3.7 Ponta Rodrigo to Ponta do Sol sector

The coastal geomorphology of Ponta Rodrigo – Ponta do Sol section is dominated by cliffs with numerous rocky indentations and embayed beaches (Figure 2.2). Like most of the Ponta do Ervatão - Ponta Rodrigo sector, the eastern segment of Ponta Rodrigo - Ponta do Sol sector presents field evidence of erosive behaviour that could not be mapped by the coastline indicator. Field evidence of coastal retreat includes cliff erosion (Figure 2.14-A) and wind-driven depletion of sand from the coastal aeolianites or palaeosoils (Figure 2.14-B).

Figure 2.14: Evidences of a coastal zone in an erosive tendency. Photograph view 14-A looking NNE - Cliff erosion and coastal indentation; Photograph view 14B looking SSW – Wind-driven depletion of the sand from the rocky outcrops (aeolianites, beachrocks and palaeossoils).

The integrated coastal evolution from 1968 to 2010, although estimated only in few transects, is characterized by shoreline progradation (24 m) mainly between 2003 and 2010, while the even sparser coastline results indicate a small retreat (-2.5 m) (Table 2.4 and Figure 2.5).

2.4 Discussion

2.4.1 Recent coastal evolution

This study presents the integrated analysis of the coastal evolution at Boa Vista island at a decadal time scale. The use of both coastline and shoreline indicators was found to be a valuable approach as they add consistency to the results and can also give complementary information. In coastal sections coincident to aeolian corridors or poor image quality it is only possibly to map the shoreline. This later indicator has also the advantage of being able to capture beach seasonal behaviour and beach rotation conveying relevant information to understand coastal response to changes in the forcing factors (e.g. waves and wind). However, as the magnitude of short-term shoreline changes can exceed tens of meters, these variations can conceal the signal of the long-term evolution. In this context, the coastline indicator was found to be the most reliable indicator to appraise long-term changes, a result that is in line with the findings of Ponte Lira *et al.* (2016).

During the studied period (1968-2010) the coast revealed a fairly stable behaviour, marginally dominated by accretion. Estimated spatially averaged coastline and shoreline evolution were 0.48 m/year and 0.18 m/year respectively. Results show significant spatial and temporal variability, with localized cyclical changes that can exceed 100 m in few years. Of the seven coastal sectors analysed, only the ones located at the south-southwest side of the island (Ponta Manga Larga - Ponta Pesqueiro Grande and Ponta Varandinha - Ponta Manga Larga) presented a consistent coastline progradation trend.

2.4.2 Source-to-sink sediment budget

To understand the drivers of coastal evolution, coastal change results were framed in a conceptual source-to-sink sand sediment budget (c.f. Silva *et al.*, 2019).

Sources

Main sand sources of Boa Vista island have origin in the sedimentary deposits at the northern insular shelf (Hernández and Suárez, 2006; Cabo Verde Natura, 2000) and are constituted by fragment of rhodoliths, corals and bivalves. Additional sediment sources can be attributed to quaternary carbonate aeolianite outcrops that covers large extents of Boa Vista island (Calvento *et al.*, 2017).

Sediment pathways

Sediment transport at Boa Vista is dominated by a unidirectional (or strongly asymmetrical) NE-SW wind field (Cabo Verde Natura, 2000) related with trade winds (Hernández and Suárez, 2006). This wind regime and low terrain elevation, free from topographic barriers, favour a sediment transport pathway that links the North and South coasts of the island (Hernández and Suárez, 2006). The NE-SW dune overpass is expressed mostly by sand sheets, but also by barchan dunes and barchanoid ridges (Cabo Verde Natura, 2000). The main aeolian corridors at Boa Vista, include: 1) a wide northern corridor that connects the sediment source areas (upwind) of Boa Esperança beach to Carlota beach (downwind) and; 2) a southwestern corridor, narrower due to topographic constrains, linking Chave beach to the coast at Ponta Varandinha – Ponta Manga Larga (Figure 2.2). The sedimentary connection between these wind corridors takes place at Carlota and Chave beaches coastal stretch, and is sustained by a persistent wave-induced southward-directed longshore drift. At the eastern side of the island, the north-south sediment transport is predominately wave-induced through sediment headland bypass compatible with a Circum-island transport model (Tinley, 1985; Calvento *et al.*, 2017). Here, overpassing only occurs at site specific locations, generally at more protrude, and low relief, headlands like Ponta do Ervatão.

Sinks

The convergence of the south-directed sediment pathways at Boa Vista suggests the existence of depositional areas, which is in-line with the coastal accretion measures of this work. This behaviour is compatible with the findings of (Cabo Verde Natura, 2000) which argued that localized sediment accumulations within the transport corridor result in the development of transverse ridges with linear crest lines.

2.4.3 Management implications

Spatial planning and management at small-sized islands is a challenging task due to their limited territorial domain. At the coastal zone these problems are particularity exacerbated in relation to the strong touristic pressure (Hall, 2001). However, as tourism is an environmentally dependent activity (Wong, 1993) the disorderly occupation of the coastal zone can put in peril not only the beach but also the sustainable development of the island. Results presented in this work show that coastal evolution has been consistently regulated by the sediment budget, with sedimentary links between island beaches but also with inland mobile sand deposits. In practice, the whole island can be regarded as a single sediment cell thus, management decisions, even at non-coastal locations, should consider a global, island-scale, perspective. For example, the well-defined progradation trend identified at Boa Vista southern coast is related to the transference of sand by overpass and bypass processes from the northern insular shelf. Any blockage of sand at the coast or at the inland domain (away from the coast) can have significative effects downwind/downdrift and hamper beach sustainability.

2.5 Main achievements

This chapter addresses island-scale coastal evolution at Boa Vista. The study is based on a comprehensive collection of aerial photographs and orthophotos maps with different spatial and spectral resolutions. The main achievements of this chapter was:

1. For long-term coastal evolution appraisal, the coastline was found to be a more consistent indicator, as the shoreline is more prone to errors related to wave and tide variability and is also affected by short-term variability such as beach rotation or beach cross-shore changes;

2. During the studied period (1968-2010), most of Boa Vista coastal evolution revealed a fairly stable behaviour, with a noticeable and consistent accretion trend only recognized at south-southwest sides of the island of about 0.76 m/year;

3. Spatially averaged coastline and shoreline evolution were 0.48 m/year and 0.18 m/year, respectively;

4. Coastline evolution was shown to be related to the sediment budget and can be explained by a simple source-to-sink sediment approach.

Chapter 3

Drivers of Coastal Change

This chapter is partially based on the work:

Gomes, C., Costa, P., Cascalho, J., Silva, A. N., Taborda, R., Santos, F. and Lopes, V. (2019). Sediment Bypass and Overpass contributions for Boa Vista Island Coastal Evolution, In "Coastal Sediments 2019: Proceedings of the 9^{th} International Conference", Wang, P., Rosati, J.D. and Vallee, M. [Eds.],Tampa/St. Petersburg, Florida, USA. doi: 10.1142/11391. `https://doi.org/10.1142/11391`.

3.1 Introduction

Understanding drivers of coastal evolution is essentially based in spatially constrained or conceptual (qualitative) models. This approach has obvious limitations due to the lack of quantitative and long-term data to support cost-benefit management analysis and decisions.

Boa Vista offers optimal conditions for an integrated study of coastal evolution due to its relatively small dimension, low anthropogenic disturbance and a beach geomorphologic setting that is analogous to other volcanic islands. Similarly, to other islands systems, Boa Vista beach evolution depends on a fragile balance between sediment sources (biological and lithic contributions), transport processes derived from the wind and wave climate, and sediment sinks. Torrential drainage can also provide further sediment to the island coastal budget. The main goal of this study is to investigate Boa Vista beach evolution considering sediment sources, transport processes and sediment sinks through a sediment budget approach. This chapter focuses on a multidisciplinary quantitative and integrated approach that includes morphological, sediment textural analysis of coastal and dune systems and transport processes derived from bypassing (wave action) and overpassing (aeolian).

3.2 Material and Methods

To accomplish the objectives of this thesis a characterization of the sedimentary dynamics of Boa Vista island was carried out. Several laboratory techniques (textural analysis: grain size; percentage of calcium carbonate; and compositional analysis) were used, and statistical analysis of the results was done.

Proxies used are applied in dunes and beaches sites. Also, it is made the dunes (namely barchans) characterization in the main aeolian corridor (Dunas de Chave). To make data analysis and understand the sedimentary dynamics characteristics, statistical analysis, Google Earth Pro imagery and ArcGis software were used.

3.2.1 Sediment sampling

During July 2017, twenty sediment samples were collected from several beaches and dunes. The samples from dunes were collected on the surface slip face along the aeolian corridor and on dunes adjacent to beach (7 samples), while beaches samples (13 samples) were collected on beach berms (Figure 3.1). Sampling locations were georeferenced using a hand-held GPS. Additionally, 91 digital images of dune and beach sediments (Figure 3.2) were acquired for textural characterization. The images presented a resolution of 16 megapixels (4608 × 3456), with a pixel size of 0.014 mm (Figure 3.1 - right).

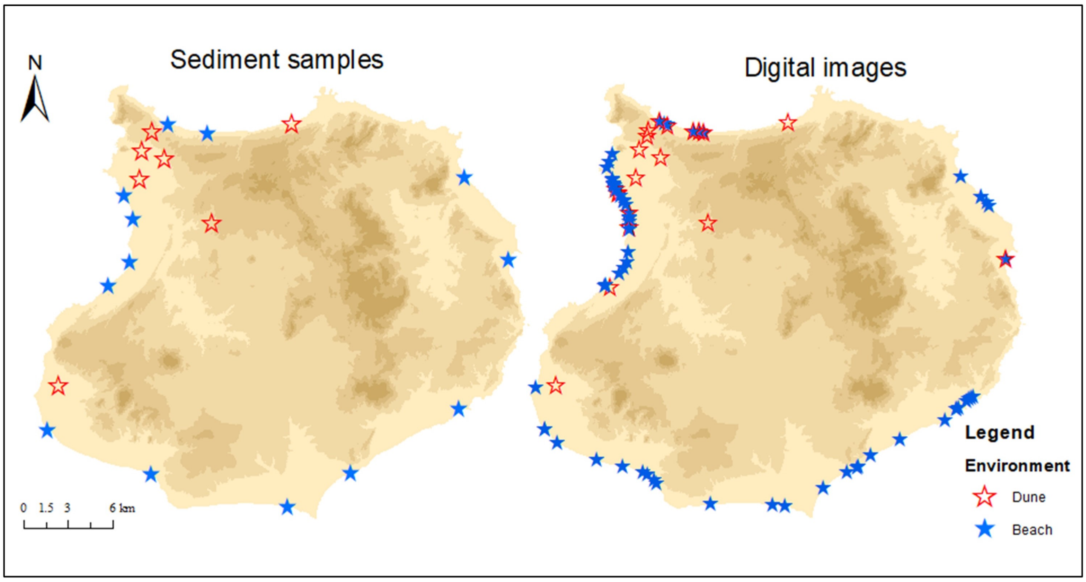


Figure 3.1: Sites Samples at Boa Vista island: Red stars (Dunes) and Blue stars (Beaches).

Figure 3.2: Example of digital images of Boa Vista sediments: A (fine grained); B (coarse grained).

3.2.2 Textural and composition analysis

Digital images

The broad textural characterization of Boa Vista sediments, on the 91 digital images, was performed by the digital image analysis application developed by Bosnic *et al.* (2011). This method estimates the median grain size of the sediment based on image autocorrelation (Rubin, 2004).

Sediment samples

Initially the samples were washed several times with tap water to remove marine salt and then dried for 48 hours, in an oven at 105º C (Figure 3.3).

After this, each sample was split into aliquots with about 100 g (Figure 3.4). The grain size was performed through dry sieving using a standard set of sieves (0.5 Φ interval (from -2 to 4 Φ). Statistical grain size parameters (e.g. mean grain size, standard deviation, kurtosis and skewness) were calculated using the graphic method (Folk and Ward, 1957) in Gradistat (Blott and Pye, 2001) software. Textural features were map-plotted to study their spatial distribution along Boa Vista island in ArcGis (version 10.6) environment.

Calcium carbonate content ($CaCO_3$) (associated with bioclasts) was determined by measuring the volume of carbon dioxide evolved during reaction with [4mol/L] hydrochloric acid using an Eijkelkamp calcimeter (Eijkelkamp, 2008) (Figure 3.5).

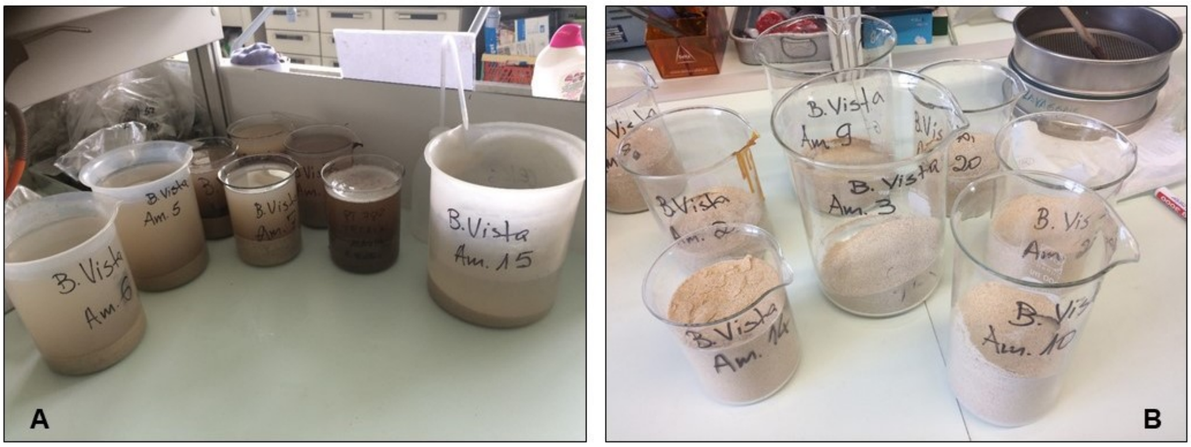


Figure 3.3: Samples washed (A) and dried (B).

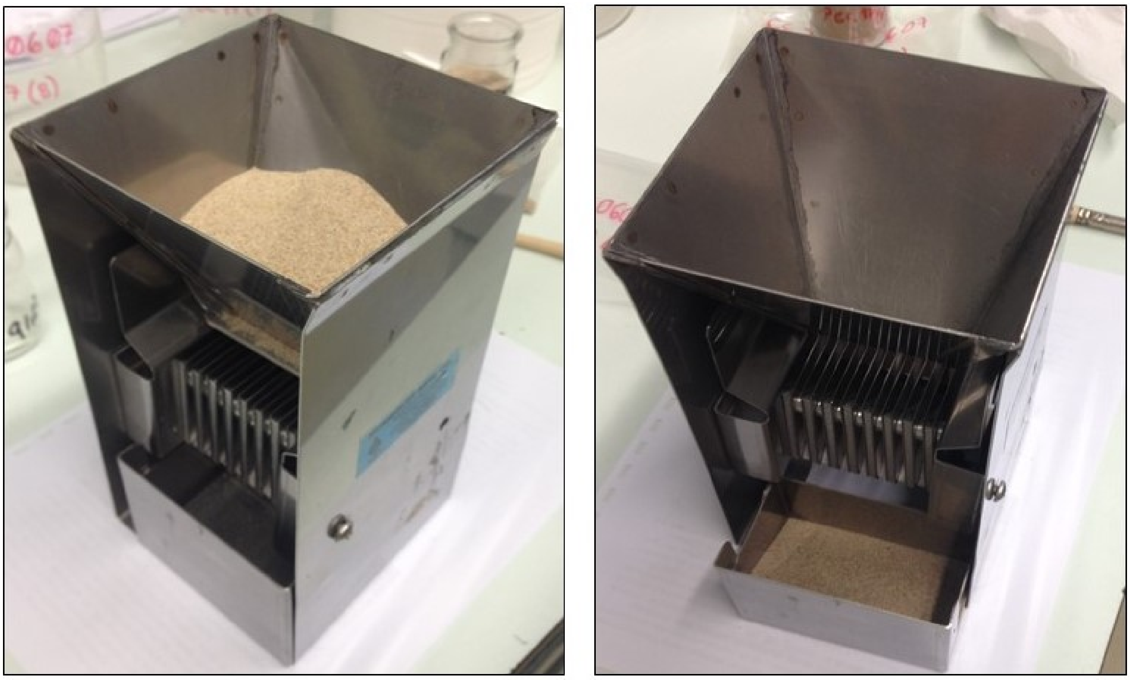


Figure 3.4: Samples splinted into aliquots of about 100 g.

Figure 3.5: Calcium carbonate content determination using Eijkelkamp calcimeter.

The main sediment components were identified in all the collected samples under a binocular microscope considering the grain size classes of 0-0.5Φ; 0.5-1Φ; 1-1.5Φ; 1.5-2Φ; 2-2.5Φ and 2-5-3Φ. A minimum of 100 grains per grain-size class sample were identified. Grains from each sample were counted and two major groups (bioclasts and terrigenous) were identified (Figure 3.6). Bioclast particles were essentially bivalves shells, rhodoliths and corals fragments. Terrigenous particles were dominated by sanidines, olivines and piroxenes. These textural and compositional data were organized to produce maps with the spatial distribution of the main sediment parameters.

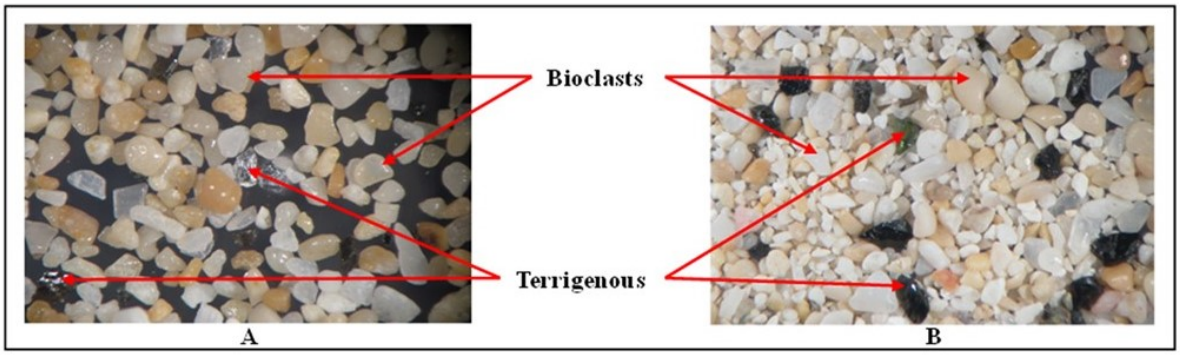


Figure 3.6: Sediments constituents from Boa Vista Island: A (beach) magnifying glass enlargement 7x; B (dune) magnifying glass enlargement 7x. .

3.2.3 Dune evolution

Dune migration on the main aeolian corridor at Boa Vista island was measured using Google Earth imagery from 2005, 2010, 2012, 2013, 2015 and 2016. From the entire aeolian corridor 29 dunes were selected (Figure 3.7). Over each dune was drawn a polygon that represents the dune position in a specific year. Afterward the polygons were exported to ArcGIS environment for the analysis bellow mentioned. The uncertainty or error (rmse) calculated for dune draw displacement in this study was estimated as 10.45 m, comparing the displacement through time, of 27 non-moving features (for example rocky outcrops).

Four dimensional dune parameters, namely height (H), width (W), length (L) and volume (V), were measured and calculated using techniques developed by Andreotti *et al.* (2002), Elbelrhiti *et al.* (2008), Jimenez *et al.* (1999) and Abu-Sbeih (2015) to characterize dune evolution. Dune height and volume were calculated using the formulas developed by (Abu-Sbeih, 2015) (equation 3.1):

$$V = 0.10228 \times L^2 \times \frac{W}{2} \tag{3.1}$$

Dune width, length and migration rate (m) were measured and calculated in ArcGis environment.

Measurements of aeolian transport rate (Q) were made by using the formula developed by (Jimenez *et al.*, 1999) (equation 3.2):

$$Q = \frac{V}{L} \times \frac{m}{W} \tag{3.2}$$

Finally, the quantification of the total sand flux transported within the dune field considered the average aeolian transport rate multiplied by the width of the Dunas de Chaves aeolian corridor (about 800 m).

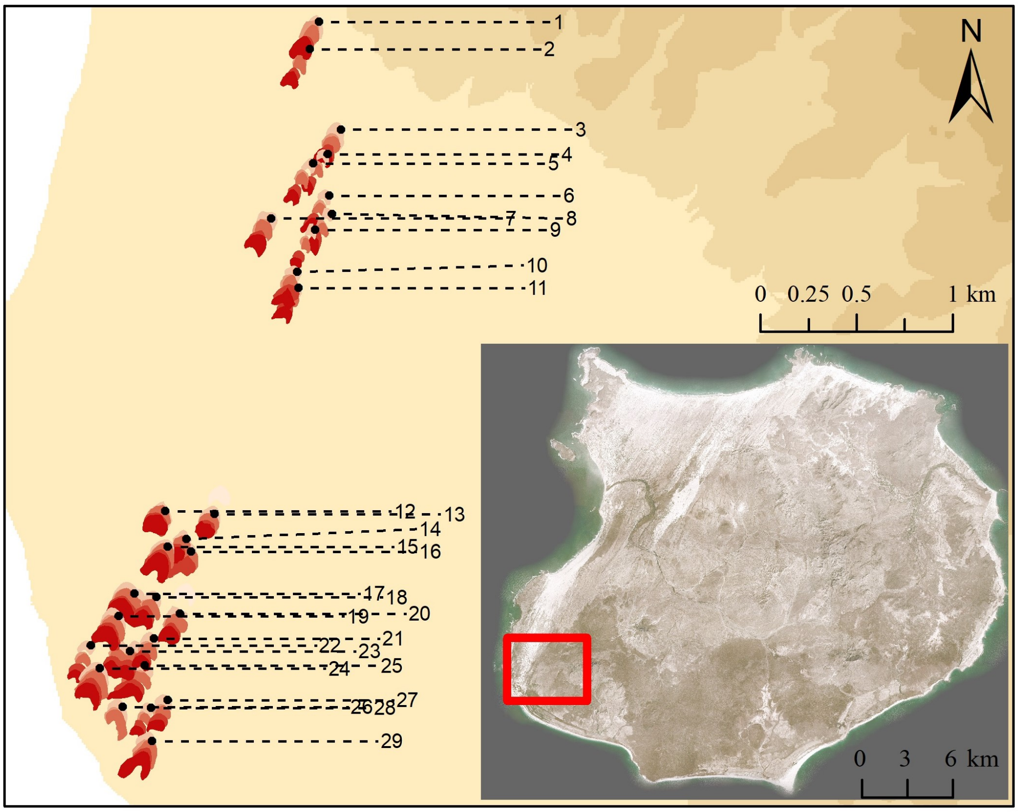


Figure 3.7: Monitored barchans dunes at the Dunas the Chaves aeolian corridor (between 2010 and 2016, light and dark colors respectively; the numbers represent the dune ID).

Winds drawing direction was perfomed in a ArcGis environment using aerial photographs (1968, 1983 and 1991) and orthophoto maps 2003 and 2010, based on dune displacements.

3.2.4 Coastal evolution: observations

Boa Vista coastal evolution was established using aerial photos (1968, 1983 and 1991) and orthophotos (2001 and 2010) and variations on coastline and shoreline position as described in Gomes *et al.* (2019). These parameters were manually vectorized in GIS environment at visualization scales ranging from 1:2 000 to 1:10 000 along the entire low-lying sandy coast of Boa Vista for the time-window of observation (1968-2010). Coastline and shoreline evolution changes were quantified in GIS environment using the Digital Shoreline Analysis System ArcMap extension (Thieler *et al.*, 2017). The results presented in Gomes *et al.* (2019), showed that the only coastal sectors that presented a consistent long-term tendency were the southwest and south sectors, with long-term evolution rates of 24.1 m and 38.8 m (respectively for P. Varandinha to P. Manga Larga and P. Manga Larga - P. Pesqueiro Grande sectors) (Figure 3.13).

The magnitude of coastline retreat or advance, combined with the information beach prism depth (berm height minus the closure of depth, that defines the seaward limit of the beach) is used to determine the total volume of sand withdrawn or accumulated at the coast.

The closure depth, at the southwest coast of Boa Vista, was estimated based on the hindcast wave data (from 2005 to 2017 `http://polar.ncep.noaa.gov/waves/hindcasts/`) using the Hallermeier (1978) formulation (equation 3.3, where the inner closure depth limit (d_i) is defined:

$$d_i = 2\overline{H}_s + 11\sigma_s \tag{3.3}$$

Where, $\overline{H}_s$ is the annual mean significant wave height, and σ_s is the associated standard deviation of the significant wave height. The berm elevation was considered 3 m above mean sea level, based on the berm nest elevation (of *Caretta caretta,* marine turtle specie) (Ferreira Júnior *et al.*, 2008).
Depth of closure was determined following Hallermeier (1978) at 4.5 m below mean sea level, located broadly 200 m seaward from the coastline.

3.2.5 Coastal evolution related with Sea Level Rise

Local sea level change are induced by eustatic, isostatic and tectonic changes. In a volcanic islands tectonic vertical movements may dominate sea level changes (Silva *et al.*, 2019). Boa Vista island take parts of Cabo Verde islands group that exhibit evidence for stability or complex uplift–subsidence histories (Ramalho *et al.*, 2010a).

At Boa Vista island, the SLR data used was measured from satellite radar altimeters, wich the general trend of sea-level change shows a relative SLR at an average rate of 2.5 mm year^{-1} between 1992 and 2018 (Laboratory for Satellite Altimetry, 2018). This value is in line with global ocean estimates and indicates that sea level rise is dominated by the eustatic component.

There is an increasing consensus that an accelerating SLR scenario due to climate change will have significant impacts on the coastal zone (Mimura *et al.*, 2007; Santos *et al.*, 2017; Bijlsma *et al.*, 1996). Thus, the existence of tools to evaluate the potential influence of SLR on shoreline evolution it is fundamental (Taborda and Ribeiro, 2015). In that sense, Bruun (1962) theory or it is conceptual model for an quantitative approaches have clearly been dominated (Fenneman *et al.*, 1902; Taborda and Ribeiro, 2015). According (Bruun, 1954) theory SLR as a cause of shore erosion, assuming a profile of equilibrium (Fenneman *et al.*, 1902; Bruun, 1954), as sea level rises material eroded from the upper beach is deposited on the nearshore bottom down to a limiting depth between predominant nearshore and offshore material. Taborda and Ribeiro (2015) proposed a model that evaluate the effects of SLR at platform beaches. This model relies on the assumptions of conservation of beach sand volume and beach profile shape, considering that the beach berm elevation remains in equilibrium with mean sea level. Accordingly, the impact of the SLR on the position of the shoreline corresponds solely to retreat of the berm crest with reduction of supratidal beach surface, but sediment loss to the shelf is null or negligible.
Bruun's rule (Bruun, 1962) was used where the whole active beach profile develops over sandy substrate. Thus, depth of closure was determined (see previous section). Taborda and Ribeiro (2015) model was used in coastal sectors where the subtidal beach develops over a rocky platform, the sandy section of the profile terminates landward of the depth of closure.

3.3 Results

3.3.1 Textural and Compositional Data

Grain-size parameters for the 20 samples taken from the dune and beach environments of Boa Vista are represented in Table 3.1.

Table 3.1: Grain-size descriptive statistics of 20 samples from Boa Vista island.

	Beaches	Dunes	Total
Mean	1.86 ± 0.31	1.94 ± 0.29	1.89 ± 0.30
Sorting	0.49 ± 0.14	0.58 ± 0.15	0.52 ± 0.15
Skewness	- 0.07 ± 0.10	0.06 ± 0.08	- 0.03 ± 0.11

From the textural point of view, dune and beach sands are almost identical, being characterized mostly by symmetrical, well sorted, medium to fine sand. The spatial distribution of mean grain size (either from sieving and image analysis - Figures 3.8 and 3.9) do not show any clear pattern, although a tendency for minor particles located in the southwest coast (downwind of the Dunas de Chaves aeolian corridor) can be recognized.

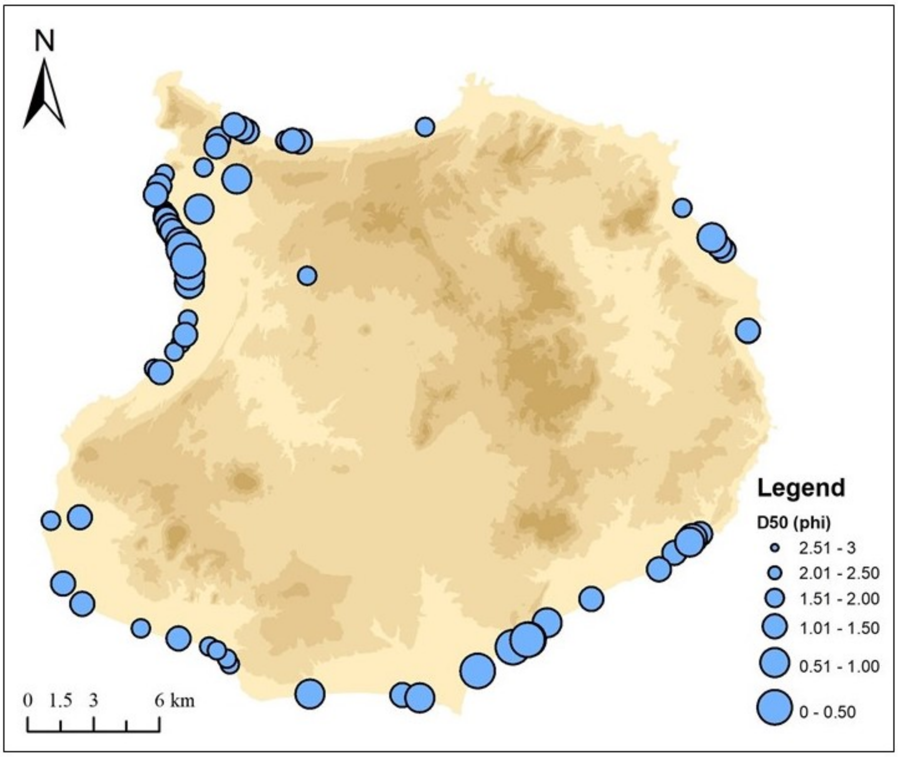


Figure 3.8: Spatial distribution of median grain-size (D50) along Boa Vista Island (derived from digital images).

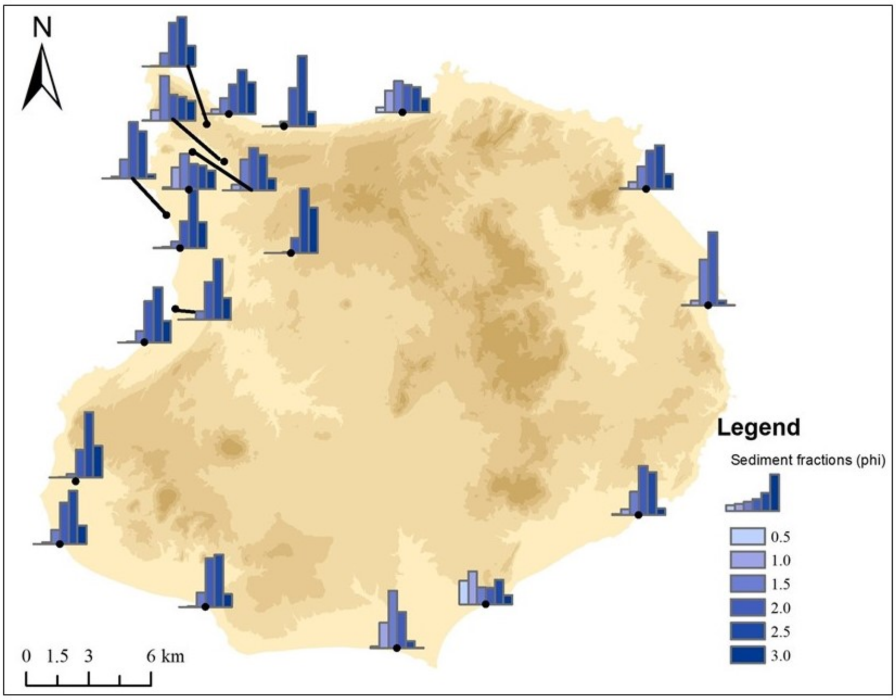


Figure 3.9: Spatial distribution of grain-size classes along Boa Vista Island (textural analysis on sediment samples).

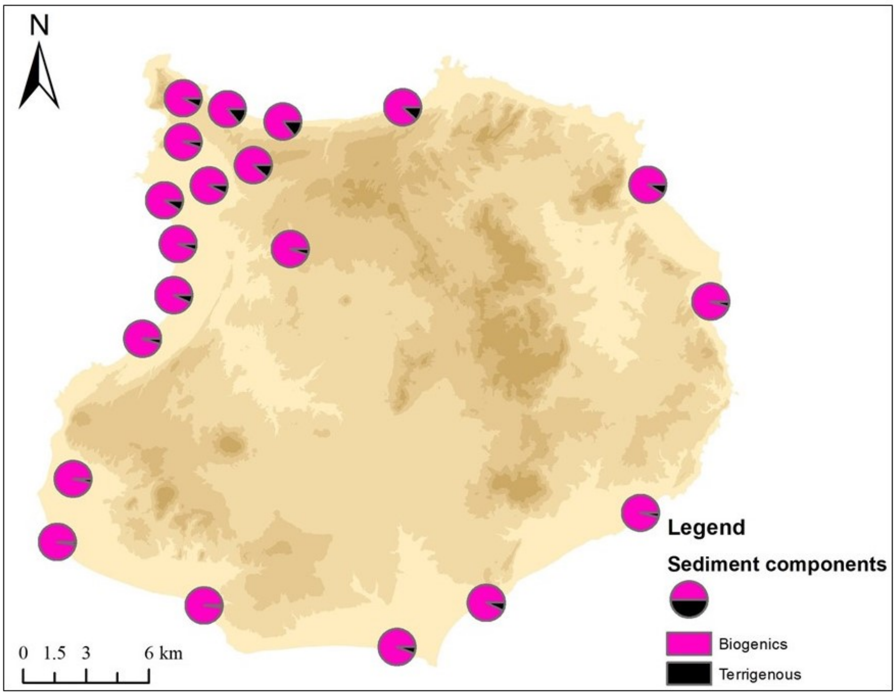


Figure 3.10: . Sediment components spatial distribution along Boa Vista island.

Both beach and dune, sediments are clearly dominated by biogenic particles (figure 3.10), ranging from 71 to 99 %. Biogenic component is composed essentially by bivalve shells, rhodoliths and corals fragments while the terrigenous component is mainly comprised by mineral grains (sanidine, olivine and pyroxene) and few rock fragments. The terrigenous content is slight larger at the north-western sector of the island.

3.3.2 Dune Geometry and Dune Evolution

Table 3.2 displays dune dimensions for the 29 monitored barchans. Results show an average width, length and height of 97.6 m, 69.0 m and 13.1 m, respectively. Barchan dune dimensions in the Dunas de Chaves aeolian corridor, as well as in other regions, are linearly related to each other. An example is the relationship between the dune length and its width displayed in Figure 3.12, which shows a clear linear correlation. Estimated dune volume from about 7×10^3 m^3 to 63×10^3 m^3, with an average value of 27×10^3 m^3.

The migration rate of barchan dunes presents an average value of 26.7 m $year^{-1}$ and shows clearly the inverse relationship with dune volume (Figure 3.11 and 3.12). In fact, smaller barchans migrate more rapidly than larger barchan dunes, a behaviour that is in-line with observations reported in previous studies (Jimenez *et al.*, 1999).

Table 3.2: Descriptive morphometric data of Dunas de Chaves aeolian corridor (n = 29), Boa Vista island.

	Width (W) (m)	Length (L) (m)	Height (H) (m)	Volume (V) (m^3)	Migration rate (m) (m $year^{-1}$)	Transport rate (Q) (m^3 m^{-1} $year^{-1}$)
Mean	97.6	69.0	13.1	26610	26.7	92.9
SD	26.6	13.3	2.5	15075	5.6	14.5
Maximum	158.0	91.6	17.4	63613	36.7	126.1
Minimum	56.1	45.9	8.7	6837	17.1	66.7

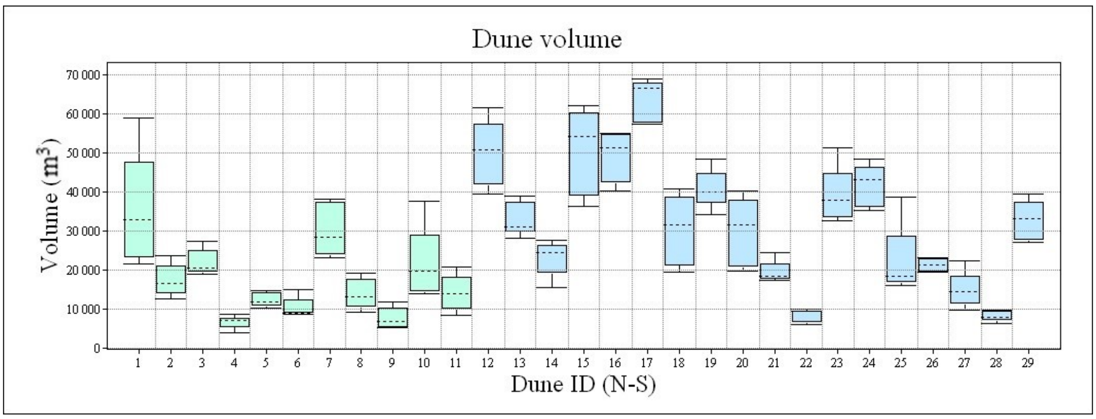


Figure 3.11: Estimated barchans volume at the monitored dunes (ID 1 to ID 29 from north (N) to south (S), location in Figure 3.7). Green box - represent barchans from N and blue box - represent barchans from S.

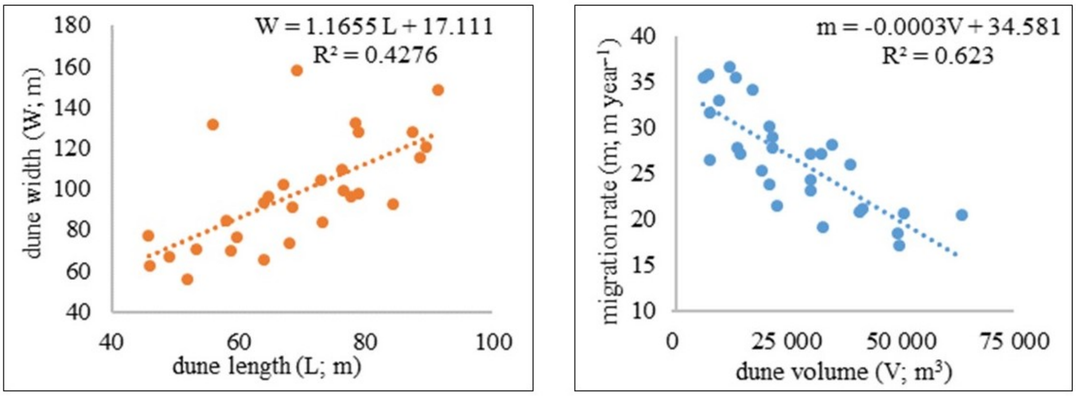


Figure 3.12: Barchans morphometric relationships (left) and barchan migration vs dune volume (right) at Boa Vista island.

Dune migration rates were used to estimate the magnitude of aeolian transport rates along a dune field. In fact, dune migration should be considered as the response of the sand at an aggregated scale to wind action (Jimenez *et al.*, 1999).

Results for barchans in Boa Vista island give an average aeolian transport rate of 93 m^3 m^{-1} $year^{-1}$ with a maximum value of 126 m^3 m^{-1} $year^{-1}$ and a minimum of 67 m^3 m^{-1} $year^{-1}$ (Table 3.2). Considering a width for the aeolian corridor of about 800 m, the total aeolian volume of sand transported each year is estimated in $74{\times}10^3$ m^3 $year^{-1}$.

Estimation of sand accumulation rate in the two southwestern-most sectors of the island (P. Varandinha and P. Pesqueiro Grande) was established based in the long-term evolution rates coupled with the information on the beach prism depth (11 m) and each sector length (11 km and 7.75 km, at the P. Varandinha to P. Manga Larga and P. Manga Larga – P. Pesqueiro Grande sectors, respectively). The approximate total volume of sand accumulated at the P. Varandinha to P. Manga Larga was estimated in 69 $\times 10^3$ m^3 $year^{-1}$ while at the P. Manga Larga – P. Pesqueiro Grande was $79{\times}10^3$ m^3 $year^{-1}$ (Figure 3.13).

Results did not significant difference in dune propagation direction during the studied period, last 42 years (1968 until 2010), that could be associate to changes in wind directions at same period.

3.3.3 Coastal evolution induced by Sea Level Rise (SLR)

According to results displayed on Table 3.3, during last 42 years (1968 to 2010), conducing a SLR of 0.0025 m $year^{-1}$, coastal areas of Boa Vista island presented a total retreats of 5 m and 2 m for platform beach and other beaches, respectively. In that sense, the sedimentary budget exceed the SLR related to coastal evolution (see Figure 2.5 and Table 2.4)

Table 3.3: Estimated coastal evolution due to SLR (0.0025 m year^{-1}) at Boa Vista island between 1968 and 2010.

	Average profile slope	Retreat rate (m year^{-1})	Total retreat (m)
Platform beaches	0.0225	0.11	5
Other beaches	0.05	0.05	2

3.4 Discussion

Beaches in volcanic islands are fragile environments whose evolution depends on a delicate balance between sediment sources and sinks. Despite the existence of conceptual models that highlight the connections between the different sedimentary systems (Calvento *et al.*, 2017) a quantitative approach is still absent. In this work the integrated analysis of morphological and sedimentological data (compositional and textural) permits to build the foundations of a quantitative sediment budget approach that explain Boa Vista beach evolution.

Textural and compositional sediment data shows a strong degree of similarity between beach and dune sediments across the island entire coastal fringe (Figures 3.8, 3.9 and 3.10). Conceptually, dune sediments are typically better sorted than beach sediments. Furthermore, sediment transport distance and time will increase the sorting of a sandy grain population. In Boa Vista the prevailing winds are from NNE. Therefore, the main biogenic source is located upwind, at the north island shelf, and feeds the main aeolian corridor of Boa Vista. This biogenic fraction corresponds to $>$90% of total sediment in the analyzed samples. On the other hand, the terrigenous content is probably related with the erosion of coastal cliffs and rock outcrops. This type of particles is poorly represented in total sediment ($<$10%), hence the magnitude of this contribution can be minimized as its representativeness in total sediment is low.

Based in the textural and compositional analysis (Figures 3.8, 3.9 and 3.10) of loose sedimentary deposits that covers the island seems to show that, after entering the coastal system at the northern coast, at the western side of the island the sediment is mainly transported SW by wind (overpass), while at the eastern side the sediment is transported at the island rim by waves and currents (headland bypass). In the western sector of the island, this is demonstrated by the higher terrigenous content (mineral and volcanoclasts) in the extreme northern samples and by its progressive decrease towards the south (Figure 3.10). On the other hand, on the eastern sector this change is not so clear and for example sample (João Barrosa) displays a higher terrigenous content. Furthermore, textural analysis does not allow to establish evident grain-size trends that could facilitate the identification of preferred sediment paths. Nevertheless, one can observe that smaller grain-size samples are preferentially located in the southernmost sector of the island, suggesting a wind-related particle winnowing.

The combination of all available data (sediment composition and texture, dune morphometric relationships, island morphology and prevailing winds) suggests the existence of considerable differences between the sediment transport paths around the island. At the eastern side the north to south sediment transport is dominated by longshore drift with headland bypassing. In turn, at the western part the sediment is transported along the aeolian corridor (overpass transport). The first process is found to be less selective than the overpass (dune corridor). All sediments converge to the southern (downdrift) coast, where sediment accumulation is translated in long-term coastline progradation, reflecting the major sediment sink of Boa Vista island. This interpretation is further supported by the estimated aeolian sand transport at Dunas de Chaves corridor which roughly matches the coastal evolution observed at the downwind beaches (Figure 3.13) P. Varandinha – P. Manga Larga. Beach accretion at P. Manga Larga - P. Pesqueiro Grande sector is probably related to the wave related bypass that dominates the sand transport at the eastern part of the island.

The approach developed in this work can be easily applied to other be volcanic islands systems and be used to support the development of beach evolution scenarios that account for changes in climate and anthropogenic forcing.

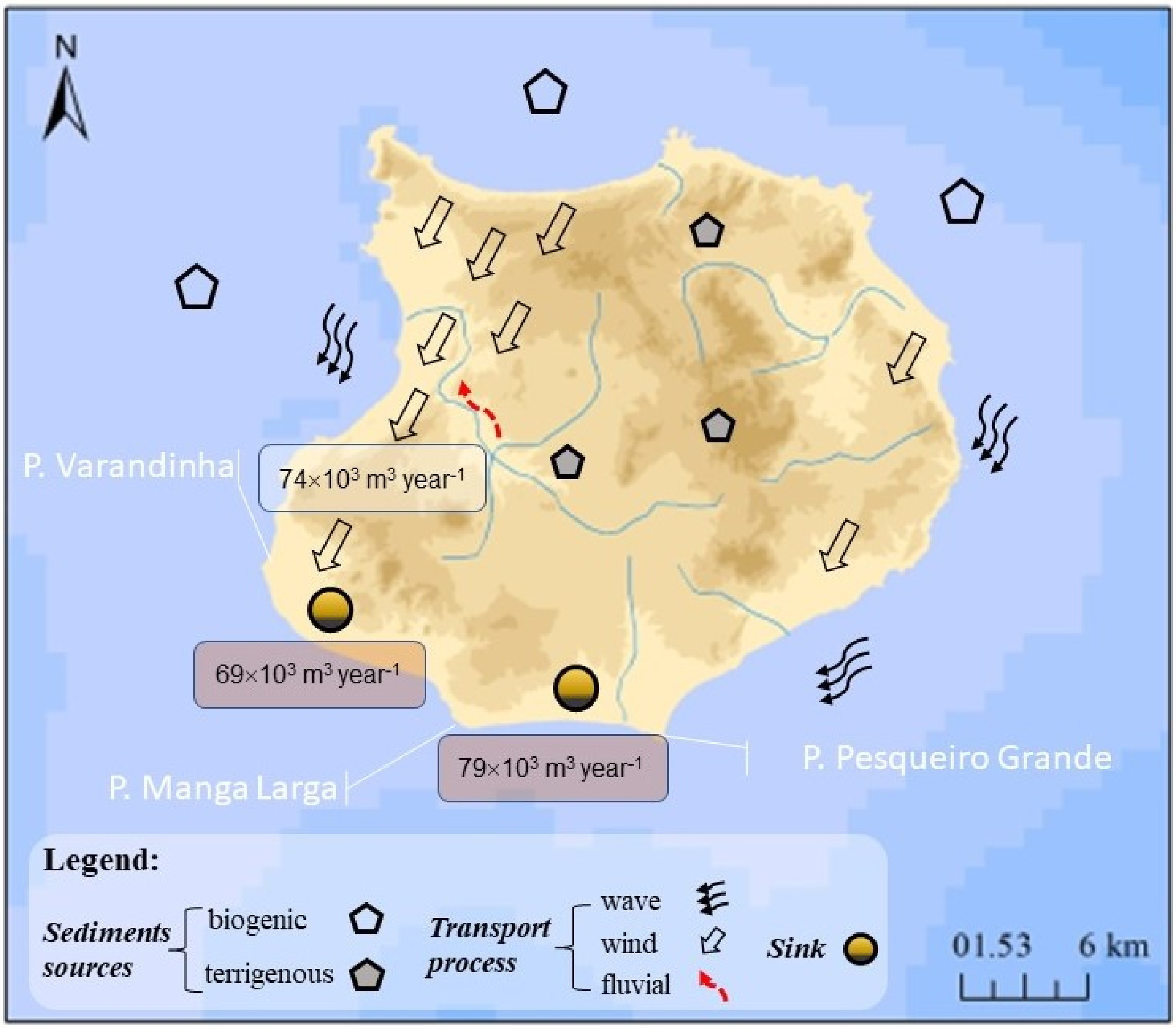


Figure 3.13: Conceptual semi-quantitative model of sediment transport at Boa Vista island.

3.5 Main achievements

In this chapter was conducted an integrated analysis of major coastal drivers (sediment budget and sea level rise) of Boa Vista island in order to understand the dynamical coastal area along island. The main achievements are summarised below:

1. Boa Vista island shows the existence of considerable differences between the sediment transport paths around the island;
2. The eastern side, the north-south sediment transport, is dominated by headland bypassing, while at the western side the sediment is mostly transported along the aeolian corridor by overpass transport;
3. Differences between the sediment transport paths around the island is supported by sediment composition and texture (mainly biogenics and fine sand present along aeolian corridor) and island morphology relationships, where western side present an planar morphology;
4. Sediment transport through aeolian corridor are contributing to sector P. Varandinha and P. Manga Larga. Their magnitudes were estimated through sediments transport rate quantification at the Dunas de Chaves aeolian corridor with 74 $\times$ 10^3 m^3 $year^{-1}$ and the sink value was estimated in 69 $\times$ 10^3 m^3 $year^{-1}$;
5. The wind related transport (overpass) is found to be a more selective than the wave related headland bypass;
6. The sediments transported by the two-transport processes above mentioned converge to southern coast (between P. Varandinha and P. Pesqueiro Grande) where sediment accumulation translated in long-term coastline progradation is recognized, reflecting a major sedimentary sink of Boa Vista island with total of about 150 $\times$ 10^3 m^3 $year^{-1}$;
7. Dune displacement direction shows no significant difference during the last 42 years, wich demonstrate that change wind directions at same period is not significant;
8. Coastal Evolution due to SLR during studied period (42 years) was estimated by empirical models, was found to be lower than 5 m. This results put in evidence that the sedimentary budget exceed the SLR related to coastal evolution.

Chapter 4

Scenarios of Coastal Change

4.1 Introduction

The Intergovernamental Painel on Climate Change (IPCC) fourth Assessment Report (AR4), has been stressing that it is necessary to extend coastal impact of climate change, besides of sea level rise effects, taking into account other coastal drivers, namely interest in how wind-wave respond to a changing climate (Hemer *et al.*, 2012).

Rising sea levels constitutes one of the most recognized climate change threats to low-lying coastal areas (Cazenave and Llovel, 2010; Nicholls and Cazenave, 2010; Anthoff *et al.*, 2006). This is particularly important in small islands where the majority of human communities and infrastructure are located in coastal zones with limited on-island relocation opportunities.

With the projected sea level rise (SLR) until the end of the century, the impacts of the projected increases in wave heights will increase, with a drastic impacts on coastal ecosystems, namely: higher risk of inundation, overtopping caused by waves of sea defences with consequent failure and damage to infrastructure or coastal erosion and drive longshore drift and associated coastal sediment budgets (Hemer *et al.*, 2012).

According to the results obtained previously, it was verified that the rising of sea level during the 20^{th} century had a minor role in the recent coastal evolution of the island under study (see Chapter 3). However, with SLR projections for 2100, this driver will influence the coastal zones of the island in the medium and long term. Furthermore, as referred above, coastal areas have experienced several coastal drivers in a climate change context, but in this study only the following drivers where analysed because they were considered more relevant to the coastal areas in analysis: ***Sea Level Rise (SLR)***; ***Wind***; ***Waves*** and ***Sediment Sources***.

4.1.1 Sea Level Rise - SLR

Research in sea level change is of considerable interest, due to its potential impact on coastal and islands ecosystems.

Since 1990, there has been a great effort in research focused on understanding the biogeophysical effects of climate change and particularly SLR on coastal zones and small islands (Bijlsma *et al.*, 1996).

Sea level is very sensitive to changes in the various components of climate system. For example, the oceans reaction of global warming, sea waters heat and expand, and thus sea level increases (Cazenave and Llovel, 2010).

Satellite observations available since the early 1990s provide more accurate sea level data with nearly global coverage. This decade (1993-2009), long satellite altimetry data set shows that since 1993, sea level has been rising at a rate of around 3 mm year^{-1} (Nerem *et al.*, 2010), significantly higher than the average during the previous half century. Coastal tide gauge measurements confirm this observation, and indicate that similar rates have occurred in some earlier decades (Bindoff *et al.*, 2007). Moreover, according to Wigley (1995) and Church and White (2011) model projections show that sea level will continue to rise beyond the year 2100 due to lags in climate response, even if its assumed a stabilization of global greenhouse gas emissions.

According Bijlsma *et al.* (1996) SLR differ at local, regional and global levels. This phenomenon is explained by two reasons: (i) vertical land movements affect sea level. Regionally and locally, vertical land movements can be quite large, even on the decadal time scale; ii) oceanic circulation, that produces dynamic effects in wind and pressure patterns, and ocean-water density, influencing the variations in the level of the sea surface with respect to the geoid. In this regard, the impact of SLR depends on the total net rise resulting from the relative vertical movements of the land and of the sea. In areas where that have natural eustatic uplifting of the land derived by tectonic plate movement, glacial rebound, and vulcanism, there will be little relative rise of sea level. On the other hand, in land areas that are naturally falling as in the southeastern USA, due to tectonic and compaction forces, impacts of sea level rise will be more important (IPCC, 1990). For example according Nerem *et al.* (2010) between 1993–2010, the standard deviation of regional trends based on satellite altimetry is as large as the global mean trend, with the highest rates of regional SLR having occurred in the western tropical Pacific.

Several studies have been conducted on SLR projection until the end of the century. Furthermore, Figure 4.1 below summarises SLR scenarios for 2100 proposed by some authors, IPCC assessment reports and NOAA (2017). The SLR projections values for 2100, ranges between 0.11 m given by IPCC (2001) to 3.45 m proposed by Hoffman *et al.* (1983). Notwithstanding, the variability minimum and maximum SLR values projected until the end of the century, in the last decade the extremes values are mostly higher than 1 meters. Hinkel *et al.* (2013) affirmed that with the SLR scenarios projected by the end of 21st century some 6.000 to 17.000 km^2 of beaches and land may be lost globally, leading to in about 1.6 to 5.3 million coastal inhabitants being forced to migrate with migration costs of US dollar 300-1000 billion.

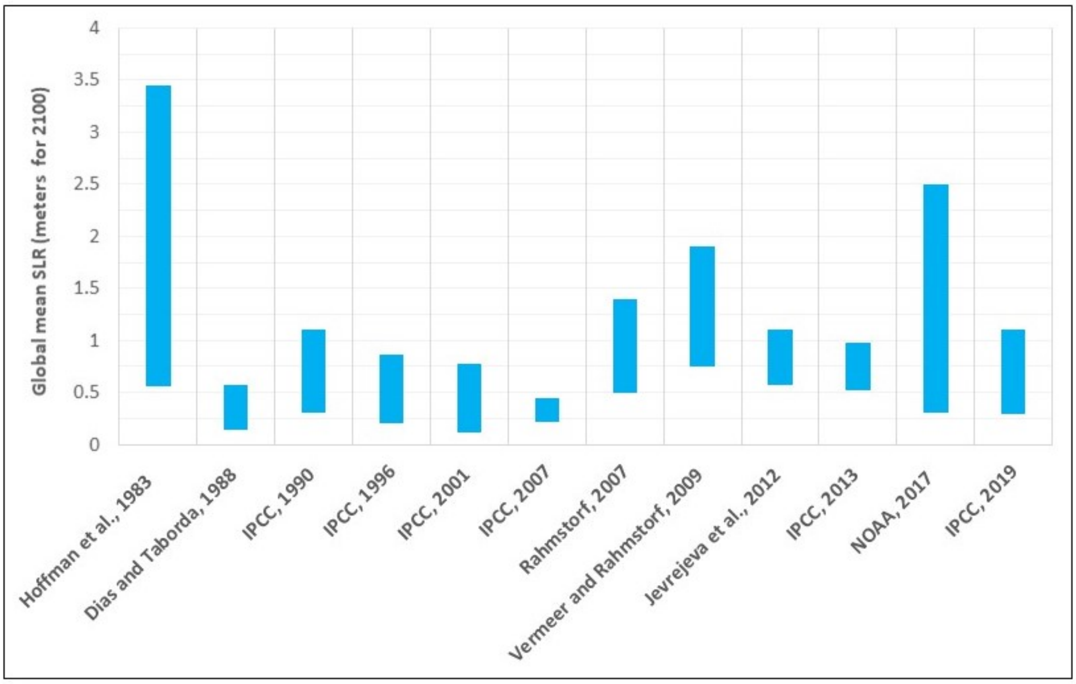


Figure 4.1: End of century (2100) estimates for global mean sea level rise in meters.

4.1.2 Wind

Global assessment of projected future climate change impacts on winds, have received little attention, although the potential for large geophysical and social impacts (McInnes *et al.*, 2011; Hemer *et al.*, 2013). Wind speed changes can affect: a) the viability of wind energy operations (Pryor *et al.*, 2006); b) wave climates and storm surges (Debernard and Roed, 2008); c) soil moisture, evaporation and water resources (McVicar *et al.*, 2008), that may influence the evolution of arid and semi-arid environments (Okin *et al.*, 2006). Also, changes in wind direction are relevant, namely in coastal regions, where they have an important role in hydrodynamic agents such as waves and storm surge cite (McInnes *et al.*, 2011). Changes to wind and wave climate therefore can affect sediment dynamics, shoreline processes and interferes with the sediment budget. (e.g. Aagaard *et al.*, 2004; Reguero *et al.*, 2013). Thus, McInnes *et al.* (2011) argue that littoral transport is sensitive to directional changes in wave climate due to wind direction changes. An example of this, is the research developed by Andrade *et al.* (2007), which concluded that erosion may increase on the Portuguese coast, because of a projected clockwise rotation of the wave climate by 2070–2099 relative to 1961–1990.

Projected wind changes for 2081–2100 relative to 1981–2000, reveals that wind speed increases across northern Europe and northern Africa, the South Pacific and Southern Ocean will can vary between 10 and 25°S (McInnes *et al.*, 2011).

At Boa Vista island, projected wind until 2100, will probably affect sedimentary transport, notably along the aeolian corridor located at the western side.

4.1.3 Waves

Wind generated ocean waves constitutes a relevant climate driver that can affect coastal environment (Mori *et al.*, 2010) and are key contributors to shoreline erosion, storm surge and coastal flooding (Ranasinghe, 2016; Sierra and Casas-Prat, 2014). In a climate change context, assessment of potential climate change–driven impacts on the coastal areas must consider potential future changes in wave conditions (Hemer *et al.*, 2012). Changes in ocean wave heights are mainly induced by changes in surface winds, because ocean surface waves are originated by surface winds locally or remotely (Wang *et al.*, 2014). There is an increasing evidence for changes in ocean waves over past decades (Young *et al.*, 2011). These changes have been attributable to external forcing, namely natural and anthropogenic factors (Wang *et al.*, 2009).

There is very limited information on ocean wave behaviour in response to climate change (Silva *et al.*, 2019). Although, the magnitude of the expected changes in wave parameters is small, there is no consensus in signal (Perez *et al.*, 2015; Wang *et al.*, 2014).

According to Camus *et al.* (2017), projected waves (by 2070–2100 relative to the period 1979–2005 for the RCP 8.5 scenario) increases are mainly limited to Southern Hemisphere midlatitudes and eastern Tropical Pacific (0.06 – 0.09 meters) and Southern Ocean (with values higher than 0.3 meters). The projected waves increases in Southern Ocean is detected by Hemer *et al.* (2013) too.

Adaptation and mitigation strategies established to respond the potential impacts of climate-induced changes on the coastal and open-ocean environments required the high levels of confidence in wave-climate projections (height, length and directions) (Morim *et al.*, 2018).

4.1.4 Sediment source

The main sediment source at Boa Vista island is marine biogenic particles (Figures 3.6 and 3.10), constituted mainly by bivalve shells, rhodoliths and corals fragments. In a climate change context, marine organisms will be affected by ocean acidification (OA), caused by ocean uptake of CO_2 (Fabry *et al.*, 2008; Doney *et al.*, 2009; Caldeira and Wickett, 2003; Broecker and Clark, 2001; Orr *et al.*, 2005).This phenomenon is a consequence of rising levels of anthropogenic CO_2 concentrations in the atmosphere, resulting in a gradual acidification of seawater (Broecker and Clark, 2001; Roleda et al., 2015). When CO_2 reacts with seawater it forms carbonic acid (H_2CO_3), which is highly reactive and reduce seawater pH, reduces the concentration of carbonate ion ($CO_3{}^{2-}$) and consequently reduces the availability of aragonite, important source of $CaCO_3$ (Orr *et al.*, 2005 ; Rafferty *et al.*, 2014). This, can affect shell formation for marine animals such as corals, plankton and shellfish (Rhein *et al.*, 2013). In fact, OA could cause wide-ranging effects to marine ecosystems, by affecting individual organisms at all trophic levels, from bacteria to fish, and therefore ecosystem functioning (Moya *et al.*, 2012; Rhein *et al.*, 2013; Haigh et al., 2015; Fabry *et al.*, 2008).

Caldeira and Wickett (2003) suggest that future atmospheric and oceanic CO_2 concentrations indicate that, by the end of this century, the average surface ocean pH could be lower than it has been for more than 50 million years. Marine scientists expect that coral, shellfish, and other marine calcifiers (organisms that use carbonates) will be less able to obtain the raw materials that they use to build and maintain their skeletons and shells in coming decades (Doney *et al.*, 2009; Rhein *et al.*, 2013; Fabry *et al.*, 2008; Rafferty *et al.*, 2014). Indeed, according Orr *et al.* (2005) the changes in seawater chemistry projected to occur during this century could have severe consequences for calcifying organisms, particularly shelled pteropods: the major planktonic producers of aragonite.

Orr *et al.* (2005) developed 13 models of the ocean–carbon cycle to assess calcium carbonate saturation under the IPCC IS92a 'business-as-usual' scenario for future emissions of anthropogenic CO_2. They concluded that Southern Ocean surface waters will begin to become undersaturated with respect to aragonite by the year 2050. By 2100, this undersaturation could extend throughout the entire Southern Ocean and into the subarctic Pacific Ocean (Feely *et al.*, 2009; Orr *et al.*, 2005).

The consequences of ocean acidification on marine organisms at Boa Vista island, will certainly affect sedimentary supply along coastal areas, with consequences for the coastal and marine ecosystem. However, present knowledge is still limited and does not allow to support a quantitative model of change in related to the reference situation as displayed in Figure 3.13.

4.2 Coastline Projections under Sea Level Rise Scenario

According to all drivers mentioned above, SLR constitutes the only one that is possible to support a quantitative model of change. Considering the similarity between local and global sea level records, sea level scenarios at Boa Vista island were based upon global projections until the end of the 21st century.

The coastal evolution projected under to the SRL was performed based on the same methods used on subsection 3.3.3 (Bruun (1954) theory; and Taborda and Ribeiro (2015) model), using 3 (three) representative scenarios presented and recommended for coastal planning and risk management by US National Oceanic and Atmospheric Administration (NOAA, 2017) (Figure 4.1) for the end of the century. These representative scenarios correspond to Global Mean Sea Level (GMSL) rise by 2100, of 0.3 m; 1.0 m and 2.5 m that correspond to Low, Intermediate and Extreme scenarios, respectively. The environments (**ENV**) used in this analysis, were described in section 1.4.3 (see Figure 1.3 and Table 1.1).

According to Table 4.1 in the Low scenario of NOAA, the projected values of coastal evolution show a total retreat of 13 m for $\mathbf{ENV_1}$ (sand shore) and a total retreat of 6 m for $\mathbf{ENV_2}$ to $\mathbf{ENV_4}$ (environments with intertidal beach). For environments $\mathbf{ENV_2}$ to $\mathbf{ENV_4}$ (without intertidal beach) was not possible to calculate the total retreat.

In a NOAA Extreme scenario, $\mathbf{ENV_1}$ indicates a total retreat of 111 m and subtidal beach show a total retreat of 50 m (Table 4.2). In that sense, SLR exceed sedimentary balance only in NOAA Extreme scenario.

Table 4.3 show the coastal evolution in a representative NOAA scenarios for Ponta Varandinha to Ponta Pesqueiro Grande coastal section (Figure 4.2 - B) (stretch that displayed relevant coastal progradation) for 2100. In a recent coastal evolution, this stretch exhibit more accretion (37 m) than could be explained by SLR (-5 m). At a projected NOAA scenarios, assuming that wind, waves and sediment source will keep stable, SLR exceed sedimentary budget along the entire island only in Extreme scenario.

Regarding coastal evolution scenarios for other Boa Vista coastal sections for 2100 (Figure 4.2 - A), SLR induced retreat exceed sedimentary budget (whose signal estimated using the spectral average evolution is marginal) in recent and in all NOAA representative scenarios (Table 4.4).

In a coastal section without beaches, as there are no reliable information on average coastal slope it was not possible to compute the SLR induced coastal retreat.

Table 4.1: Projected coastal evolution considering NOAA-0.3m (Low scenario) SLR scenario (see sub-chapter 1.4.3 for coastal environment definitions)

Environments (**ENV**)	Average beach slope	Total retreat (m)
ENV$_1$ (sandy shore)	0.0225	13
ENV$_2$ to **ENV$_4$** with intertidal beach	0.05	6
ENV$_2$ to **ENV$_4$** without intertidal beach	0 - ∞	?

Table 4.2: Projected values of coastal evolution due to SLR (NOAA-2.5m) at Boa Vista island for 2100.

Environment (**ENV**)	Average beach slope	Total retreat (m)
ENV$_1$ (sandy shore)	0.0225	111
Subtidal beach	0.05	50

Table 4.3: Coastal evolution scenarios for Ponta Varandinha to Ponta Pesqueiro Grande section for 2100 .

	NOAA Scenarios	Net (m)	Sediment Budget Component (m)	SLR Component (m)
Recent (1968 - 2010)		32	37	-5
Projected (2019 - 2100)	Low	48	61	-13
	Intermediate	17	61	-44
	Extreme	-50	61	-111

Table 4.4: Coastal evolution scenarios for Boa Vista coastal sections for 2100 (see Figure 4.2)
.

	NOAA Scenarios	Net (m)	Sediment Budget Component (m)	SLR Component (m)
Recent (1968 - 2010)		-3	-1	-2
Projected (2019 - 2100)	Low	-8	-2	-6
	Intermediate	-22	-2	-20
	Extreme	-52	-2	-50

Flooded coastal areas projection was performed using a Digital Terrain Model (DTM), that presents a very limited resolution. The DTM resolution (5 m) used here, no allows to make a quantitative assessment of flooded areas under SLR impacts. In a preliminary comparison with expected SLR, it was possible to deduce the most vulnerable areas. Results represented in Figure 4.3 show that Sal Rei City constitute one of the more vulnerable areas. The other areas, namely the southern areas as they are morphodynamically active, it is difficult to assess the real SLR impacts.

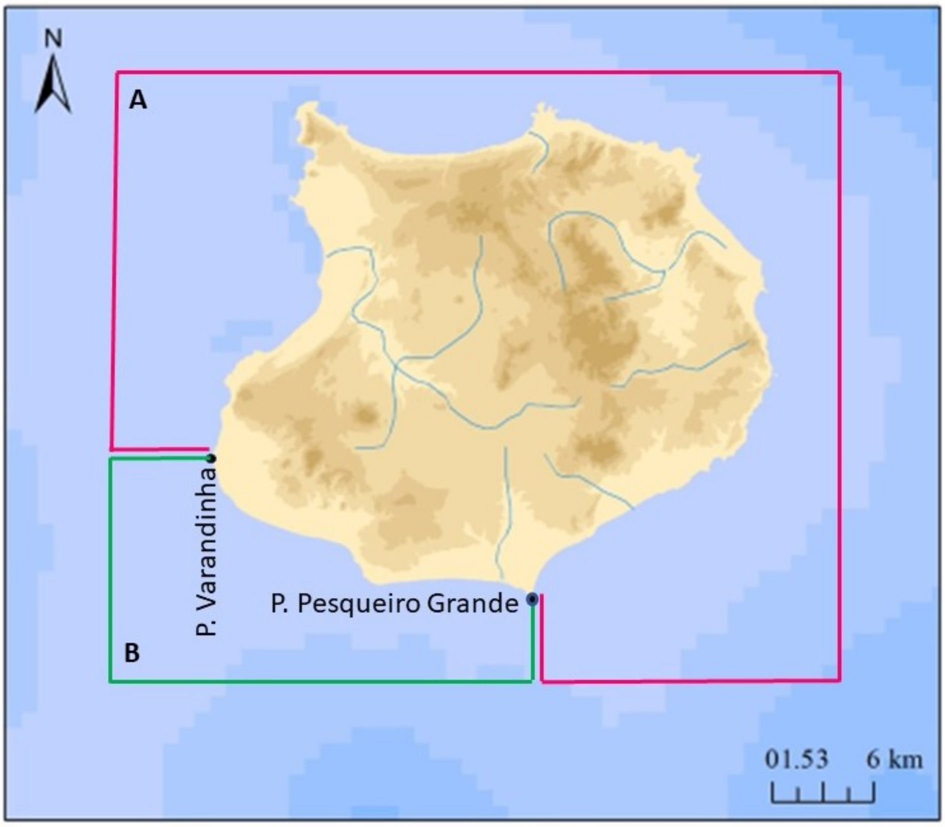


Figure 4.2: Segmentation of Boa Vista coast according to recent evolution: A - stable coast; B - a creating coast .

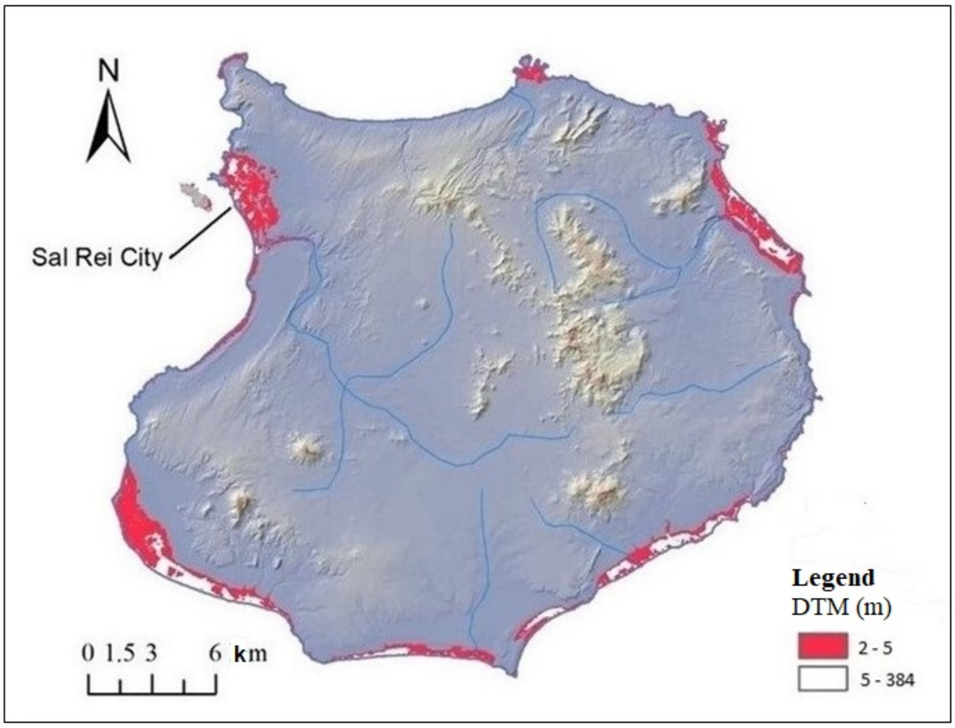


Figure 4.3: Areas prune to coastal flood by the End of century (2100) under SLR 2 m to 5 m using DTM. Results should be consider preliminary due to low resolution of DTM model used.

4.3 Main achievements

In this chapter scenarios of coastal change of Boa Vista island under climate change were developed, highlighting the main coastal evolution drivers (Figure 4.4). The main achievements are summarised below:

1. Sea level rise, Wind, Waves and Sediment source are the main drivers of coastal change;

2. Sea level rise will be probably the driver that willmost influence futur coastal change;

3. With present state of knowledge is not possible to develop a quantitative model does not allow projecting the sedimentary source evolution;

4. DTM resolution (5 m) no allows to make a quantitative assessment of flooded areas under SLR impacts. Flooded coastal areas projection using DTM, reveal that Boa Vista island present flooded coastal areas along entire island. Sal Rei City constitute the most flooded area;

5. In a Extreme scenario of NOAA (2.5m), coastal evolution projected indicates that SLR exceed sedimentary budget, including Ponta Varandinha to Ponta Pesqueiro Grande sector. Others Boa Vista coastal areas sections, show a retreat in recent and in all NOAA representative scenarios projected under SLR;

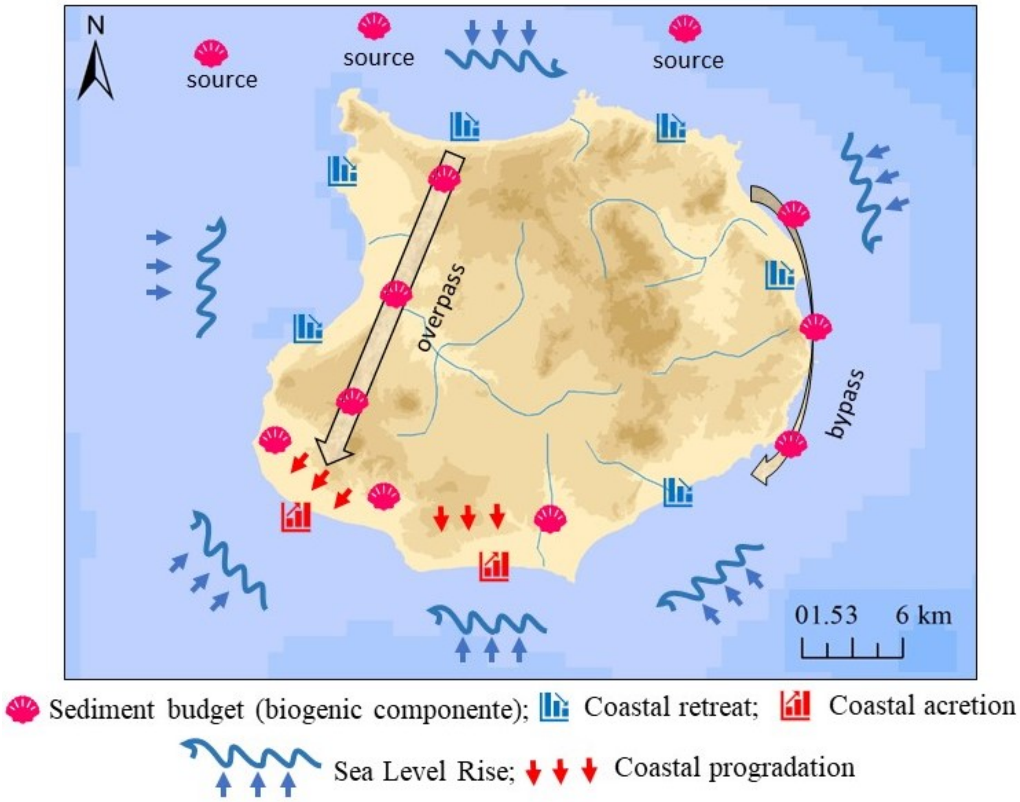


Figure 4.4: Main Drivers (sedmentary balance and SLR) of Boa Vista Coastal Evolution.

Chapter 5

Coastal Risk Under a Climate Change Scenario

5.1 Introduction

The previous chapters have shown a recent coastal evolution at a decadal time-scale, in which the sedimentary balance is a key driver responsible for the coastal configuration observed now. Projecting the coastal evolution until the end of the century (2100) show the increasing importance of the SLR component.

Many islands have a remarkable diversity of landscapes, ecosystems and species. In fact, islands face risks from both climate-related hazards that have occurred for centuries, as well as new risks from climate change, which pose a significant exposure to these islands (Sauter *et al.*, 2013; Nurse *et al.*, 2014). Climate risk constitute a particular challenge to islands, because as their pressure absorption capacity and territorial redeployment abilities are usually lower than on the mainland (Sauter *et al.*, 2013).

According to IPCC, **risk** "*is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur.*" and **risk assessment** "*is the qualitative and/or quantitative scientific estimation of risks.*"(IPCC, 2014b, p.1772).

Nurse *et al.* (2014) claims that on islands the key risks of climate change are: loss of livelihoods, coastal settlements, infrastructure, ecosystem services and economic stability, decline and possible loss of coral reef and interaction of rising global mean sea level in the 21^{st} century with high-water-level events will threaten low-lying coastal areas. Comparatively to other areas, small islands are disproportionately affected by current hydro-meteorological extreme events, both in terms of the percentage of the population affected and losses as a percentage of GDP (Anthoff *et al.*, 2010). In a climate change context, the risks of damage and associated losses are expected to continue to rise (Nicholls and Cazenave, 2010). Adaptation to climate change and risk assessment aims to reducing exposure and vulnerability and increasing resilience to the potential adverse impacts of climate change, even though risks cannot fully be eliminated (IPCC, 2012b).

5.2 Key Components of Risk

Risk results from the interaction of: a) hazards, the climatic events; b) exposure and c) vulnerability to these hazards (Cardona *et al.*, 2012; IPCC, 2014b). Also, hazard refers to the possible, future occurrence of natural or human-induced physical events that may have adverse effects on vulnerable and exposed elements (IPCC, 2014b; UNDHA, 1992; UNDRO, 1980).

Hazard events can be partly determined by environmental degradation and human intervention in natural ecosystems (Lavell, 1996). Exposure refers to the inventory of elements in an area in which hazard events may occur (Cardona, 1990; IPCC, 2001). Impacts of extreme weather events depends heavily on the exposure and vulnerability level of particular areas to these extreme events (IPCC, 2012b, p.10).

Vulnerability refers to the propensity of exposed elements such as human beings, their livelihoods, and assets to suffer adverse effects when impacted by hazard events (Cardona, 1990; IPCC, 2001; UNDRO, 1980).

Exposure and vulnerability are dynamic, depending on the temporal and spatial scales of economic, social, geographical, demographic, cultural, institutional, governance and environmental factors (IPCC, 2012b, p.7).

Although there is often confusion between exposure and vulnerability, they are distinct. Thus, according to Cardona *et al.* (2012) exposure is a necessary but not sufficient risk determinant. It is possible to be exposed but not vulnerable (e.g. living on a floodplain, but with sufficient means to modify the structure and behaviour of the building in order to mitigate the potential loss). However, to be vulnerable to an extreme event, it is also necessary to be exposed. Figure 5.1, below summarise the relationship existent among key risk determinants described above, identified in the study area from this work.

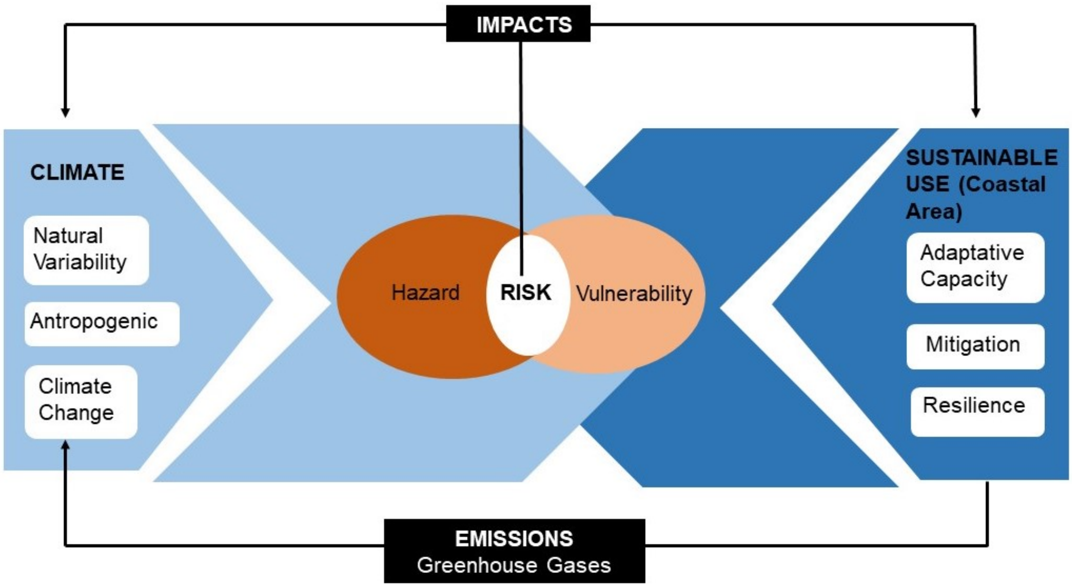


Figure 5.1: Scheme of the interaction among the physical climate system, hazard and vulnerability producing risk in study area . Source: Adapted from IPCC (2012b) and Oppenheimer *et al.* (2014).

5.3 Evolution of Coastal Risk

Coastal areas have a range of socio-economic activities relevant to the country's economy. These activities includes, among other, tourism and recreation, exploitation of living and non-living resources and nature conservation (Bijlsma *et al.*, 1996). Urban expansion on the coastal area and unsustainable use of marine resources can induce environmental degradation and hazard vulnerability (Dey *et al.*, 2002; Mills *et al.*, 2005). Development, sustainable management, and safe occupation of coastal areas require an understanding of natural coastal hazards and how they influenced human activity (Solomon and Forbes, 1999).

Boa Vista island is the least populated island of the archipelago (Sánchez-Cañizares and Castillo-Canalejo, 2014), with only 3% (16.620 inhabitants in 2017) of the total population of the country (537.231 inhabitants in 2017) (IMC, 2017).

According to Table 5.1, between 1960 and 2000, Boa Vista population has gradually increased. However, between 2000 (4206 inhabitants) and 2010 (9162 inhabitants) the population has more than doubled. This growth has been mainly driven by tourism (Aguilera *et al.*, 2018), due to the tourist dynamics, mainly tourist investments that promote the internal and external migration flow (mainly people from mainland Africa) originated an increase in the supply of jobs and better living conditions (Lima, 2012).

Boa Vista is the second most important Cabo Verde island in terms of tourism, with a strong increase in the last two decades (Eusébio *et al.*, 2018). Between 2000 and 2017, the number of guests has wondrously increased from 9.402 to 206.614, respectively, an very high growth more than 20 times (Figure 5.2) (INE-CV, 2018). This phenomenon started in 2007 (Figure 5.2) with the construction of Boa Vista International Airport (Lima, 2012). Tourism plays an important role in islands, because it provides a dynamic model for economic growth and is the largest contributor to the country's Gross National

Product (GNP), (Bijlsma *et al.*, 1996; Holzner, 2011; Schubert *et al.*, 2011).

Table 5.1: Population evolution of Boa Vista island from 1960 until 2010. Source: INE-CV (2010).

Year	1960	1970	1980	1990	2000	2010
Population	3263	3569	3372	3452	4193	9162

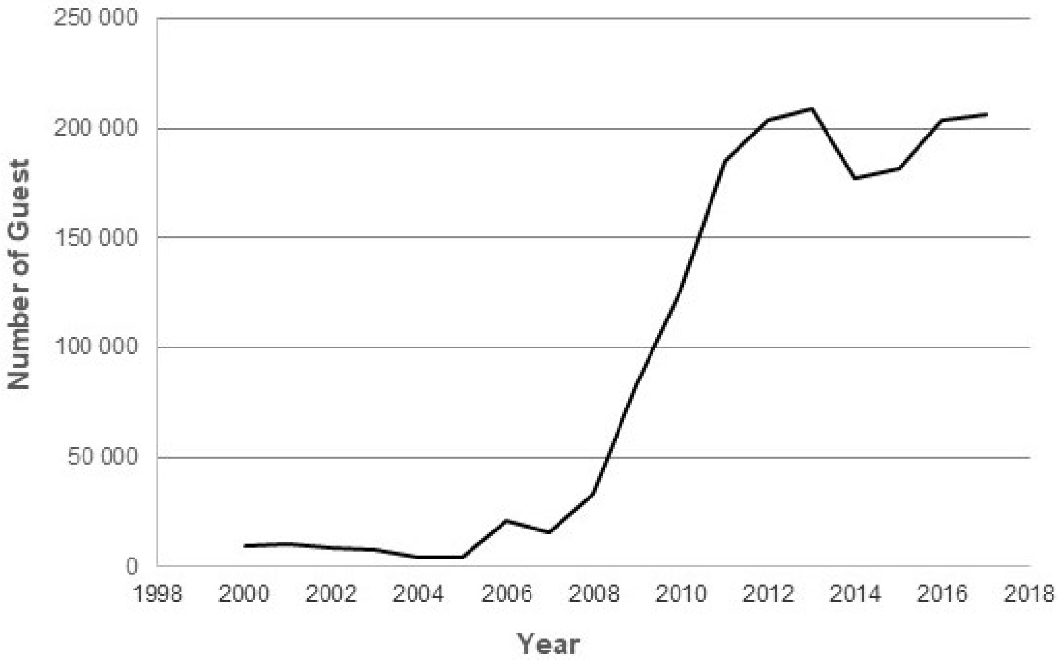


Figure 5.2: Guest evolution between 2000 and 2017 at Boa Vista island. Source: INE-CV (2018).

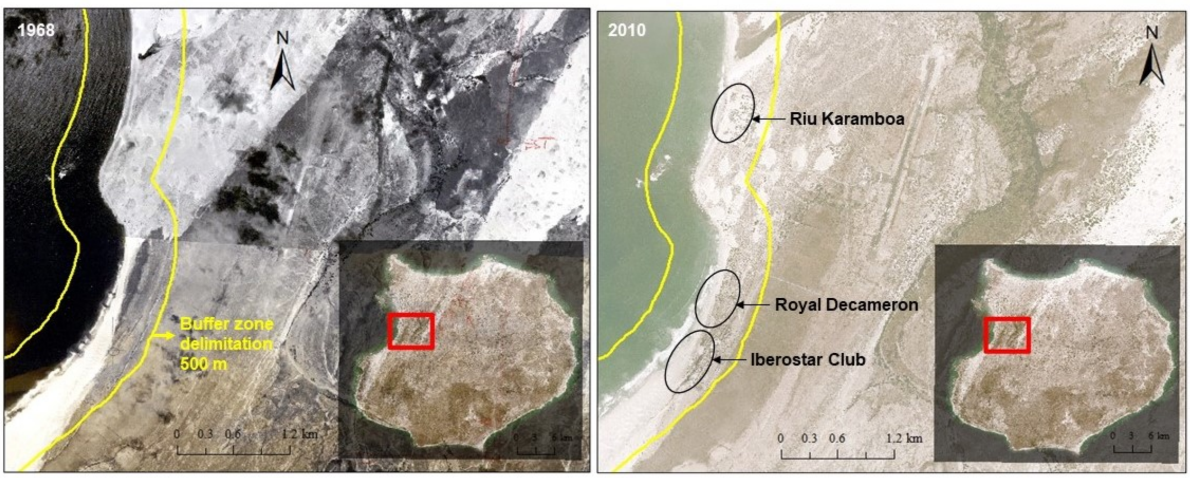


Figure 5.3: Example of evolution of increase in the exposure assets at Boa Vista coastal areas between 1968 (left) and 2010 (right).

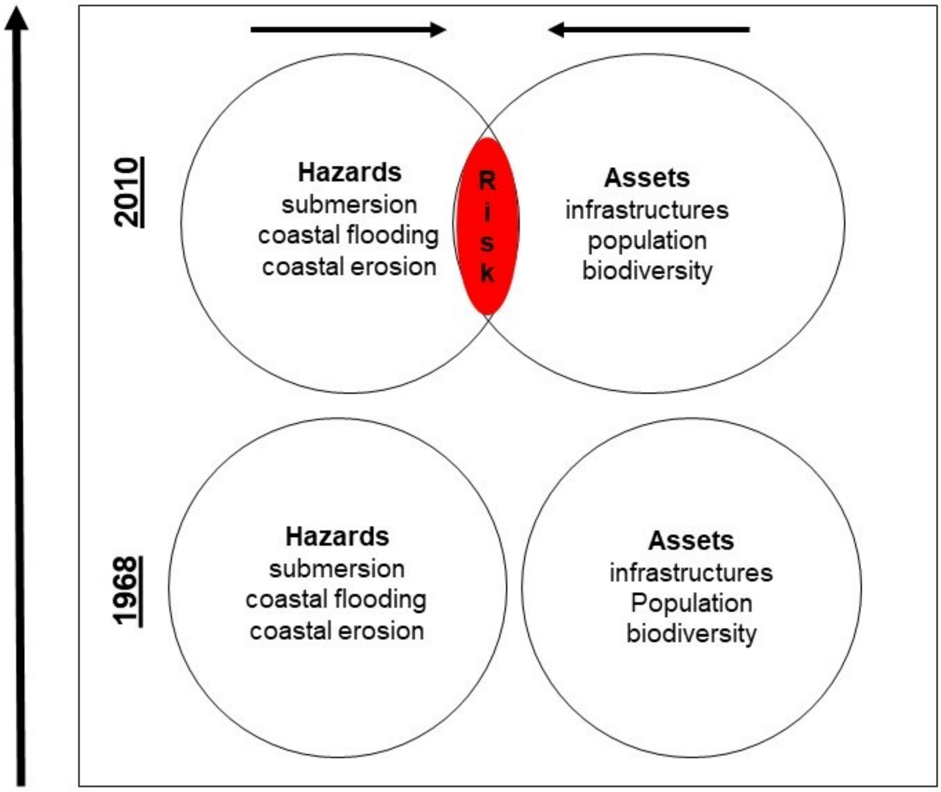


Figure 5.4: Simplified model of risk increase due to coastal developement.

Figures 5.3 and 5.4 display the coastal assets evolution between Carlota Beach and Chave Beach (see Figure 2.2) from 1968 until 2010. The assets indicated in Figure 5.4 represents a part of the coastal vulnerability. According to these figures, in 1968 in this coastal stretch no tourism infrastructures existed while 2010 some tourism infrastructure are observed. Therefore, this support Sillitoe (2009) affirmation that in recent years, Boa Vista island has exhibited a highest rate grown of tourism and it has happened in an unsustainable way, with several environment negative impacts, for example:

1. The legally established distance of 80 meters from the coast is frequently ignored and constructions are carried out within that area;

   Cabo Verde has a Law (Law nº 44/VI/2004, de 12 de Julho, artigo 3º, alínea e) that establishes delimitation of maritime public domain assets: "*the seafront, including beaches and lands of coasts, inlet, contiguous bays of maximum high water line in a 80 meters wide buffer zone*". According to the Law above, private buildings will be away, at least, 80 meters from the high water line. In Figure 5.6 is put in evidence a touristic enterprise at a distance of about 56 meters from the coastal high water line. In this sense, it is a non-compliance with the law, which is in-line with one of the several negative impacts of tourism at Boa Vista island referred by Sillitoe (2009).

2. The continuous evolution of tourism-related constructions along the Boa Vista coastline and Integrated Tourist Development Zone (ZDTI, portuguese acronym) proposals are environmentally and socially detrimental and ultimately inhibit the development of a tourism industry, rendering it

unattractive to visitors , limiting access and overlooking the beach and the sea;

3. The natural sea barrier is destroyed, damaged or impaired (dune systems, coral reefs);

4. The natural nourishment of the beach and dunes is impaired;

5. Environmentally harmful tourism activities are provoked by motorbikes on beaches and dunes, with harmful consequences for dune vegetation, leading to their destruction and destabilization of this ecosystem. This practice has a negative consequences for sea turtles, especially in the nesting season, destroying their nests. Besides that, it also destroy nests of shorebirds that use dune vegetation to nest.

Additionally, to the environmental impacts above-mentioned, the occupation of coastal areas at Boa Vista island as an unsustainable way, could constitutes a risk factor for the exposed elements (e.g. infrastructures, population and biodiversity) (Figures 5.4, 5.5 and 5.6), in a climate change context (namely with SLR) notably coastal erosion and coastal flood (see Figure 4.3) .

Figure 5.5: Sal Rei City.

Figure 5.6: Example of risk coastal area infrastructures.

5.4 Strategies for Coastal Adaptation

According to Santos *et al.* (2017) coastal zones constitute a complex adaptive system comprising two components: human systems (e.g. built heritage, human activities, coastal zones management and governance) and natural systems (e.g. diversity of geological formations and ecosystems) that interact amongst themselves.

Since the Second Assessment Report (SAR) publication in 1996, significant barriers to climate change adaptation strategies in island settings have been discussed in considerable detail (Nurse *et al.*, 2014). According (Sovacool, 2012), this barriers include: i) inadequate access to financial, technological, and human resources; ii) issues related to cultural and social acceptability to counter measures; iii) constraints imposed by the existing political and legal framework; iv) the emphasis on island development as opposed to sustainability; v) a tendency to focus on addressing short-term climate variability rather than long-term climate change; and vi) community preferences for “hard” adaptation measures such as seawalls instead of “soft” measures such as beach nourishment. Notwithstanding, there exist several ways about climate adaptation that can be undertaken *in situ*, namely reducing socio-economic vulnerabilities, building adaptive capacity, enhancing disaster risk reduction, or building longer term climate resilience (e.g. McGray *et al.*, 2007; Eakin *et al.*, 2009).

One of the most appropriate climate change adaptation strategy for small islands is community-based adaptation (CBA) principles to island communities, with purpose to facilitate adaptation planning and implementation (e.g. Warrick, 2009; Kelman *et al.*, 2011)

According Nurse *et al.* (2014) there is a lack of information on quantitative climate risk assessments for many small islands, which require that the future adaptation decisions will rely on responses to past and present climatic extremes and climate variability, or assumed/hypothetical impacts of climate change based on type of island.

5.4.1 Review of Boa Vista island Coastal Management Tools

As stated before, Cabo Verde is highly vulnerable to climate change, with a low capacity to adapt (Moreira and Shikui, 2014). There is a growing body of literature that discusses the benefits and possibilities of mainstreaming or integrating climate change policies in development plans (Nurse *et al.*, 2014).

Territorial management, is a tool for spatial coordination and integration in several sectoral policies. Furthermore, it plays a key role in reducing vulnerabilities of territories to the climate dynamics effects, either through mitigation or adaptation measures aimed at reducing exposure to risk and reinforce the resilience of territorial systems in a serious accidents (Campos and Mourão, 2012). Additionally, local action to reduce existing stress on island people and ecosystems is a critical part of enhancing resilience (Finucane *et al.*, 2012). Additionaly, research and long-term monitoring are a sustained assessment process. Moreover, public engagement in the development of useful information will enhance Islanders' ability to address the climate challenges (Finucane *et al.*, 2012).

Climate change items included in coastal management laws in Cabo Verde and Boa Vista island are as follows: there is no coastal planning plan (namely POOC, portuguese acronym), although it exists a regulation on the elaboration process and implementation for coastal and adjacent sea planing (POOC-M, portuguese acronym)(Decree-Law no. 14/2016 of 1^{st} March 2016). Examining this Decree-Law, it does not mentions climate change issues, only refers that is prohibited to construct on "areas at risk of advance of sea water" (ANNEX I, number 1 line g).

In general, climate change policies in Cape Verde related on coastal areas has been focusing mainly on plans/programs and projects developed and implemented at national/local level, often in compliance with international obligations. For example, the National Adaptation Program to Climate Change (2008-2012), Intended Nationally Determined Contribution (INDC, 2015), Sectoral Studies, Vulnerability and Adaptation to Climate Change in Cabo Verde (Fragoso, 2007).

Taking into account the Cabo Verde archipelagic nature with fragile and vulnerable ecosystems, integration of the climate change issues in all policies related to territory planning and management, namely on the coastal areas, constitutes an added value in increasing climate change adaptive capacity and resilience.

Bearing in mind that Cabo Verde has no POOC-M yet, it is prudent to recommended:

1. One POOC-M per island;
2. Promote all stakeholders participation on POOC-M elaboration and implementation fase;
3. Special attention should be given to low-lying islands, namely Sal, Boa Vista and Maio, with regard to their vulnerability to climate change, namely sea level rise;
4. Increased awareness and public education on climate change issues;
5. Research and long-term low-lying coastal areas monitoring to minimize the unsustainable use on this environment.

Finally, this work demonstrates that Boa Vista island present a peculiar behaviour related to coastal evolution, namely in the south stretch. So, the sketch provided in Figure 5.7 elaborated by Barwell (2011), gives a graphical illustration of how all the different components are combined when setting the coastal setback line, which may be included in the Boa Vista island POOC-M, as the existence of a buffer area for wind blown sand is essential for maintain the sediment budget across the island. Moreover, the inclusion of buffer areas for aesthetics, biodiversity, heritage, etc, reasons is very important measure to assure the sustainability of coastal areas and preserve the tourist potential of the island.

5.5 Main achievements

In this chapter a coastal risk assessment under a climate change scenario was discussed. The main achievements are summarised below:

1. Boa Vista island present a strong increase in tourism essentially on the coastal area during the last two decades ;
2. The highest rate grown of tourism at Boa Vista island has happened in an unsustainable way, with several environment negative impacts, namely in biodiversity, and dunar and beach systems;
3. Use the community-based adaptation as one of the most appropriate climate change adaptation strategy;
4. Its urgent the preparation and implementation of the POOC-M to promote the sustainable use of coastal areas on the Boa Vista island. The development of these plans should incorporate the specificity of Boa Vista Coastal dynamics.

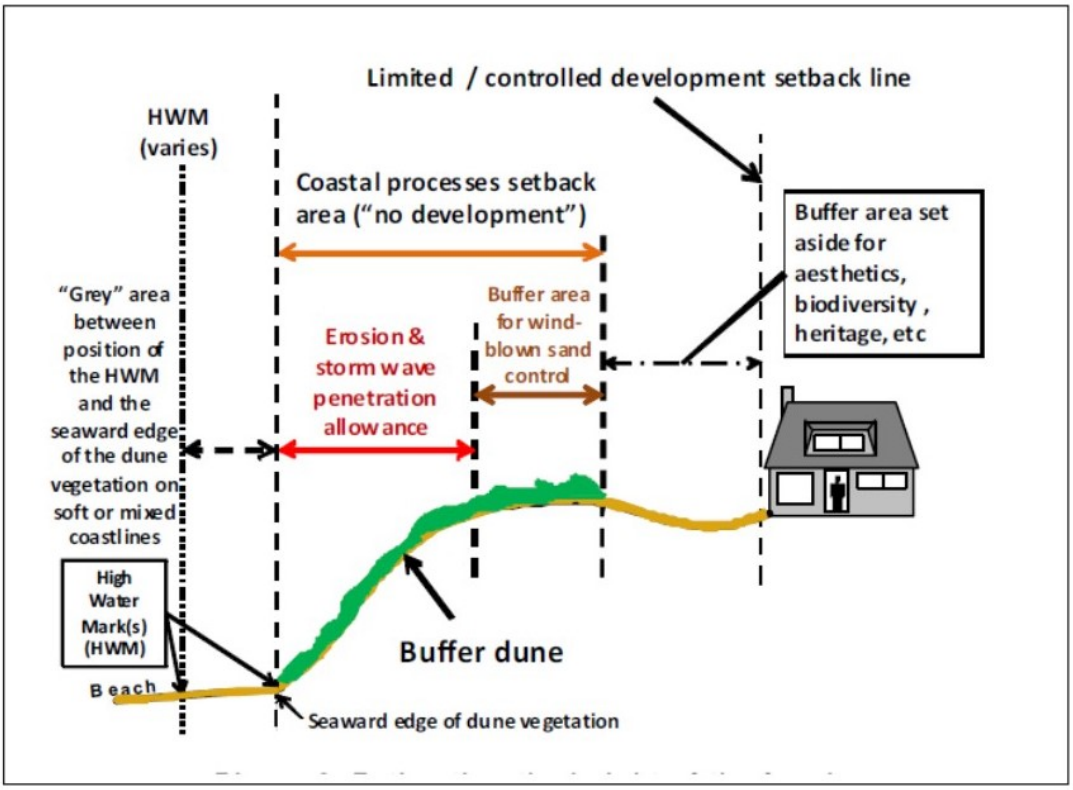


Figure 5.7: How all different components are combined in setting the coastal setback line (Barwell, 2011).

Chapter 6

Conclusion

In this thesis a profile of climate change impacts on coastal area evolution of Boa Vista island was developed. Boa Vista has a relatively low-lying morphology island and is considered one of the most vulnerable islands of Cabo Verde to climate change. Notwithstanding, Boa Vista island is the second most important island in terms of sun and sand tourism that assumes critical relevance in Cabo Verde, generating about 44,9% GDP. The following paragraphs summarise the major findings of this work and address the future direction of research on Boa Vista island.

6.1 Main Achievements

The research conducted contributed to improve the understanding of coastal evolution along the entire low-lying Boa Vista island, based on a comprehensive collection of aerial photographs and orthophotos maps with different spatial and spectral resolutions.

The major findings of this work is related to the fact that the recent (1968 to 2010) Boa Vista coastal area evolution was controlled only by the sedimentary budget, with a spatially averaged coastline and shoreline evolution of 0.48 m year^{-1} and 0.18 m year^{-1}, respectively. Moreover, in a long-term coastal evolution assessment, coastline was found to be a more consistent indicator, as the shoreline is more prone to errors related to wave and tide variability and is also affected by short-term variability such as beach rotation or beach cross-shore changes.

Additionally, during the studied time-window of observation (1968-2010), most of Boa Vista coastal evolution revealed a fairly stable behaviour, with a noticeable accretion trend only recognized at south-southwest sides of the island. To identify the key factor that induced this coastal evolution, research to understand the key drivers of change was conducted. In that sense, it was possible to identify two different sediment transport process across the island: a) on the eastern side, the north south sediment transport is dominated by headland bypassing; b) on the western side, the sediment is mostly transported along the aeolian corridor by overpass (dune corridor) transport. This phenomenon is supported by sediment composition and texture (mainly biogenics and fine sand present along aeolian corridor), and island morphological relationships, where the western side presenting a flatter planar morphology.

The sediments transported by the two-transport processes above mentioned converge to the southern coast (between Ponta Varandinha and Ponta Pesqueiro Grande) where sediment accumulation is translated on long-term coastline progradation, reflecting its character as the major sedimentary sink of Boa Vista island with total of 148 $\times$ 10^3 m^3 $year^{-1}$.

Island-scale observations conducted in this work, permit to capture the sedimentary connections between beach systems, that often control rate of coastal evolution.

Regarding to coastal evolution projected for 2100, using NOAA representative scenario under SLR, in all coastal areas except Ponta Varandinha to Ponta Pesqueiro Grande sector of Boa Vista island, SLR exceed sedimentary budget. At Ponta Varandinha to Ponta Pesqueiro Grande sector, SLR exceed sedimentary budget only in Extreme SLR scenario. Therefore, Boa Vista flooded coastal areas by SLR projected until the end of century (2100) using DTM, reveal that Sal Rei City constitute the area most prune to flooding.

Finally, it was shown that to avoid negative impacts of climate change context, required a strong strategies policies for coastal adaptation. Thus, research, continued monitoring, a sustained assessment process, and public engagement in the development of useful information will enhance ability to address the climate challenges.

Having in consideration the results obtained and taking into account the relevance of Boa Vista island on sun and sand tourism in terms of economic revenue at national level, it is necessary to highlight the vulnerability of the sedimentary links between coastal and dune systems, and therefore there is an absolute need to avoid the creation of any physical obstacles to sediment transport that can put in peril the delicate coastal equilibrium.

6.2 Outlook

Measure coastal evolution based on coastline and shoreline indicators was developed in chapter 2. Seeing that shoreline is more prone to errors related to wave and tide variability and is also affected by short-term variability such as beach rotation or beach cross-shore changes, we suggested that future research conducts detailed analysis on the shoreline indicator, with the aim to clarify the role of this indicator on the coastal evolution of the study area. This study is important to evaluated coastal response to change in wave climate.

Drivers of change was addressed on chapter 3, here efforts should be made in the future to measure the wind action to obtain a better understanding of change in magnitude and direction. Still, in the same chapter was estimated the sediment sink quantification, so future work in this regard would be of great value.

Still on chapter 3, textural and compositional analysis was conducted. Thus, efforts should be made in the future to study bioclast content on the continental shelf that is the main feeder of sediments to Boa Vista coastal area. Understanding the effects of climate change in the source of biogenic particles of utmost important to understand future changes in the sedimentary budget, which, in this work, was considered. This change include the response of the source organisms to change in sea water temperature and acidity. An analogous approach should be followed for terrigenous sediments.

On chapter 4, SLR Projection for 2100 and its effects on coastal evolution was presented. In the future, efforts should be made to better evaluate this driver impact.

References

Aagaard, T., Nielsen, J., Jensen, S.G. and Friderichsen, J. (2004). Longshore sediment transport and coastal erosion at Skallingen, Denmark. *Geografisk Tidsskrift-Danish Journal of Geography*, 104(1), 5-14. doi:10.1080/00167223.2004.10649499

Abu-Sbeih, M.Z. (2015). Approximating the Volume of Sand Dune. 1–10. https://blossoms.mit.edu/sites/default/files/video/transcript/transcript-sanddunes-eng.pdf

Adnan, F.A., Hamylton, S.M. and Woodroffe, C.D. (2016). A Comparison of Shoreline Changes Estimated Using the Base of Beach and Edge of Vegetation Line at North Keeling Island. *Journal of Coastal Research*, 75(1), 967-971. doi:10.2112/si75-194.1

Aguilera, M., Medina-Suárez, M., Pinós, J., Liria, A., López-Jurado, L.F. and Benejam, L. (2018). Assessing the effects of multiple off-road vehicle (ORVs) tyre ruts on seaward orientation of hatchling sea turtles: implications for conservation. *Journal of Coastal Conservation*, 23(1), 111-119. doi:10.1007/s11852-018-0641-x

Ahmad, S.R. and Lakhan, V.C. (2012). GIS-Based Analysis and Modeling of Coastline Advance and Retreat Along the Coast of Guyana. *Marine Geodesy*, 35(1), 1-15. doi:10.1080/01490419.2011.637851

Alesheikh, A.A., Ghorbanali, A. and Nouri, N. (2007). Coastline change detection using remote sensing. *International Journal of Environmental Science and Technology*, 4(1), 61-66. doi:10.1007/bf03325962.

Alesheikh, A.A., Ghorbani, A. and Talebzadeh, A. (2004). Generation the coastline map for Urmia Lake by TM and ETM + imagery. https://www.researchgate.net (available on 10th April 2019).

Alves, M.V.M. (2007). Detection of Physical Shoreline Indicators in an Object-Based Classification Approach: Study Case: Island of Schiermonnkoog. Enschede, The Netherlands: The International Institute for Geo-Information Science and Earth Observation, Master's thesis, 53p.

Andrade, C., Pires, H.O., Taborda, R. and Freitas, M.C. (2007). Projecting future changes in wave climate and coastal response in Portugal by the end of the 21st Century. *Journal of Coastal Research*, 50, 263–257.

Andreotti, B., Claudin, P. and Douady, S. (2002). Selection of dune shapes and velocities Part 1: Dynamics of sand, wind and barchans. *The European Physical Journal B - Condensed Matter*, 28(3), 321-339. doi:10.1140/epjb/e2002-00236-4

Anthoff, D., Nicholls, R.J. and Tol, R.S.J. (2010). The economic impact of substantial sea-level rise. *Mitigation and Adaptation Strategies for Global Change*, 15(4), 321-335.

Anthoff, D., Nicholls, R.J., Tol, R.S.J. and Vafeidis, A.T. (2006). Global and regional exposure to large rises in sealevel: a sensitivity analysis. Tyndall Centre for climate change. *Research Working* paper 96

Antunes, C. and Taborda, R. (2009). Sea Level at Cascais Tide Gauge: Data, Analysis and Results. *Journal of Coastal Research*, 2009(SI 56), 218–222.

Barwell, L. (2011). Integrity Assessment Procedure for Buffer Dune Systems on the Cape South Coast, South Africa. Faculty of Engineering, Stellenbosch University, Master of Science Thesis, 190p.

Bermúdez, R., Feng, Y., Roleda, M.Y., Tatters, A.O., Hutchins, D.A., Larsen, T., Boyd, P.W., Hurd, C.L., Riebesell, U. and Winder, M. (2015). Long-Term Conditioning to Elevated pCO2 and Warming Influences the Fatty and Amino Acid Composition of the Diatom Cylindrotheca fusiformis. *PLOS ONE*, 10(5), e0123945. doi:10.1371/journal.pone.0123945

Bijlsma, L., Ehler, C.N., Klein, R.J.T., Kulshrestha, S.M., McLean, R.F., Mimura, N., Nicholls, R.J., Nurse, L.A., Nieto, H. P., Stakhiv, E.Z., Turner, R.K., and Warrick, R.A. (1996). Coastal zones and small islands. In: Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change [Watson, R.T., Zinyowera, M.C. and R.H. Moss (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 289-324.

Bindoff, N.L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C.K., Talley, L.D. and Unnikrishnan, A. (2007). Observations: Oceanic Climate Change and Sea Level. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Blott, S.J. and Pye, K. (2001). Gradistat: A grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms* 26, 1237–1248. doi: 10.1002/esp.261

Boak, E.H. and Turner, I.L. (2005). Shoreline Definition and Detection: A Review. *Journal of Coastal Research*, 214, 688-703. doi:10.2112/03-0071.1

Bosnic, I., Cascalho, J., Taborda, R., Ribeiro, M., Oliveira, A., Rodrigues, A. and Lira C. (2011). Textural Characterization of the Beach Active Layer. *Journal of Coastal Research*, SI 64, 40-44.

Broecker, W., and Clark, E. (2001). A dramatic Atlantic dissolution event at the onset of the last glaciation. *Geochemistry, Geophysics, Geosystems*, 2(11). doi:10.1029/2001gc000185

Bruun, P. (1962). Sea-level rise as a cause of shore erosion. *Journal of the Waterways and Harbors Division*, 88, 117–130.

Bruun, P. (1954). Use of small-scale experiments with equilibrium profiles in studying actual problems and developing plans for coastal protection. *Transactions, American Geophysical Union*, 35(3), 445-452. doi:10.1029/tr035i003p00445

Cabo Verde Natura (2000). Planificación y Ordenación Sostenible del território y los Recursos Naturales del Litoral de Cabo Verde y de las Islas de Sal, Boavista y Maio (B7/6200/98-10/ENV/V111). Plan de Ordenación del Territorio y de los Recursos Naturales de la Isla de Boa Vista. Unidades Territoriales (Isla de Boa Vista). 23p.

Caldeira, K. and Wickett, M.E. (2003). Anthropogenic carbon and ocean pH. *Nature*, 425, 365–365.

Calvento, L.H., Jackson, D.W., Cooper, A. and Pérez-Chacón, E. (2017). Island-Encapsulating Eolian Sedimentary Systems of the Canary and Cape Verde Archipelagos. *Journal of Sedimentary Research*, 87(2), 117-125. doi:10.2110/jsr.2017.6

Campos, V., Mourão, J. (2012). Desenvolvimento de Sistemas Territoriais de Baixo Consumo Energético e Baixo Carbono. Uma perspectiva de investigação aplicada às metodologias de elaboração e avaliação dos planos de ordenamento do território. 12p.

Camus, P., Losada, I.J., Izaguirre, C., Espejo, A., Menéndez, M. and Pérez, J. (2017). Statistical wave climate projections for coastal impact assessments. *Earth's Future*, 5, 918–933. doi:10.1002/2017EF000609

Carapuço, M.M., Taborda, R., Silveira, T.M., Psuty, N.P., Andrade, C. and Freitas, M.C. (2016). Coastal geoindicators: Towards the establishment of a common framework for sandy coastal environments. *Earth-Science Reviews*, 154, 183-190. doi:10.1016/j.earscirev.2016.01.002.

Cardona, O.D., van Aalst, M.K., Birkmann, J., Fordham, M., McGregor, G., Perez, R., Pulwarty, R.S., Schipper, E.L.F., and Sinh, B.T. (2012). Determinants of risk: exposure and vulnerability. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M. and Midgley, P.M. (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 65-108.

Cardona, O.D. (1990). Terminología de Uso Común en Manejo de Riesgos. AGID Reporte No. 13, Escuela de Administración, Finanzas, y Tecnología, Medellín, Colombia. 587-593p.

Cazenave, A. and Llovel, W. (2010). Contemporary sea level rise. *Annual Review of Marine Science*, 2, 145-173.

Chon, J., Kim, H. and Lin, C. (2010). Seam-line determination for image mosaicking: A technique minimizing the maximum local mismatch and the global cost. ISPRS. *Journal of Photogrammetry and Remote Sensing*, 65(1), 86-92. doi:10.1016/j.isprsjprs.2009.09.001.

Church, J.A., Gregory, J.M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M.T., Qin, D., Woodworth, P.L. (2001). Changes in Sea Level. In: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K. and Johnson, C.A. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

Church, J.A and White, N.J. (2011). Sea-Level Rise from the Late 19th to the Early 21st Century. *Surveys in Geophysics*, 32(4-5), 585-602. doi:10.1007/s10712-011-9119-1.

Costa, F.L., Alves-da-Silva, A. and Ventura, J.E. (2011). Contributos de Geografia Física para a Gestão Integrada do Litoral da Ilha da Boa Vista, VI Congresso Planeamento e Gestão das Zonas Costeiras dos Países de Expressão Portuguesa, 1-13.

Crowell, M., Leatherman, S.P., and Buckley, M.K. (1991). Historical shoreline change: Error analysis and mapping accuracy. *Journal of Coastal Research*, 839–852.

Debernard, J.B. and Roed, L.P. (2008). Future wind, wave and storm surge climate in the Northern Seas: a revisit. *Tellus A*, 60(3), 427-438. doi:10.1111/j.1600-0870.2008.00312.x

Decreto-Lei nº 14/2016 de 1 de Março (2016). Regula a elaboração e implementação do POOC-M em Cabo Verde. Boletim Oficial da República de Cabo Verde, I Série, N.º 12, 1 de Março de 2016.

Del Río, L. and Gracia, F.J. (2013). Error determination in the photogrammetric assessment of shoreline changes. *Natural Hazards*, 65(3), 2385-2397. doi:10.1007/s11069-012-0407-y

Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., da Silva Dias, P.L., Wofsy, S.C. and Zhang, X. (2007). Couplings between changes in the climate system and biogeochemistry. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. and Miller, H. L.(eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 501–587.

Dey, S., Dutta, S. and Adak, S.B. (2002). Holocene sea level change of West Bengal Coast. *Indian Geographical Journal*, 77(1), 7–20

Di, K., Ma, R., Wang, J. and Li, R. (2003). Coastal mapping and change detection using high-resolution IKONOS satellite imagery. ACM International Conference Proceeding Series, Vol. 130, Proceedings of the 2003 annual national conference on digital government research, pp. 1-4. Boston, MA: Digital Government Society of North America.

Dias, J.A. and Taborda, R.P.M. (1988). Evolução Recente do Nível Médio do Mar em Portugal. *Anais do Instituto Hidrográfico*, 9, 83-97.

Dolan, R., Hayden, B.P., May, P. and May, S.K.(1980). The reliability of shoreline change measured from aerial photographs. *Shore and Beach*, 48, 22-29.

Doney, S.C., Fabry, V.J., Feely, R.A. and Kleypas, J. A. (2009). Ocean Acidification: The Other CO2 Problem. *Annual Review of Marine Science*, 1(1), 169-192. doi:10.1146/annurev.marine.010908.163834

Du, Q., Raksuntorn, N., Orduyilmaz, A. and Bruce, L.M. (2008). Automatic Registration and Mosaicking for Airborne Multispectral Image Sequences. *Photogrammetric Engineering and Remote Sensing*, 74 (2), 169-181. doi:10.14358/pers.74.2.169.

Eakin, C.M., Lough, J.M. and Heron, S.F. (2009). Climate variability and change: monitoring data and evidence for increased coral bleaching stress. In: Coral Bleaching: Patterns, Processes, Causes and Consequences [van Oppen, M.J.H. and J.M. Lough (eds.)]. Ecological Studies, Vol. 205, Springer-Verlag, Berlin, Germany, pp. 41-67.

Eijkelkamp (2008). Operating Instructions: 08.53 Calcimeter. Eijkelkamp, 6 p.

Ekercin, S. (2007). Coastline Change Assessment at the Aegean Sea Coasts in Turkey Using Multitemporal Landsat Imagery. *Journal of Coastal Research*, 233, 691-698. doi:10.2112/04-0398.1

Elbelrhiti, H., Andreotti, B. and Claudin, P. (2008). Barchan dune corridors: Field characterization and investigation of control parameters. *Journal of Geophysical Research*, 113(F2). doi:10.1029/2007jf000767

Eusébio, C., Vieira, A.L. and Lima, S. (2018). Place attachment, host–tourist interactions, and residents' attitudes towards tourism development: the case of Boa Vista Island in Cape Verde. *Journal of Sustainable Tourism*, 26(6), 890-909. doi: 10.1080/09669582.2018.1425695.

Evadzi, P.I., Zorita, E. and Hünicke, B. (2017). Quantifying and Predicting the Contribution of Sea-Level Rise to Shoreline Change in Ghana: Information for Coastal Adaptation Strategies. *Journal of Coastal Research*, 336, 1283-1291. doi:10.2112/jcoastres-d-16-00119.1

Fabry, V.J., Seibel, B.A., Feely, R.A. and Orr, J.C. (2008). Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES Journal of Marine Science*, 65(3), 414-432. doi:10.1093/icesjms/fsn048

Feely, R., Doney, S. and Cooley, S. (2009). Ocean acidification: Present conditions and future changes in a high-CO2 world. *Oceanography*, 22(4), 36–47. doi:10.5670/oceanog.2009.95

Fenneman, N.M. (1902). Development of the Profile of Equilibrium of the Subaqueous Shore Terrace. *Journal of Geology*, 10(1), 1-32. doi:10.1086/620977

Ferreira Júnior, P.D., Rosa, M.F., Lorenzo, M.D., Monteiro, M. F. and Júnior, A.R. (2008). Influência das características geológicas do local de desova na duração da incubação e no sucesso da eclosão dos ovos de *Caretta caretta* na praia da Guanabara, Anchieta, Espírito Santo. *Iheringia Série Zoologia*, 98(4), 447-453. doi:10.1590/s0073-47212008000400005

Ferreira, Ó., Garcia, T., Matias, A., Taborda, R. and Dias, J.A. (2006). An integrated method for the determination of set-back lines for coastal erosion hazards on sandy shores. *Continental Shelf Research*, 26(9), 1030-1044. doi:10.1016/j.csr.2005.12.016

Finucane, M.L., Marra, J.J., Keener, V.W. and Smith, M.H. (2012). Pacific Islands Region Overview. In Keener, V.W., Marra, J.J., Finucane, M.L., Spooner, D. and Smith, M.H. (Eds.). Climate Change and Pacific Islands: Indicators and Impacts. Report for the 2012 Pacific Islands Regional Climate Assessment (PIRCA). Island Press, Washington, DC.

Folk, R.L. and Ward, W.C. (1957). Brazos River Bar: A Study in the Significance of Grain-Size Parameters. *Journal of Sedimentary Research*, 27(1), 3-26.

Ford, M. (2013). Shoreline changes interpreted from multi-temporal aerial photographs and high-resolution satellite images: Wotje Atoll, Marshall Islands. *Remote Sensing of Environment*, 135, 130-140. doi:10.1016/j.rse.2013.03.027.

Ford, M. (2012). Shoreline Changes on an Urban Atoll in the Central Pacific Ocean: Majuro Atoll, Marshall Islands. *Journal of Coastal Research*, 279, 11-22. doi:10.2112/jcoastres-d-11-00008.1

Fragoso, M.A.C. (2007). Estudos Sectoriais, Vulnerabilidade e Adaptação às Alterações Climáticas em Cabo Verde. Ministério do Ambiente e Agricultura. Projecto NAPA, GEF/PNUD. Praia. República de Cabo Verde.

Gomes, C., Silva, A.N., Taborda, R., Santos, F., Rebelo, L. and Medina, A. (2019). Drivers of island beach evolution: insights from an island-scale study at Boa Vista (Cabo Verde). *Earth Surface Processes and Landforms*, 44, 2810-2822. doi:10.1002/esp.4709

Governo de Cabo Verde (2007). Programa Nacional de Adaptação às Mudanças Climáticas 2008-2012, Praia: Governo de C. Verde, 85p.

Haigh, R., Ianson, D., Holt, C.A., Neate, H.E., Edwards, A.M. (2015). Effects of Ocean Acidification on Temperate Coastal Marine Ecosystems and Fisheries in the Northeast Pacific. *PLOS ONE*, 10(2), e0117533. doi:10.1371/journal.pone.0117533

Hall, C.M. (2001). Trends in ocean and coastal tourism: the end of the last frontier?. *Ocean and Coastal Management*, 44(9-10), 601-618.

Hallermeier, R.J. (1978). Uses for a Calculated Limit Depth to Beach Erosion. *Coastal Engineering* 1978. doi:10.1061/9780872621909.090

Hapke, C.J., Plant, N.G., Henderson, R., Schwab, W.C. and Nelson, T.R. (2016). Decoupling processes and scales of shoreline morphodynamics. *Marine Geology*, 381, 42-53. doi:10.1016/j.margeo.2016.08.008

Hapke, C.J., Reid, D., Richmond, B.M., Ruggiero, P. and List, J. (2006). National Assessment of Shoreline Change Part 3: Historical Shoreline Change and Associated Coastal Land Loss Along Sandy Shorelines of the California Coast. Open-File Report. doi:10.3133/ofr20061219

Hemer, M.A., Fan, Y., Mori, N., Semedo, A. and Wang, X.L. (2013). Projected changes in wave climate from a multi-model ensemble. *Nature Climate Change*, 3(5), 471-476. doi:10.1038/nclimate1791

Hemer, M.A., Wang, X.L., Weisse, R. and Swail, V.R. (2012). Advancing wind-waves climate science. *Bull. Am. Meteor. Soc.*, 93, 791–796. doi:10.1175/BAMS-D-11-00184.1

Hernández, L. and Suárez, C. (2006). Characterization of the contemporary aeolian sediment dynamics of Boa Vista (Cape Verde). *Journal of Coastal Research* SI 48 (Proceedings of the 3rd Spanish Conference on Coastal Geomorphology), 64-68. Las Palmas de Gran Canaria - Spain, ISSN 0749-0208

Hinkel, J., Nicholls, R.J., Tol, R.S.J., Wang, Z.B., Hamilton, J.M., Boot, G., Vafeidis, A.T., McFadden, L., Ganopolski, J.A. and Klein, R.J.T. (2013). A global analysis of erosion of sandy beaches and sea-level rise: An application of DIVA. *Global and Planetary Change*, 111, 150-158. doi:10.1016/j.gloplacha.2013.09.002

Hoffman, J.S., Keyes, D.L. and Titus, J.G. (1983). Projecting future sea level rise: methodology, estimates to the year 2100. doi:10.5962/bhl.title.39171

Holzner, M. (2011). Tourism and economic development: the beach disease?. *Tourism Management*, 32(4), 922-933.

Howard, A.D., Morton, J.B., Gad-El-Hak, M. and Pierce, D.B. (1978). Sand transport model of barchan dune equilibrium. *Sedimentology*, 25(3), 307-338. doi:10.1111/j.1365-3091.1978.tb00316.x

Hugenholtz, C.H., Levin, N., Barchyn, T.E. and Baddock, M.C. (2012). Remote sensing and spatial analysis of aeolian sand dunes: A review and outlook. *Earth-Science Reviews*, 111(3-4), 319-334. doi:10.1016/j.earscirev.2011.11.006

IMC (2017). Inquérito Multi-Objectivo Comum. Estatísticas das Famílias e Condições de Vida. 93p.

INDC (2015). Intended Nationally Determined Contribution of Cabo Verde. República de Cabo Verde. 20p.

INE-CV (2018). Evolução e Estatísticas do Turismo por ilhas, 1999 a 2017. Instituto Nacional de Estatística de Cabo Verde.

INE-CV (2017). Estatísticas do Turismo 2017. Instituto Nacional de Estatística de Cabo Verde. 48p.

INE-CV (2010). Recenseamento geral da População e Habitação 2010. Estado e Estrutura da População. Instituto Nacional de Estatística de Cabo Verde. 101p.

IPCC (2019). Chapter 4: Sea Level Rise and Implications for Low Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.O. Pörtner, D.C. Roberts, V.Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem,J. Petzold, B. Rama, N. Weyer (eds.)]. In press.

IPCC (2014a). Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

IPCC (2014b). Annex II: Glossary [Agard, J., Schipper, E.L.F., Birkmann, J., Campos, M., Dubeux, C., Nojiri, Y., Olsson, L., Osman-Elasha, B., Pelling, M., Prather, M.J., Rivera-Ferre, M.G., Ruppel, O.C., Sallenger, A., Smith, K.R., St. Clair, A.L., Mach, K.J., Mastrandrea, M.D., and Bilir, T.E. (eds.)]. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White, L.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1757-1776.

IPCC (2013a). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J. Nauels, A. Xia, Y. Bex, V. and Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2013b): Annex III: Glossary [Planton, S. (ed.)]. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2012a). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., and Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp

IPCC (2012b). Summary for Policymakers. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., Barros, V., Stocker, T.F., Qin, D,. Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., and Midgley, P.M. (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 3-21.

IPCC (2007). The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change [Solomon, S., Qin, D., Manning, M.Z., Chen, M.M., Averyt, K.B. Tignor, M. and Miller, H.L.(eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

IPCC (2001). Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp

IPCC (1995). Second Assessment Report. Climate Change 1995.

IPCC (1990). Climate Change. The IPCC Scientific Assessment Report, Press Syndicate of the University of Cambridge. Cambridge C B 2 IRP. U K.

Jevrejeva, S., Moore, J. and Grinsted, A. (2012). Sea level projections to AD2500 with a new generation of climate change scenarios. *Global and Planetary Change*, 80-81, 14-20. doi:10.1016/j.gloplacha.2011.09.006

Jimenez, J.A., Maia, L.P., Serra, J. and Morais, J. (1999). Aeolian dune migration along the Ceara coast, north-eastern Brazil. *Sedimentology*, 46(4), 689-701. doi:10.1046/j.1365-3091.1999.00240.x

Joos, F. and Spahni, R. (2008). Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years. *P. Natl. Acad. Sci. USA*, 105, 1425–1430.

Kelman, I., Lewis, J., Gaillard, J.C. and Mercer, J. (2011). Participatory action research for dealing with disasters on islands. *Island Studies Journal*, 6(1), 59-86.

Kench, P., Thompson, D., Ford, M., Ogawa, H. and McLean, R. (2015). Coral islands defy sea-level rise over the past century: Records from a central Pacific atoll. *Geology*, 43(6), 515-518. doi:10.1130/g36555.1

Laboratory for Satellite Altimetry (2018). Data available at `http://www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/LSA_SLR_maps.php`, accessed in May 2018.

Lavell, A. (1996). Degradación ambiental, riesgo y desastre urbano. Problemas y conceptos: hacia la definición de una agenda de investigación. In: Ciudades en Riesgo [Fernandez, M.A. (ed.)]. La RED-USAID, Lima, Peru, 21-59.

Lima, S.C.M. (2012). As perceções dos residentes do papel do turismo no desenvolvimento da Ilha da Boavista. Trabalho de Projecto de Investigação do Mestrado em Economia Local. Universidade de Coimbra. 97p.

Marques, R., Prudêncio, M.I., Waerenborgh, J.C., Rocha, F., Ferreira da Silva, E., Dias, M.I., Madeira, J., Vieira, B.J.C. and Marques, J.G. (2016). Geochemical fingerprints in topsoils of the volcanic Brava Island, Cape Verde. *Catena*, 147, 522-535. doi:10.1016/j.catena.2016.08.008

McGray, H., Hammil, A. and Bradley, R. (2007). Weathering the Storm: Options for Framing Adaptation and Development. World Resources Institute (WRI), Washington, DC, USA, 57p.

McInnes, K.L., Erwin, T.A. and Bathols, J.M. (2011). Global Climate Model projected changes in 10 m wind speed and direction due to anthropogenic climate change. *Atmospheric Science Letters*, 12(4), 325-333. doi:10.1002/asl.341

McVicar, T.R., Van Niel, T.G., Li, L.T., Roderick, M.L., Rayner, D.P., Ricciardulli, L., and Donohue, R.J. (2008). Wind speed climatology and trends for Australia, 1975–2006: Capturing the stilling phenomenon and comparison with near-surface reanalysis output. *Geophysical Research Letters*, 35(20). doi:10.1029/2008gl035627

Mills, J.P., Buckley, S.J., Mitchell, H.L., Clarke, P.J. and Edwards, S.J. (2005). A geomatics data integration technique for coastal change monitoring. *Earth Surf Process Landform*, 30, 651-664

Mimura, N., Nurse, L., McLean, R.F., Agard, J., Briguglio, L., Lefale, P., Payet, R. and Sem, G. (2007). Small islands. Climate Change: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 687-716.

Moreira, J. M. G. and Shikui, D. (2014). A Comparative Study of Biodiversity Conservation Coping with Climate Change in China and Cape Verde. *European Scientific Journal*, 77-84.

Mori, N., Yasuda, T., Mase, H., Tom, T. and Oku, Y. (2010). Projection of Extreme Wave Climate Change under Global Warming. *Hydrological Research Letters*, 4(0), 15-19. doi:10.3178/hrl.4.15

Morim, J., Hemer, M. A., Cartwright, N., Strauss, D. and Andutta, F. (2018). On the concordance of 21st century wind-wave climate projections. *Global and Planetary Change*, 167, 160–171. doi: 10.1016/j.gloplacha.2018.05.005

Moya, A., Huisman, L., Ball, E.E., Hayward, D.C., Grasso, L.C., Chua, C.M., Woo, H.N., Gattuso, J-P., Forêt, S., Miller, D.J. (2012). Whole transcriptome analysis of the coral *Acropora millepora* reveals complex responses to CO2-driven acidification during the initiation of calcification. *Molecular Ecology*, 21(10), 2440-2454. doi:10.1111/j.1365-294x.2012.05554.x

Nerem, R.S., Chambers, D.P., Choe, C., and Mitchum, G.T. (2010). Estimating mean sea level change from the TOPEX and Jason altimeter missions. *Marine Geodesy*, 33(Suppl 1), 435–446. doi:10.1080/01490419.2010.491031

Nicholls, R.J. (2010). Impacts of and responses to sea-level rise. In: Understanding Sea-level Rise and Variability [Church, J.A., Woodworth, P.L., Aarup, T. and Wilson, W.S.(eds.)]. Wiley-Blackwell, Chichester, UK and Hoboken, NJ, USA, pp. 17-51.

Nicholls, R.J. and Cazenave, A. (2010): Sea-level rise and its impact on coastal zones. *Science*, 328(5985), 1517-1520.

NOAA (2017). Global and Regional Sea Level Rise Scenarios for the United States. Technical Report NOS CO-OPS 083. 75p.

Nurse, L.A., R.F. McLean, J. Agard, L.P. Briguglio, V. Duvat-Magnan, N. Pelesikoti, E. Tompkins, and A. Webb. (2014). Small islands. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1613-1654.

O'Brien, K., Leichenko, R., Kelkar, U., Venema, H., Aandahl, G., Tompkins, H., Javed, A., Bhadwal, S., Barg, S., Nygaard, L. and West, J. (2004). Mapping vulnerability to multiple stressors: climate change and globalization in India. *Global Environmental Change-Human and Policy Dimensions*, 14, 303-313.

Okin, G., Gillette, D. and Herrick, J. (2006). Multi-scale controls on and consequences of aeolian processes in landscape change in arid and semi-arid environments. *Journal of Arid Environments*, 65(2), 253-275. doi:10.1016/j.jaridenv.2005.06.029

Oppenheimer, M., Campos, M., Warren, R., Birkmann, J., Luber, G., O'Neill, B., and Takahashi, K. (2004). Emergent risks and key vulnerabilities. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., and White, L.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1039-1099.

Orr, J.C., Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R.M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R. G., Plattner, G.K., Rodgers, K.B., Sabine, C.L., Sarmiento, J.L., Schlitzer, R., Slater, R.D., Totterdell, I.J., Weirig, M.F., Yamanaka, Y. and Yool, A. (2005). Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, 437(7059), 681-686. doi:10.1038/nature04095

Pajak, M.J. and Leatherman, S., (2002). The high water line as shoreline indicator. *Journal of Coastal Research*, 18(2), 329–337.

Parker, B., and Miller, S.E. (2012). Marine, Freshwater, and Terrestrial Ecosystems on Pacific Islands. In Keener, V.W., Marra, J.J., Finucane, M.L. Spooner, D. and Smith, M.H. (Eds.). Climate Change and Pacific Islands: Indicators and Impacts. Report for the 2012 Pacific Islands Regional Climate Assessment (PIRCA). Washington, DC: Island Press.

Perez, J., Menendez, M., Camus, P., Mendez, F.J. and Losada, I.J. (2015). Statistical multi-model climate projections of surface ocean waves in Europe. *Ocean Modelling*, 96, 161-170. doi:10.1016/j.ocemod.2015.06.001

Ponte Lira, C., Silva, A.N., Taborda, R., Andrade, C.F. (2016). *C*oastline evolution of Portuguese low-lying sandy coast in the last 50 years: an integrated approach. *Earth System Science Data Discussions*, 1-22. doi:10.5194/essd-2016-5

Pryor, S.C., Schoof, J.T. and Barthelmie, R.J. (2006). Winds of change? Projections of near-surface winds under climate change scenarios. *Geophysical Research Letters*, 33(11). doi:10.1029/2006gl026000

Rafferty, J.P. (2014). Ocean Acidification. Encyclopædia Britannica, September, 2014. Available online at `http://eds.a.ebscohost.com/eds/detail/detail` (www.b-on.pt) on January 2016.

Rahmstorf, S. (2007). Response to Comments on "A Semi-Empirical Approach to Projecting Future Sea-Level Rise". *Science*, 317, 1866. doi:10.1126/science.1141283

Ramalho, R., Quartau, R., Trenhaile, A., Mitchell, N., Woodroffe, C. and Ávila, S.P. (2013). Coastal evolution on volcanic oceanic islands: a complex interplay between volcanism, erosion, sedimentation, sea-level change and biogenic production. *Earth-Science Reviews*. 127, 140-170. doi:10.1016/j.earscirev.2013.10.007

Ramalho, R., Helffrich, G., Schmidt, D.N. and Vance, D. (2010a). Tracers of uplift and subsidence in the Cape Verde archipelago. *Journal of the Geological Society*, 167 (3), 519-538. doi:10.1144/0016-76492009-056

Ramalho, R., Helffrich, G., Cosca, M., Vance, D., Hoffmann, D. and Schmidt, D.N. (2010b). Episodic hotspot swell growth inferred from variable uplift from the Cape Verde hot spot Islands. *Nature Geoscience*, 3(11), 774-777. doi:10.1038/ngeo982

Ranasinghe, R. (2016). Assessing climate change impacts on open sandy coasts: A review. *Earth-Science Reviews*, 160, 320-332. doi:10.1016/j.earscirev.2016.07.011

Rasmussen, K., May, W., Birk, T., Mataki, M. and Mertz, O. (2011). Prospects for climate change on three Polynesian outliers in Solomon Islands: Exposure, sensitivity and adaptive capacity, Geografisk Tidsskrift-Danish. *Journal of Geography*, 111(1), 43-57. doi:10.1080/00167223.2011.10669521

Rasmussen, K., May, W., Birk, T., Mataki, M., Mertz, O. and Yee, D. (2009). Climate change on three Polynesian outliers in the Solomon Islands: impacts, vulnerability and adaptation. Geografisk Tidsskrift-Danish. *Journal of Geography*, 109(1), 1-13.

RCM (2016). Resolução do Concelho de Ministro nº 37/2016. Estratégia e Plano de Conservação da ilha da Boa Vista. Boletim Oficial da República de Cabo Verde. I SÉRIE. Nº 17.

Reguero, B., Méndez, F., and Losada, I. (2013). Variability of multivariate wave climate in Latin America and the Caribbean. *Global and Planetary Change*, 100, 70-84. doi:10.1016/j.gloplacha.2012.09.005

Rhein, M., Rintoul, S.R., Aoki, S., Campos, E., Chambers, D., Feely, R.A., Gulev, S., Johnson, G.C., Josey, S.A., Kostianoy, A., Mauritzen, C., Roemmich, D., Talley, L.D., Wang, F. (2013) Observations: Ocean. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Richier, S., Fiorini, S., Kerros, M.E., von Dassow, P., Gattuso, J.P. (2011). Response of the calcifying coccolithophore *Emiliania huxleyi* to low pH/high pCO2: From physiology to molecular level. *Marine Biology*, 158, 551–560. PMID: 24391258

Roleda, M.Y., Cornwall, C.E., Feng, Y., McGraw, C.M., Smith, A.M. and Hurd, C.L. (2015). Effect of Ocean Acidification and pH Fluctuations on the Growth and Development of Coralline Algal Recruits, and an Associated Benthic Algal Assemblage. *PLOS ONE*, 10(10), e0140394. doi:10.1371/journal.pone.0140394.

Rooney, J.J. and Fletcher, C.H. (2005). Shoreline Change and Pacific Climatic Oscillations in Kihei, Maui, Hawaii. *Journal of Coastal Research*, 213, 535-547. doi:10.2112/03-0077.1

Rubin, D.M. (2004). A Simple Autocorrelation Algorithm for Determining Grain Size from Digital Images of Sediment. *Journal of Sedimentary Research*, 74(1), 160-165. doi:10.1306/052203740160

Ruggiero, P. and List, J. H. (2009). Improving Accuracy and Statistical Reliability of Shoreline Position and Change Rate Estimates. *Journal of Coastal Research*, 255, 1069-1081. doi:10.2112/08-1051.1

Sánchez-Cañizares, S.M. and Castillo-Canalejo, A.M. (2014). Community based island tourism: the case of Boa Vista in Cape Verde. *International Journal of Culture, Tourism and Hospitality Research*, 8(2), 219-233. doi:10.1108/ijcthr-04-2012-0015.

Santos, F.D., Lopes, A.M., Moniz, G., Ramos, L., Taborda, R. (2017). Grupo de Trabalho do Litoral: *Gestão da Zona Costeira: O desafio da Mudança*. Santos, F.D., Penha-Lopes, G., Lopes, A.M. (Eds). Lisboa (ISBN: 978-989-99962-1-2).

Santos, F.D. and Miranda, P. (Eds) (2006). *Alterações Climáticas em Portugal. Cenários, Impactos e Medidas de Adaptação*. Projecto SIAM II, Gradiva, Lisboa.

Santos, F.D., Forbes, K. and Moita, R. (Eds) (2002). *Climate Change in Portugal. Scenarios, Impacts and Adaptation Measures* - SIAM I Project. Projecto SIAM II, Gradiva, Lisboa.

Sauter, R., ten Brink, P., Withana, S., Mazza, L., Pondichie, F. with contributions from Clinton, J., Lopes, A, Bego, K. (2013). Impacts of climate change on all European islands, A report by the Institute for European Environmental Policy (IEEP) for the Greens/EFA of the European Parliament. Final Report. Brussels. 2013.

Schubert, S.F., Brida, J.G. and Risso, W.A. (2011). The impacts of international tourism demand on economic growth of small economies dependent on tourism. *Tourism Management*, 32(2), 337-385.

Scripps: The Keeling Curve, available at: `http://keelingcurve.ucsd.edu/`, last access: 26 june 2019.

Serralheiro, A., Alves, C., Macedo, J. and Silva, L. (1974). Note preliminaire sur la géologie de l'île de Boa Vista (Cap-Vert). Garcia de Orta. *Serviços Geológicos*, 1, 53-60.

Sierra, J.P. and Casas-Prat, M. (2014). Analysis of potential impacts on coastal areas due to changes in wave conditions. *Climatic Change*, 124(4): 861-876. doi: 10.1007/s10584-014-1120-5

Sillitoe, A. (2009). PPG-Project phase GEF-4176. Consolidation of Cape Verde's Protected Areas System: Ecotourism and Livelihoods.

Silva, A.N., Taborda, R., Andrade, C. and Ribeiro, M. (2019). The future of insular beaches: Insights from a past-to-future sediment budget approach. *Science of The Total Environment*, 676, 692-705. doi:10.1016/j.scitotenv.2019.04.228

Solomon, S.M. and Forbes, D.L. (1999). Coastal hazards and associated management issues on South Pacific Islands. *Ocean and Coastal Management*, 42(6), 523-554. doi:10.1016/s0964-5691(99)00029-0

Sovacool, B.K. (2012). Expert views of climate change adaptation in the Maldives.*Climatic Change*, 114(2), 295-300.

Srinivasan, U.T. (2010). Economics of climate change: risk and responsibility by world region. *Climate Policy*, 10(3), 298-316.

Stockdon, H.F., Holman, R.A., Howd, P.A. and Sallenger, A.H. (2006). Empirical parameterization of setup, swash, and runup. *Coastal Engineering*, 53(7), 573-588. doi:10.1016/j.coastaleng.2005.12.005

Stronkhorst, J., Huisman, B., Giardino, A., Santinelli, G., Santos, F.D. (2018). Sand nourishment strategies to mitigate coastal erosion and sea level rise at the coasts of Holland (The Netherlands) and Aveiro (Portugal) in the 21st century. *Ocean Coastal Management*, 156, 266-276. doi:10.1016/j.ocecoaman.2017.11.017

Taborda, R. and Ribeiro, M.A. (2015). A simple model to estimate the impact of sea-level rise on platform beaches. *Geomorphology*, 234, 204-210. doi:10.1016/j.geomorph.2015.01.015

Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L. and Ergul, A. (2017). Digital Shoreline Analysis System (DSAS) version 4.0 - An ArcGIS extension for calculating shoreline change (ver.4.4, July 2017): U.S. Geological Survey Open-File Report 2008-1278. `https://pubs.er.usgs.gov/publication/ofr20081278/`

Tinley, K.L. (1985). Coastal dunes of South Africa. S. Afr. Natl. SC. Programmes Report No. 109. CSIR, Pretoria, 300p.

UNDHA (1992). Internationally agreed glossary of basic terms relating to disaster management. UNDHA, Geneva, Switzerland.

UNDRO (1980). Natural Disasters and Vulnerability Analysis. Report of Experts Group Meeting of 9-12 July 1979, UNDRO, Geneva, Switzerland.

Verhoeven, G., Doneus, M., Briese, C. and Vermeulen, F. (2012). Mapping by matching: a computer vision-based approach to fast and accurate georeferencing of archaeological aerial photographs. *Journal of Archaeological Science*, 39(7), 2060-2070. doi:10.1016/j.jas.2012.02.022.

Vermeer, M. and Rahmstorf, S. (2009). Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences*, 106(51), 21527-21532. doi:10.1073/pnas.0907765106

Wan, Y., Wang, D., Xiao, J., Lai, X. and Xu, J. (2013). Automatic determination of seamlines for aerial image mosaicking based on vector roads alone, *ISPRS Journal of Photogrammetry and Remote Sensing*, 76, 1-10. doi:10.1016/j.isprsjprs.2012.11.002.

Wang, X.L., Feng, Y. and Swail, V.R. (2014). Changes in global ocean wave heights as projected using multimodel CMIP5 simulations. *Geophysical Research Letters*, 41, 1026–1034. doi:10.1002/2013GL058650

Wang, X.L., Swail, V.R., Zwiers, F.W., Zhang, X. and Feng, Y. (2009). Detection of external influence on trends of atmospheric storminess and ocean wave heights. *Climate Research Division*, 32, 189–203. doi:10.1007/s00382-008-0442-2.

Wang, C., Stefanidis, A., Croitoru, A. and Agouris, P. (2008). Map Registration of Image Sequences Using Linear Features. *Photogrammetric Engineering and Remote Sensing*, 74(1), 25-38. doi:10.14358/pers.74.1.25

Warrick, O. (2009). Ethics and methods in research for community-based adaptation: reflections from rural Vanuatu. *Participatory Learning and Action*, 60, 76-87.

Webb, A.P. and Kench, P.S. (2010). The dynamic response of reef islands to sea-level rise: Evidence from multi-decadal analysis of island change in the Central Pacific. *Global and Planetary Change*, 72(3), 234-246. doi:10.1016/j.gloplacha.2010.05.003

Wigley, T.M.L. (1995). Global-mean temperature and sea level consequences of greenhouse gas stabilization. *Geophysical Research Letters*, 22, 45-48.

Wong, P.P., Losada, I.J., Gattuso, J.P., Hinkel, J., Khattabi, A., McInnes, K.L., Saito, Y. and Sallenger, A. (2014): Coastal systems and low-lying areas. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S. and Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White, L.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 361-409.

Wong, P.P. (Ed.) (1993). Tourism versus Environment: the case for coastal areas. Dordrecht, Boston: Kluwer Academic Publishers.

WTTC, World Travel and Tourism Council (2018). Travel and Tourism Economic Impact 2018: Cape Verde. London: World Travel and Tourism Council.

Young, I.R., Zieger, S. and Babanin, A.V. (2011). Global trends in wind speed and wave height. *Science*, 332, 451–455. doi:10.1126/science.1197219

Appendices

Appendix A

Definition of some terms by IPCC related to Climate Change

The terminology adopted in this thesis follows the Fifth Assessment Report (AR5) of Working Group I of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2013b, p. 1450-1451):

Climate - "*Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.*"

Climate system - "*The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and anthropogenic forcings such as the changing composition of the atmosphere and land use change.*"

Climate change - "*Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.*"

For a better understanding and an efficient assessment of climate change impacts on coastal areas, it is prudent to define the following items adopted the IPPC, Intergovernmental Panel on Climate Change definition:

Adaptive Capacity

Is "*the ability of a system to adjust to climate change (including climate variability and extremes) to* *moderate potential damages, to take advantage of opportunities, or to cope with the consequences*" (IPCC, 2001, p. 982).

Impacts

"*Generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as consequences and outcomes*" (IPCC, 2014b, p. 1767).

Exposure

Is "*the nature and degree to which a system is exposed to significant climatic variations‘ where the exposure unit is ‘an activity, group, region, or resource that is subjected to climatic stimuli*" (IPCC, 2001, p. 987).

Hazard

Is "*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*" (IPCC, 2014b, p. 1766).

Mitigation

Is "*an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases*" (IPCC, 2001, p. 990) .

Resilience

Is "*the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions*" (IPCC, 2012a, p. 563).

Sensitivity

Is "*the degree to which a system or species is affected, either adversely or beneficially, by climate variability or change*" (IPCC, 2014b, p. 1772) .

Vulnerability

Is "*the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity*" (IPCC, 2001, p. 995).

Appendix B

Supplementary Material to Chapter 1 - Classification of Coastal Environments

Terrestrial Zone (TZ)	Adjacent Sea Zone (ASZ)	Length
Dune	Beach	5374.35
Dune	Beach	109.89
Cliff	Beach	43.71
Dune	Beach	1525.62
Cliff	Beach	116.69
Cliff	Beach	75.94
Dune	Beach	496.45
Dune	Beach	372.60
Dune	Beach	215.47
Dune	Beach	479.61
Cliff	Beach	120.87
Cliff	Beach	146.58
Cliff	Beach	205.55
Cliff	Beach	521.96
Dune	Beach	120.10
Dune	Beach	1128.21
Cliff	Beach	468.06
Dune	Beach	27.94
Cliff	Beach	828.20
Dune	Beach	183.18
Dune	Beach	2005.25
Dune	Beach	219.33
Dune	Beach	839.40
Dune	Beach	430.77
Dune	Beach	4743.68
Dune	Beach	7410.21

Terrestrial Zone (TZ)	Adjacent Sea Zone (ASZ)	Length
Dune	Beach	209.34
Dune	Beach	9530.20
Dune	Beach	799.76
Structure	Beach	197.53
Dune	Beach	217.01
Dune	Beach	93.94
Dune	Beach	44.83
Dune	Beach	250.42
Dune	Beach	2469.68
Cliff	Beach	339.33
Dune	Beach	89.30
Dune	Beach	99.92
Dune	Beach	232.60
Dune	Beach	520.38
Cliff	Beach	23.11
Dune	Beach	72.55
Dune	Beach	121.22
Dune	Beach	100.50
Dune	Beach	56.58
Dune	Beach	367.82
Dune	Beach	374.31
Cliff	Beach	317.45
Dune	Beach	289.97
Dune	Beach	148.24
Dune	Beach	1071.66
Dune	Beach	201.96
Dune	Beach	139.17
Cliff	Beach	168.12
Cliff	Beach	271.01
Cliff	Beach	173.86
Cliff	Beach	112.99
Cliff	Beach	135.79
Cliff	Beach	39.80
Dune	Beach	677.17
Dune	Beach	446.30
Cliff	Platform	8006.62
Cliff	Platform	208.46
Cliff	Platform	13301.55
Cliff	Platform	724.09
Cliff	Platform	1235.05
Cliff	Platform	949.18
Cliff	Platform	112.09
Cliff	Platform	1330.27
Cliff	Platform	3411.21
Cliff	Platform	1351.35
Cliff	Platform	380.64

Terrestrial Zone (TZ)	Adjacent Sea Zone (ASZ)	Length
Dune	Platform	155.61
Cliff	Platform	240.04
Cliff	Platform	575.53
Cliff	Platform	1234.76
Cliff	Platform	741.88
Dune	Platform	2671.20
Dune	Platform	351.72
Dune	Platform	535.79
Dune	Platform	3077.60
Cliff	Platform	948.24
Cliff	Platform	707.42
Dune	Platform	494.38
Cliff	Platform	261.36
Cliff	Platform	531.82
Cliff	Platform	548.91
Dune	Platform	580.76
Cliff	Platform	337.38
Cliff	Platform	675.33
Cliff	Platform	92.69
Dune	Platform	297.35
Cliff	Platform	6674.52
Structure	Platform	216.69
Structure	Platform	161.48
Structure	Platform	1237.70
Cliff	Platform	222.36
Dune	Platform	144.59
Dune	Platform	259.10
Cliff	Platform	521.20
Cliff	Platform	88.96
Structure	Platform	78.93
Dune	Platform	723.47
Dune	Platform	309.55
Cliff	Platform	1010.77
Dune	Platform	164.28
Cliff	Platform	2006.46
Cliff	Platform	72.36
Cliff	Platform	193.34
Cliff	Platform	363.31
Dune	Platform	49.50
Cliff	Platform	791.09
Dune	Platform	443.35
Dune	Platform	95.08
Cliff	Platform	398.21
Cliff	Platform	1043.32
Cliff	Platform	249.75
Cliff	Platform	337.60

Terrestrial Zone (TZ)	Adjacent Sea Zone (ASZ)	Length
Dune	Platform	226.51
Cliff	Platform	1309.07
Cliff	Platform	1086.40
Dune	Platform	261.12
Cliff	Platform	309.08
Dune	Platform	311.60
Dune	Platform	262.82
Dune	Platform	181.20
Dune	Platform	100.73
Dune	Platform	167.75
Cliff	Platform	119.37
Dune	Platform	206.80
Dune	Platform	117.82
Dune	Platform	143.37
Cliff	Platform	947.75
Dune	Platform	26.46
Dune	Platform	84.15
Cliff	Platform	259.40
Cliff	Platform	183.42
Dune	Platform	137.80
Cliff	Platform	422.67
Dune	Platform	126.51
Cliff	Platform	23.81
Cliff	Platform	54.55
Dune	Platform	390.74
Cliff	Platform	82.60
Cliff	Platform	425.00
Cliff	Platform	31.53
Cliff	Platform	155.18
Dune	Platform	85.16
Dune	Platform	52.46
Dune	Platform	80.62
Cliff	Platform	713.04
Cliff	Platform	713.04
Dune	Platform	146.60
Dune	Platform	119.20
Cliff	Platform	195.75
Cliff	Platform	168.29
Cliff	Platform	113.09
Dune	Platform	228.40
Dune	Platform	242.87
Dune	Platform	190.77

Appendix C

Supplementary Material to Chapter 2 - Aerial Photos and Orthophotomaps from Boa Vista Island

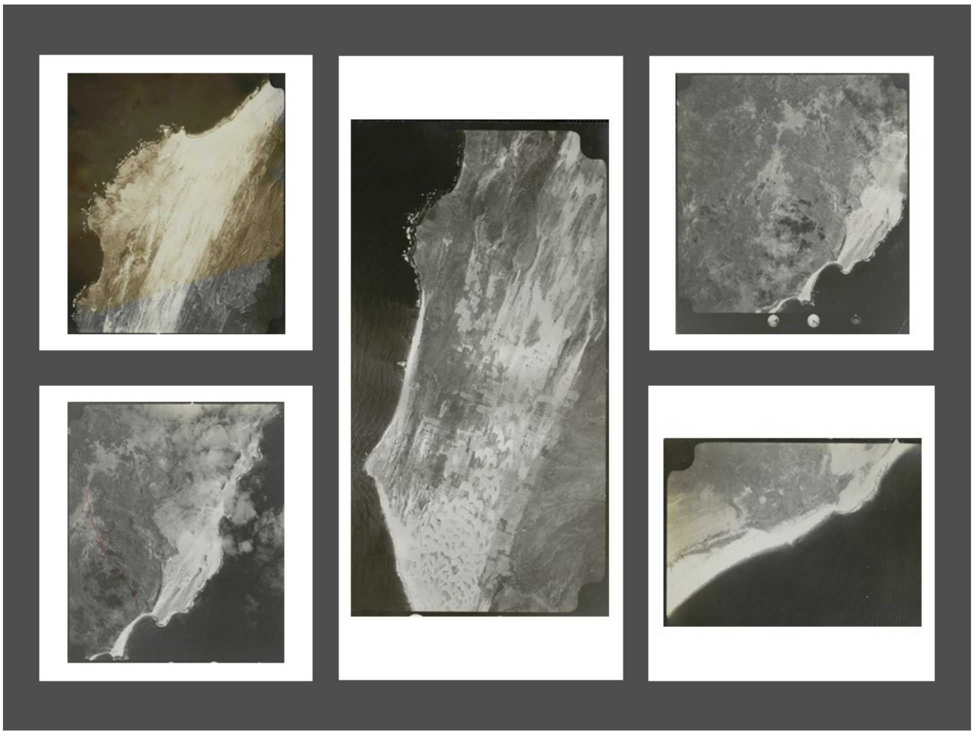


Figure C.1: Aerial Photos - 1968.

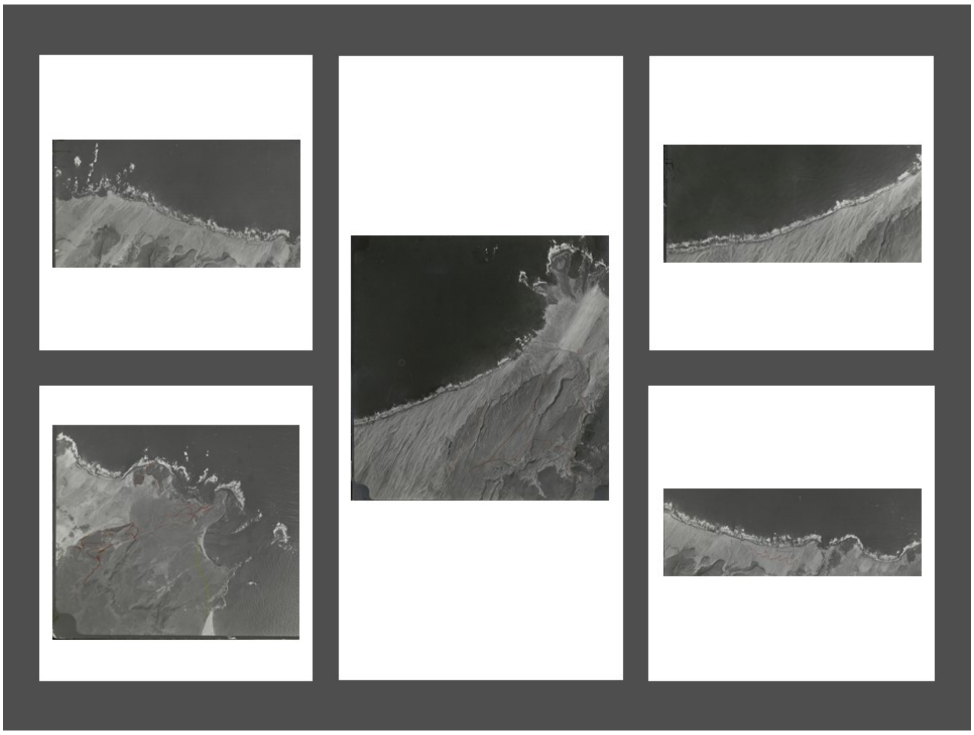


Figure C.2: Aerial Photos - 1968.

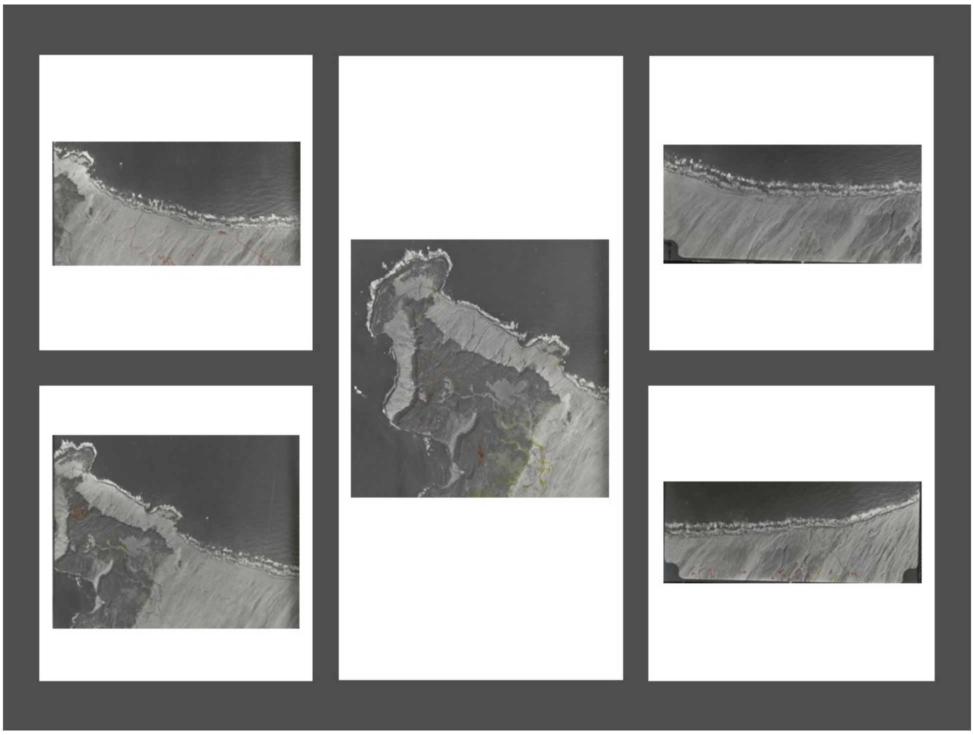


Figure C.3: Aerial Photos - 1968.

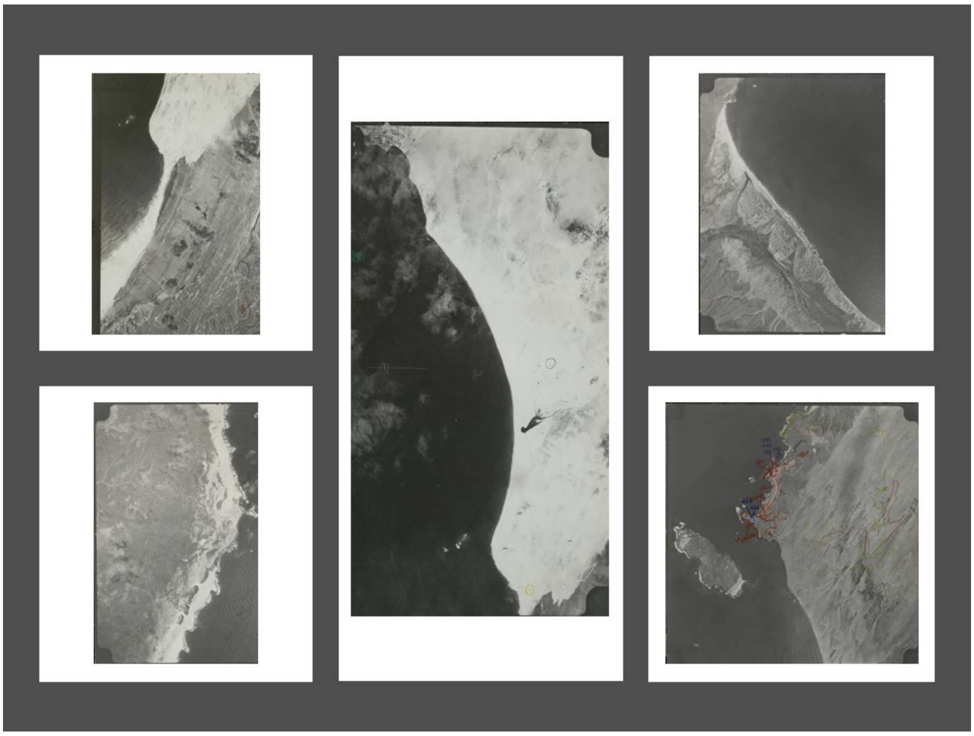


Figure C.4: Aerial Photos - 1968.

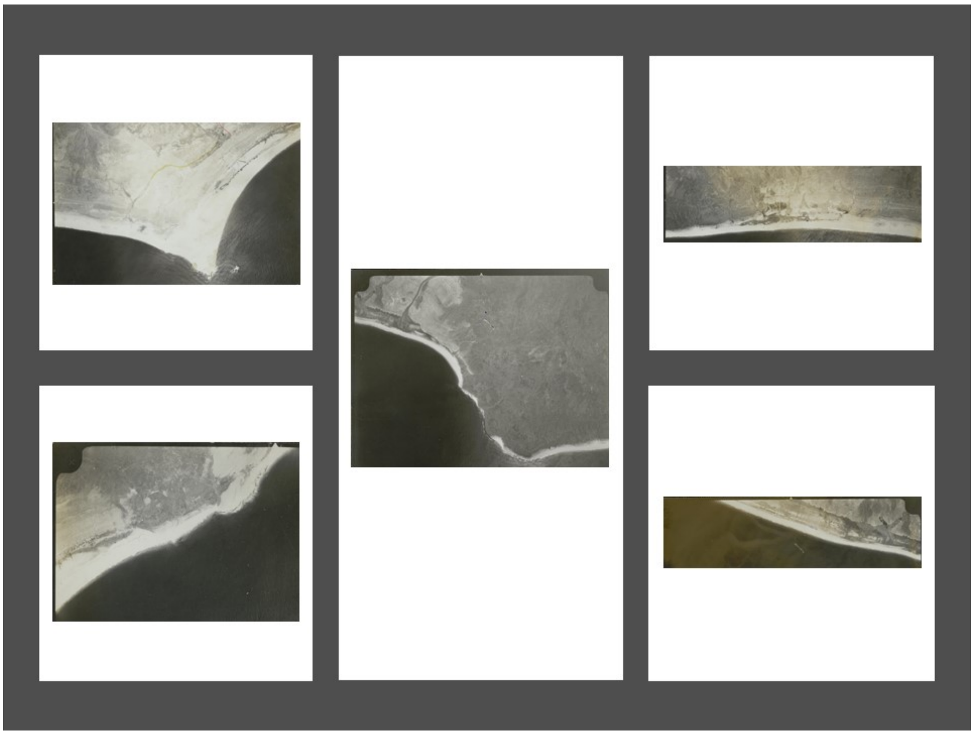


Figure C.5: Aerial Photos - 1983.

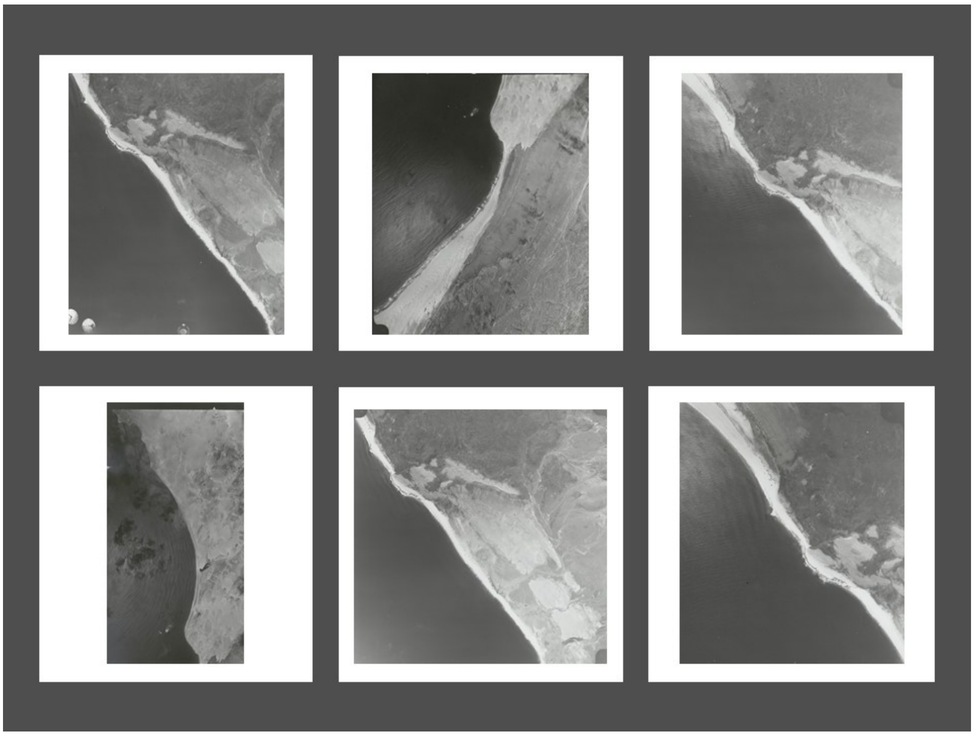


Figure C.6: Aerial Photos - 1983.

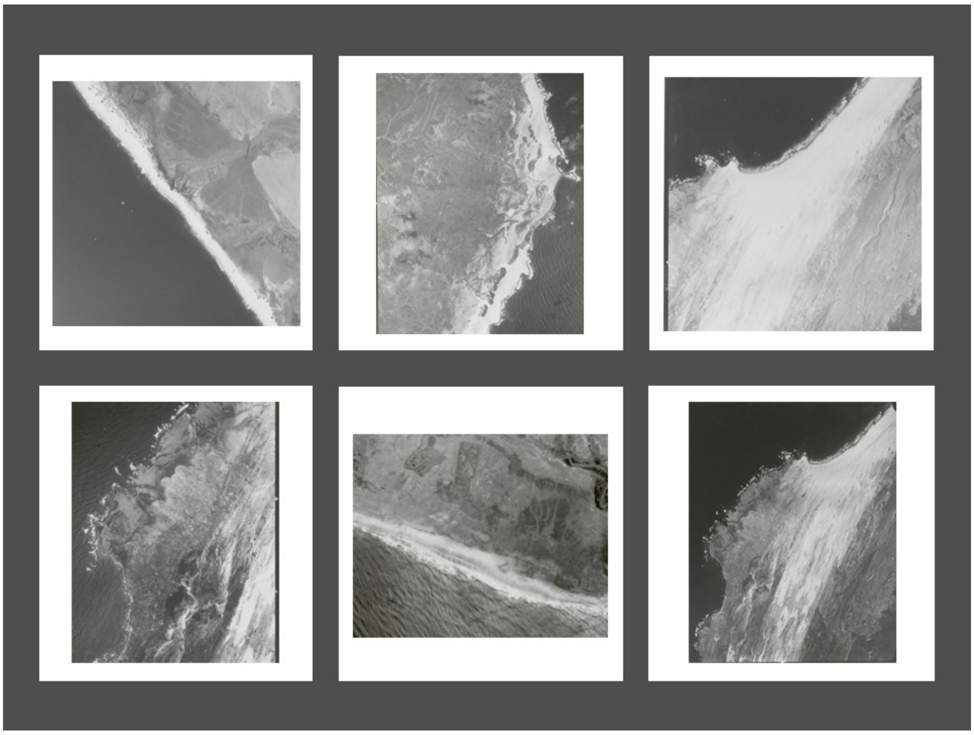


Figure C.7: Aerial Photos - 1983.

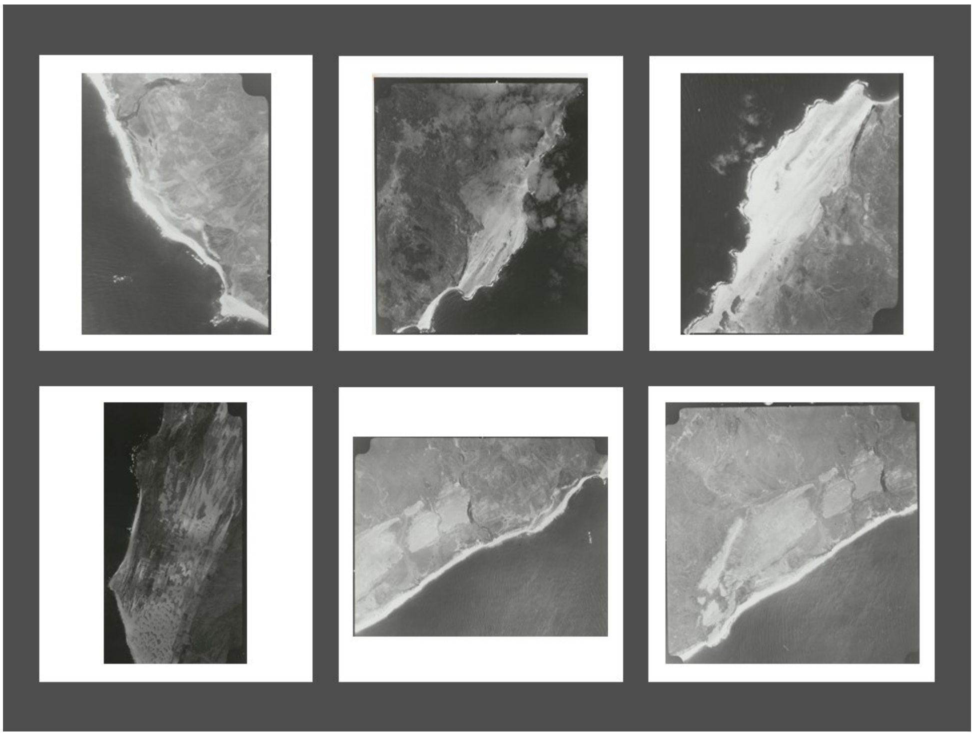


Figure C.8: Aerial Photos - 1983.

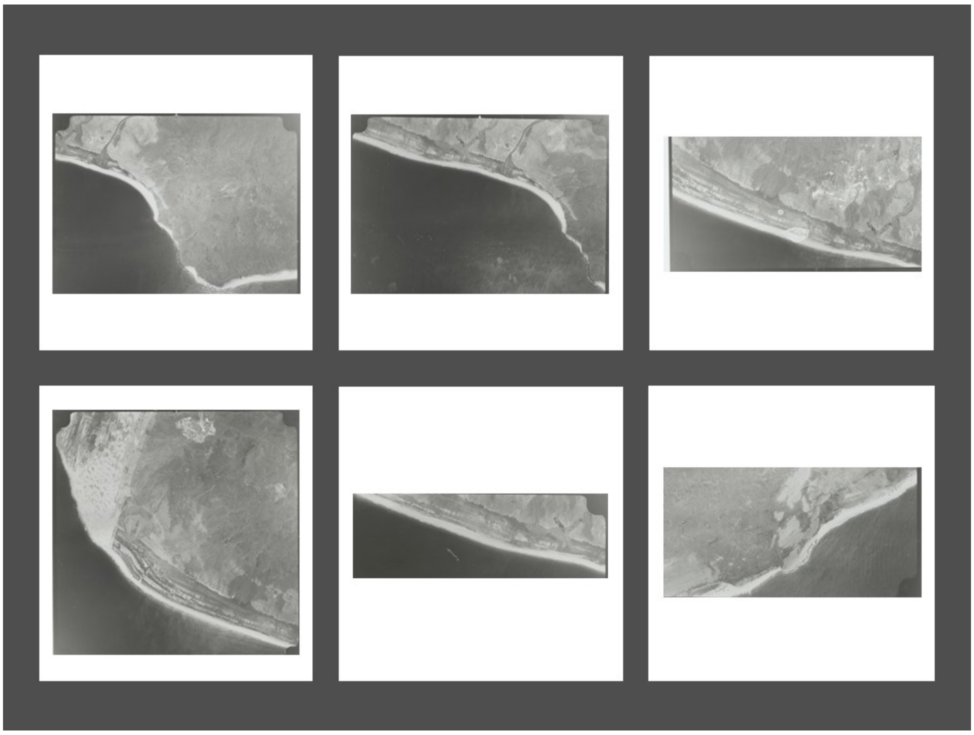


Figure C.9: Aerial Photos - 1983.

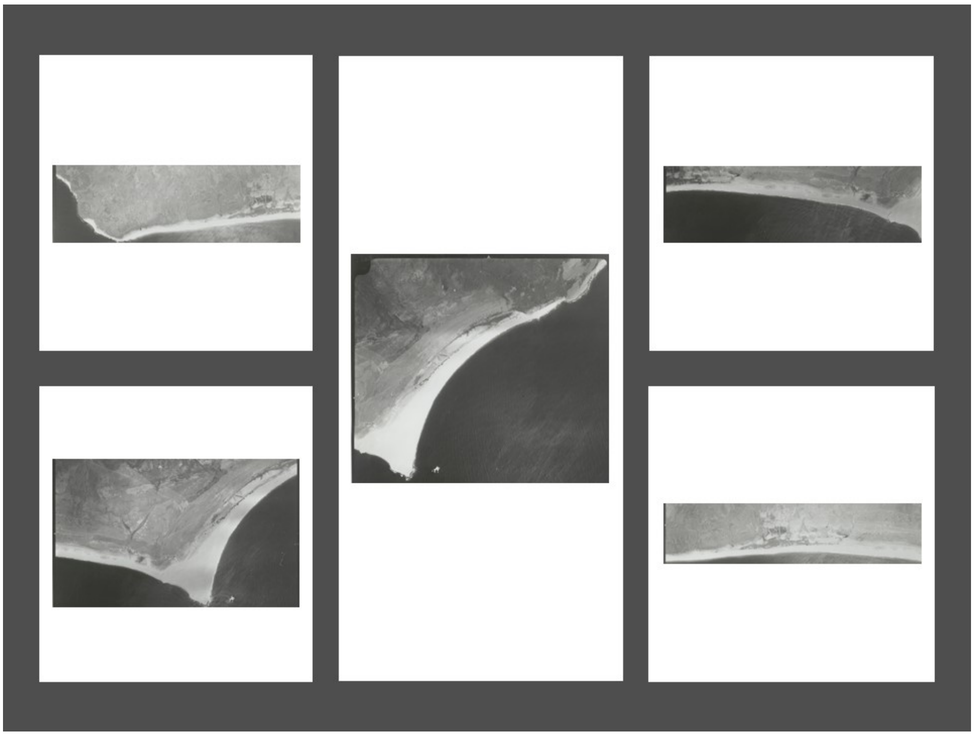


Figure C.10: Aerial Photos - 1991.

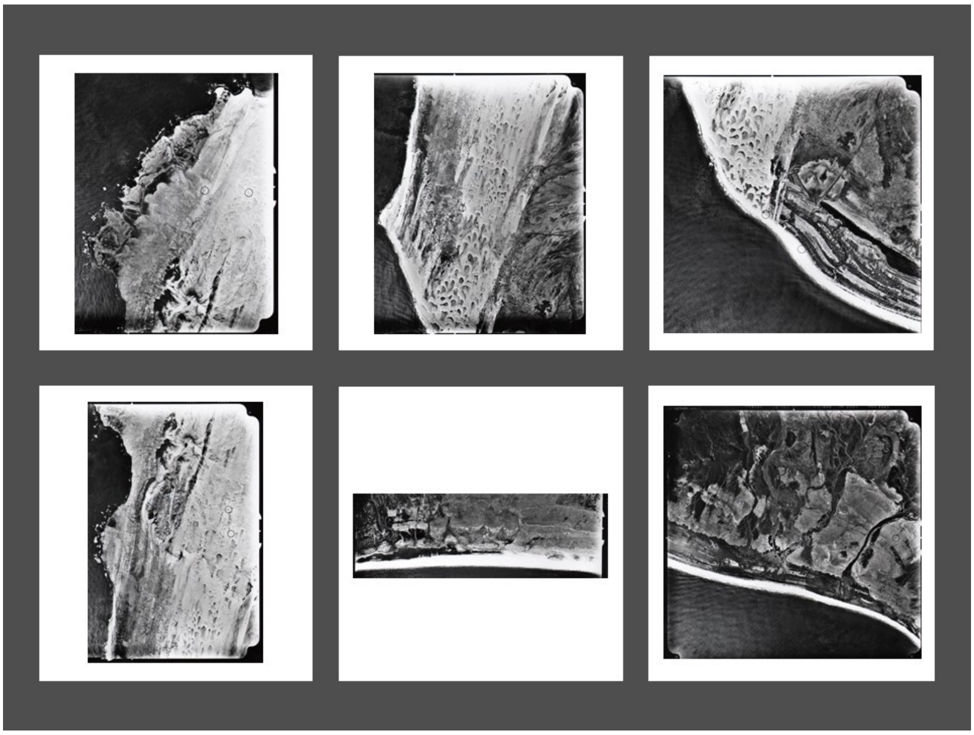


Figure C.11: Aerial Photos - 1991.

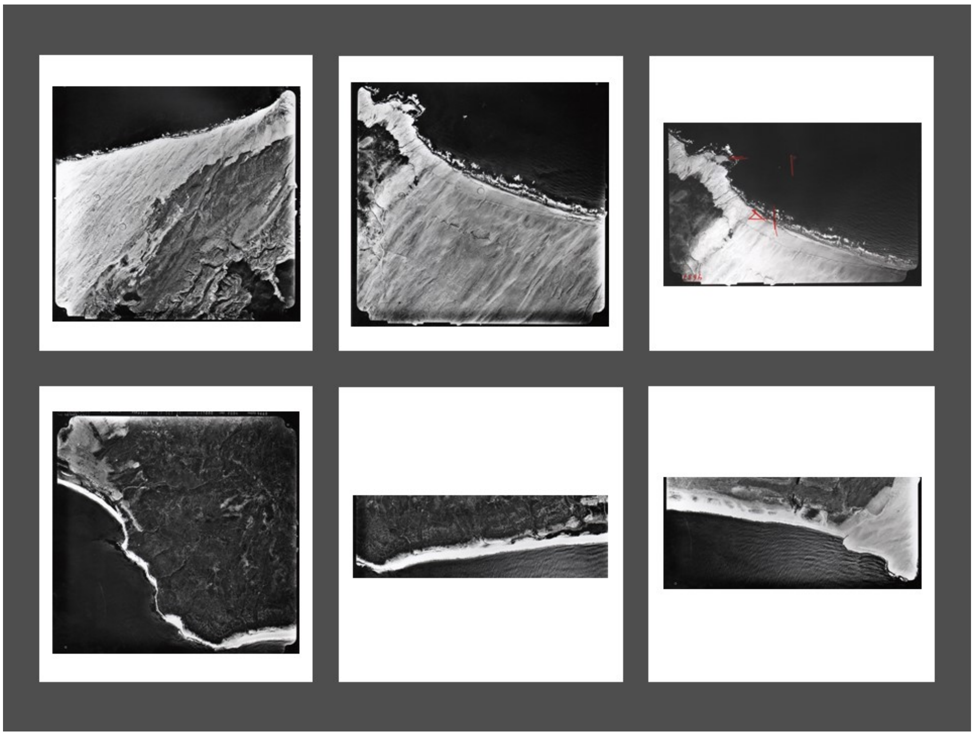


Figure C.12: Aerial Photos - 1991.

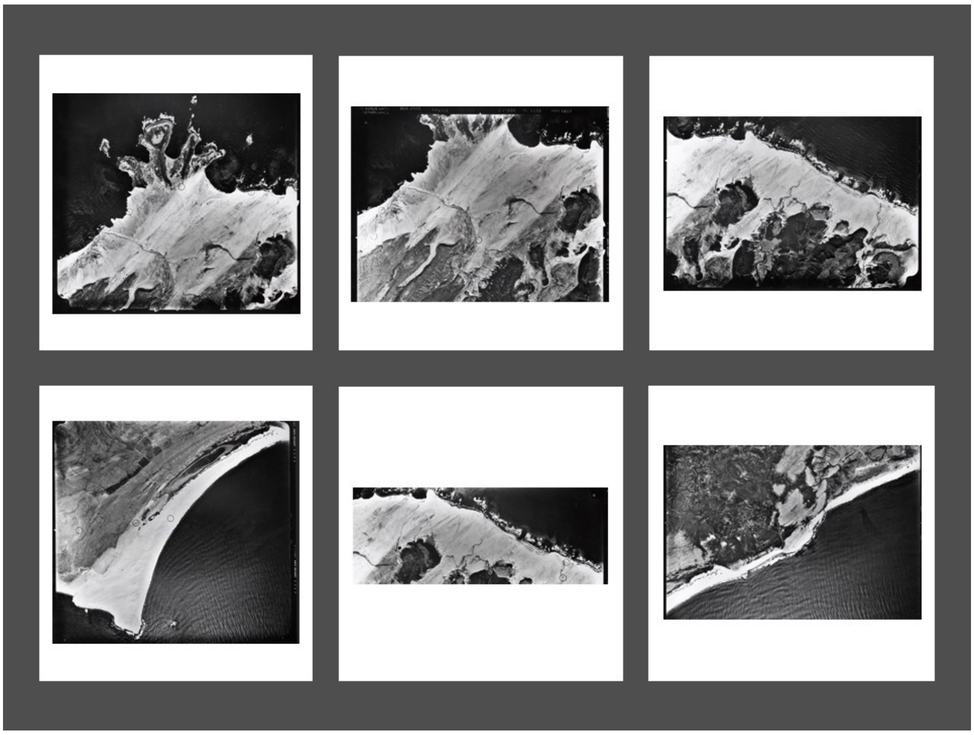


Figure C.13: Aerial Photos - 1991.

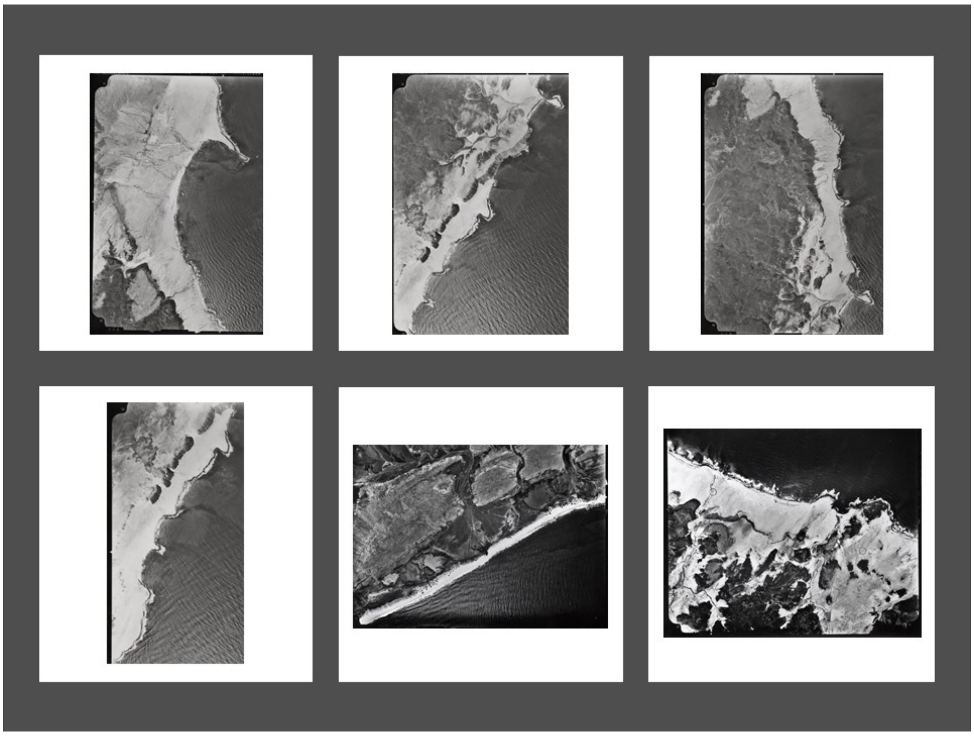


Figure C.14: Aerial Photos - 1991.

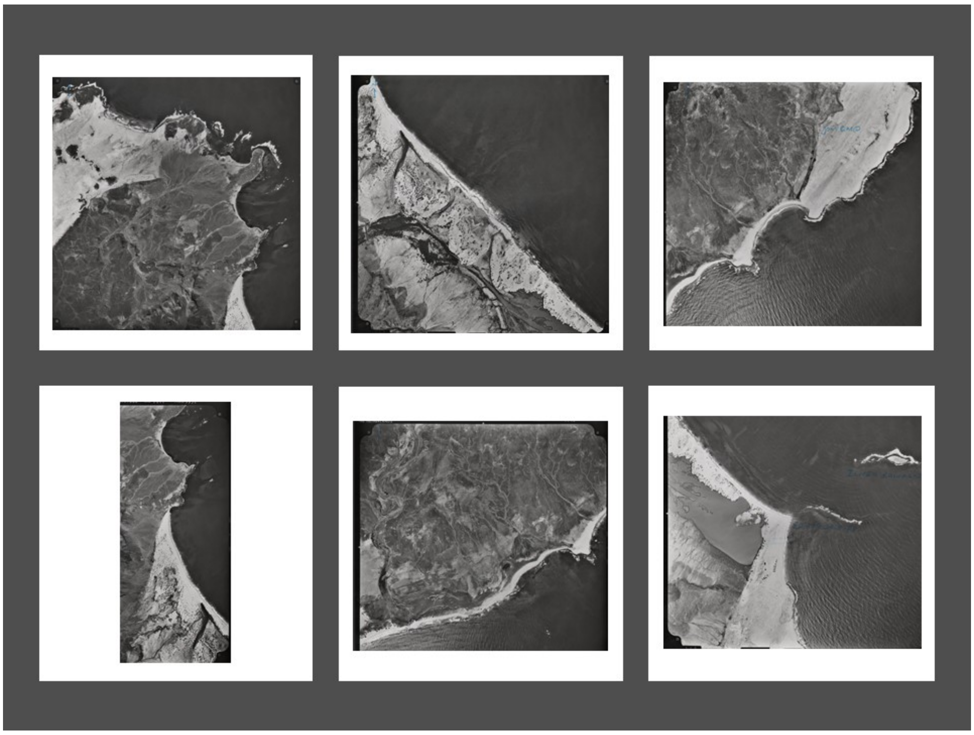


Figure C.15: Aerial Photos - 1991.

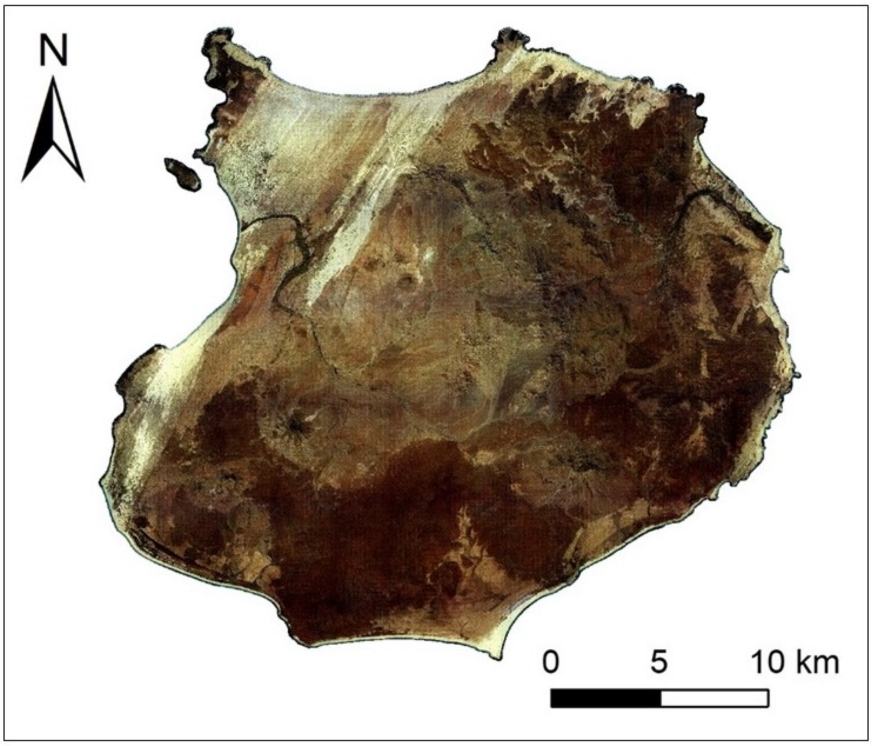


Figure C.16: Ortophoto - 2003.

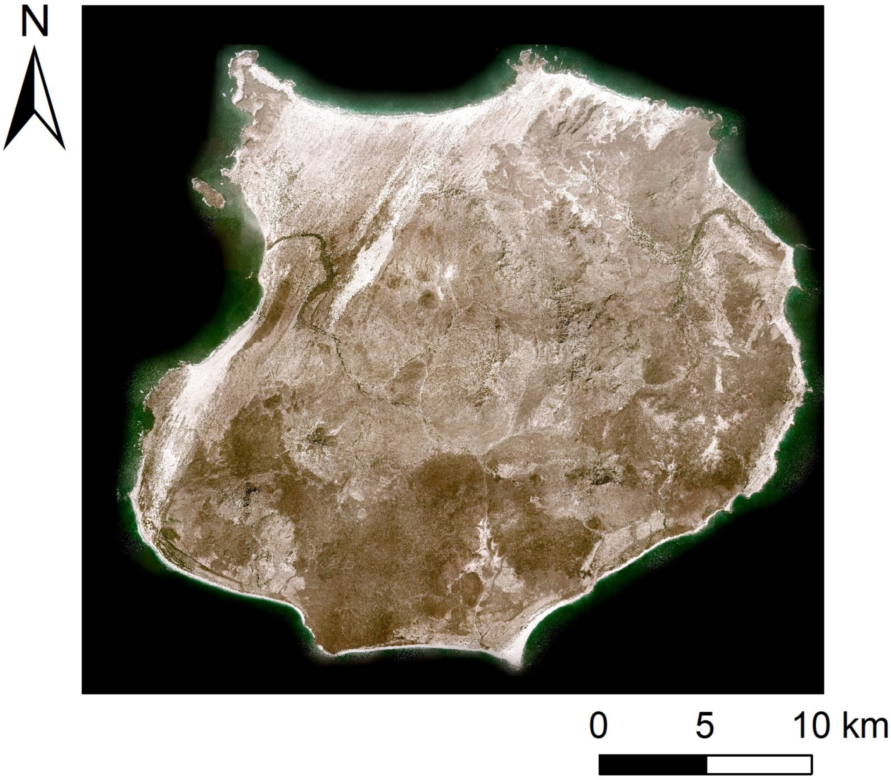


Figure C.17: Ortophoto - 2010.

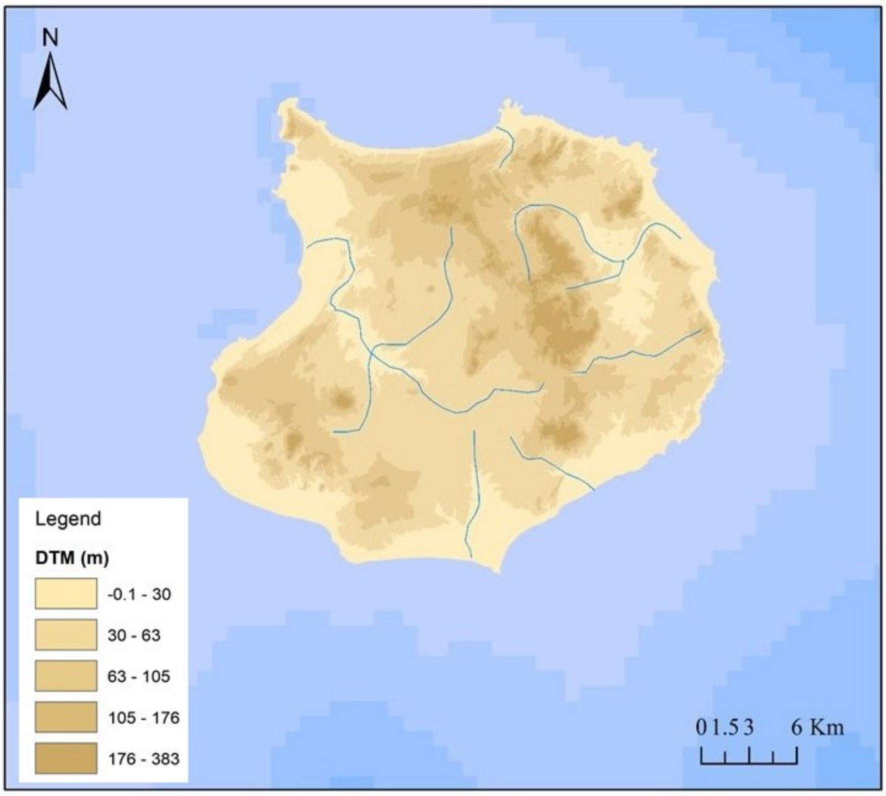


Figure C.18: Digital Terrain Model

Appendix D

Supplementary Material to Chapter 2 - Aerial Photos Georreferencing Errors

Points number	Points of 10%	Text number	Total	minimum	mean	maximum	Stand. Pad	Mean quadratic error	Buffer (m)
100	10	5	50	0	3.7	8.81	2.27	4.34	500
91	9	6	54	0.42	5.82	22.93	5.28	7.86	500
62	6	9	54	0.36	3.7	8.54	2.41	4.4	500
87	9	6	54	0.35	3.02	14.38	2.72	4.07	500
50	5	10	50	0.32	4.13	55.13	7.52	8.7	500
42	4	13	52	0.34	10.95	57.24	15.16	18.7	1000
88	9	6	54	0.35	2.24	22.7	3.3	4	500
74	7	8	56	0.32	2.1	6.61	1.27	2.45	1000
52	5	10	50	0.32	4.51	23.01	5.99	7.5	500
44	4	13	52	0.7	2.4	12.05	1.89	3.06	500
44	4	13	52	0.2	1.37	33.11	4.46	4.67	500
55	6	9	54	0.33	1.99	7.81	1.44	2.46	500
176	18	3	54	0.67	1.91	4.5	0.9	2.11	500

Aerial photos: 1968

Square Root: 7.135225726

Points number	Points of 10%	Text number	Total	minimum	mean	maximum	Stand. Pad	Mean quadratic error	Buffer (m)
55	6	9	54	0.34	2.67	7.13	1.68	3.15	1000
100	10	5	50	0.33	2.68	10.74	1.98	3.33	500
79	8	7	56	1.16	5.47	34.34	6.83	8.75	1000
61	6	9	54	0.29	3.95	15.42	3.4	5.21	500
83	8	7	56	0.31	3.04	9.67	2.03	3.65	500
102	10	5	50	0.33	3.85	12.99	2.58	4.64	500
100	10	5	50	0.28	3.62	12.23	2.64	4.48	500
111	11	5	55	0.76	5.89	28.24	6.07	8.46	500
125	13	4	52	0.33	4.92	35.69	6.81	8.41	500
134	13	4	52	0.32	2.59	16.28	2.62	3.68	500
169	17	3	51	0.67	3.38	8.29	2.09	3.98	500

Aerial photos: 1983

Square Root: 5.65141173

Points number	Points of 10%	Text number	Total	minimum	mean	maximum	Stand. Pad	Mean quadratic error	Buffer (m)
258	26	2	52	0.26	1.67	4.91	1.08	1.99	500
70	7	8	56	0.27	1.39	3.74	0.83	1.62	500
316	32	2	64	0	1.08	4.23	0.75	1.31	500
348	35	2	70	0.19	1.46	5.2	0.99	1.76	500
300	30	2	60	0	1.42	15.34	2.04	2.48	500
200	20	3	60	0	1.75	8.37	1.27	2.16	500
103	10	5	50	0.53	1.5	3.82	0.89	1.75	500
239	24	3	72	0	1.62	5.61	1.04	1.93	500

Aerial photos: 1991

Square Root: 1.903995798

Appendix E

Supplementary Material to Chapter 3 - Textural and Compositional Analysis, and Dune Displacement Errors

	SAMPLES	% COARSE	% FINES	MEAN	SORTING	SKEWNESS	KURTOSIS	DESCRIPTION				FLEMMING 2000	% $CaCO_3$
DUNES	**1**	81.58	18.42	1.62	0.76	0.06	0.87	MS	MSt	SI	P	MSd	91.13
	4	98.56	1.44	2.06	0.49	-0.03	1.02	FS	WS	SI	Mk	Sd	90.75
	5	99.35	0.65	1.81	0.56	0.04	0.90	MS	MWS	SI	Mk	Sd	89.25
	6	99.70	0.30	1.78	0.68	0.20	0.82	MS	MWS	FSk	P	Sd	90.00
	7	99.56	0.44	1.69	0.75	0.13	0.83	MS	MSt	FSk	P	Sd	89.41
	13	99.58	0.42	2.24	0.42	-0.01	1.18	FS	WS	SI	L	Sd	89.98
	22	100.00	0.00	2.40	0.39	0.05	0.96	FS	WS	SI	Mk	Sd	91.75
BEACHES	**2**	100.00	0.00	2.090	0.377	-0.098	1.023	FS	WS	SI	Mk	Sd	79.95
	3	100.00	0.00	2.105	0.595	-0.140	0.947	FS	MWS	CS	Mk	Sd	89.23
	8	100.00	0.00	1.889	0.414	-0.064	0.918	MS	WS	SI	Mk	Sd	81.88
	9	100.00	0.00	2.105	0.447	-0.090	1.057	FS	WS	SI	Mk	Sd	84.02
	9B	100.00	0.00	2.177	0.444	-0.107	1.283	FS	WS	CS	L	Sd	85.13
	10	100.00	0.00	2.069	0.463	-0.087	1.027	FS	WS	SI	Mk	Sd	87.36
	14	100.00	0.00	2.025	0.479	-0.111	1.037	FS	WS	CS	Mk	Sd	91.13
	15	100.00	0.00	1.987	0.450	-0.059	1.012	MS	WS	SI	Mk	Sd	89.57
	16	100.00	0.00	1.337	0.469	0.040	1.001	MS	WS	SI	Mk	Sd	80.36
	17	100.00	0.00	1.211	0.890	0.205	0.729	MS	MSt	FSk	P	Sd	88.72
	18	100.00	0.00	1.818	0.491	-0.122	0.931	MS	WS	CS	Mk	Sd	87.30
	19	100.00	0.00	1.550	0.329	-0.169	0.771	MS	VWS	CS	P	Sd	84.74
	20	100.00	0.00	1.875	0.583	-0.136	1.011	MS	MWS	CS	Mk	Sd	89.08

MS-Medium Sand; MSt-Moderately Sorted; St-Sorted; SI-Symmetrical; P-Platykurtic; MSd-Mud Sand ; FS-Fine Sand; WS-Well Sorted; Mk-Mesokurtic; Sd-Sand; MWS-Moderately Well Sorted; FSk-Fine Skewned; L-Leptokurtic; CS-Coarse Skewed;

Compositional analisis of Boa Vista island sediments

Samples	Biogenics	Terrigenous
1	88.3	11.7
4	92.1	7.9
5	94.7	5.3
6	88.5	11.5
7	92.8	7.2
13	96.7	3.3
22	94.9	5.1
2	85.6	14.4
3	86.2	13.8
8	90.9	9.1
9	93.2	6.8
9b	94.6	5.4
10	95.5	4.5
14	97.5	2.5
15	98.2	1.8
16	94.4	5.6
17	93.0	7.0
18	96.3	3.7
19	95.5	4.5
20	91.2	8.8

Descriptive morphometric data of Dunas de Chaves aeolian corridor (n = 29), Boa Vista Island.

Dunes	Migration rate (m) (m/ano)	Volume (V) (m^3)	Width (W) (m)	Length (L) (m)	Height (H) (m)	Aeolian transport rate (Q) (m^3 m^{-1} $year^{-1}$)	Total transport (m) (m^3 m^{-1} $year^{-1}$)
1	28.11	35098.93	92.622	84.428	16.04	126.15	126153.86
2	34.21	17560.24	73.252	68.046	12.93	120.52	120523.14
3	28.99	21974.52	90.768	68.618	13.04	102.29	102294.79
4	35.44	6837.24	62.49	45.924	8.73	84.43	84427.82
5	36.68	12474.76	70.11	58.878	11.19	110.85	110849.18
6	33.03	10417.37	70.724	53.29	10.13	91.31	91306.29
7	27.17	30264.85	96.624	77.814	14.78	109.35	109346.75
8	35.41	13995.17	65.284	64.096	12.18	118.43	118430.96
9	35.87	7850.15	56.104	51.97	9.87	96.57	96572.91
10	30.08	21427.33	96.08	64.696	12.29	103.68	103683.64
11	27.76	14214.22	76.386	59.77	11.36	86.43	86425.43
12	17.13	49944.98	120.58	89.69	17.04	79.12	79116.21
13	19.23	32876.48	97.625	79.05	15.02	81.94	81942.44
14	21.44	23136.69	83.69	73.174	13.90	81.00	80997.79
15	20.63	50677.08	128.04	87.412	16.61	93.41	93413.53
16	18.53	49579.23	115.35	88.61	16.84	89.87	89865.38
17	20.47	63613.02	148.45	91.574	17.40	95.78	95780.09
18	24.27	30361.86	99.04	76.492	14.53	97.27	97266.59
19	20.87	40937.27	127.82	79.004	15.01	84.61	84606.43
20	23.20	30335.18	104.37	72.98	13.87	92.39	92386.90
21	25.39	19600.21	93.162	64.02	12.16	83.44	83444.04
22	31.70	8401.53	77.152	45.85	8.71	75.29	75294.49
23	25.97	38995.49	158.01	69.204	13.15	92.62	92617.91
24	21.13	41786.64	132.02	78.56	14.93	85.14	85143.33
25	27.79	21929.69	131.47	56.004	10.64	82.77	82771.23
26	23.82	21397.65	102.39	67.182	12.76	74.09	74085.48
27	27.10	14915.46	84.824	57.996	11.02	82.16	82155.03
28	26.46	8286.32	67.01	49.054	9.32	66.69	66692.01
29	27.17	32813.91	109.74	76.35	14.51	106.39	106393.91

Verification Points of Dunes displacements - X Coordinates

Dunes (ID)	Years							
	2005	2010	2012	2013	2015	2016	Media	Sd. Dev.
1	273828.3	273820.5	273820.7	273837.7	273816.2	273819.4	273823.8	7.9
2	273916.8	273912.7	273911.5	273891	273909	273911	273908.6	9.0
3	273949.7	273944.5	273944.3	273956.8	273940.1	273934.7	273945	7.6
4	273794.2	273792.8	273788.2	273800	273801	273803.2	273796.6	5.8
5	273800.3	273794.8	273795.8	273807.9	273793.9	273791.4	273797.3	6.0
6	273638.3	273630.1	273628.9	273643.3	273627.8	273628.6	273632.8	6.4
7	273378.1	273372.7	273372.8	273386.3	273368.3	273369.7	273374.6	6.6
8	273389.4	273381.5	273380	273394.8	273380	273379.1	273384.1	6.5
9	273521	273514.1	273513.2	273526.8	273511	273511.7	273516.3	6.3
Media	273690.7	273684.8	273683.9	273693.8	273683	273683.2		
Sd. Dev.	217.9	218.8	218.8	214.3	219.3	218.8		

Verification Points of Dunes displacements - Y Coordinates

Dunes (ID)	Years							
	2005	2010	2012	2013	2015	2016	Media	Sd. Dev.
1	151715.2	151715.2	151714.2	151723.1	151711.6	151715.8	151715.9	3.8
2	151653.5	151652.5	151650.6	151662.4	151647.8	151651.1	151653	5.0
3	151714	151716.6	151713	151727.1	151710.9	151712.9	151715.7	5.9
4	150600.7	150602.1	150602.6	150620.6	150619.1	150621.1	150611	10.1
5	150690.9	150689.9	150688.9	150697.9	150688.8	150690.4	150691.1	3.4
6	150623.1	150623	150622.1	150631.6	150620.2	150624	150624	4.0
7	152584.6	152582.9	152581.1	152592.6	152579.3	152582.9	152583.9	4.6
8	152639.7	152637	152636	152648.3	152636	152638.9	152639.3	4.6
9	152580.7	152579.8	152578.1	152588.6	152578.9	152578.9	152580.8	3.9
Media	151644.7	151644.3	151642.9	151654.7	151643.6	151646.2		
Sd. Desv.	851.7	850.9	850.4	850.0	848.0	847.9		

Appendix F

Supplementary Material to Chapter 4 - Global Mean Sea Level Rise Projected for 2100

Source	Sea Level Rise - Projections for 2100	Methods used
(Hoffman *et al.*, 1983)	0.56 to 3.45 m	Approach assumptions and models
Dias and Taborda (1988)	0.140 to 0.572 m	Tide Gauges
IPCC (1990)	0.31 to 1.10 m	Business-as-Usual emissions scenario IPCC IS92a forcing scenario using a climate sensitivity of 2.5°C
IPCC (1996)	0.20 to 0.86 m	For the mid projection and 1.5°C; 4.5°C for the low and high projections, respectively
IPCC (2001)	0.11 to 0.77 m	Using a range of AOGCMs following the IS92a scenario
IPCC (2007)	0.22 to 0.44 m	Under the IPCC (SRES) A1B scenario
Rahmstorf (2007)	0.50 to 1.4 m	Based in global mean surface temperature
Vermeer and Rahmstorf (2009)	0.75 to 1.90 m	Tested on synthetic data from a global climate model for the past millennium and the next century
Jevrejeva *et al.* (2012)	0.57 to 1.10 m	Physically plausible sea level model constrained by observations and forced with 4 new RCP radiative forcing scenarios
(IPCC, 2013a)	0.52 to 0.98 m	IPCC - RCP scenarios – 8.5
(NOAA, 2017)	0.30 to 2.5 m	Global Mean Sea Level (GMSL)
(IPCC, 2019)	0.29 to 1.10 m	Global Mean Sea Level (GMSL)