Chapter 1
Tropical Marine Environments of Brazil and Impacts of Climate Change

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Abstract Ongoing climate change has the potential to severely affect the tropical marine environments of Brazil. This chapter provides a brief overview of these environments with a major focus on deltas, mangrove forests, reefs, continental shelves, the zoo- and ichthyoplankton communities of pelagic ecosystems and major processes operating in the Tropical Atlantic. The impacts of ongoing climate change are also summarized. Additionally, the book organization is presented, including a brief description of each chapter.

Keywords Mangroves · Deltas · Coral reefs · Continental shelf · Pelagic ecosystems · Tropical Atlantic · Climate variability

1.1 Introduction

Climate change will affect the physical, biological, and biogeochemical characteristics of coastal zones and oceans, impacting their ecological structure and the different services provided to humankind. These changes have the potential to cause serious socioeconomic impacts at the local (coastal), regional (platform and shallow seas), and global (ocean) scales. The responses of marine environments to climate change will also depend on the natural variability of these systems and other changes introduced by humans as a result of the use of marine resources, making coastal and shelf areas more vulnerable to natural hazards.

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The tropical region of Brazil presents a unique opportunity to assess how the spatial and temporal heterogeneity of tropical marine environments influences the response patterns of these environments and their resilience to climate change that will affect the region in this century. This region contains the main reef constructions of the southwestern Atlantic Ocean, the Brazilian deltas, the second largest area of mangroves in the world in a single country, a continental shelf that varies from the narrowest to the widest in Brazil, the main islands and seamounts, extreme variations in sediment and nutrient flows, and an undeniable importance in interhemispheric heat and mass transfer (Fig. 1.1).

This book summarizes the major advances in knowledge of the marine environments of tropical Brazil as a result of the execution of the National Institute for Science and Technology in Tropical Marine Environments (inctAmbTropic) project. The National Institutes of Science and Technology Program (INCTs) was started in 2008 and financed by the National Fund for Scientific and Technological Development (FNDCT) in partnership with state research support foundations. This program enabled the configuration of interregional networks of collaboration with national coverage and academic, scientific, and technological performance compatible with the best international programs.

The inctAmbTropic conducts research at three spatial scales: (i) coastal zone—characterized by great physical and biological heterogeneity and the interface of interactions between natural and anthropogenic forcings, (ii) continental shelf—an area also of great heterogeneity and still poorly understood and (iii) ocean—a component of the Earth system influenced by mass transport and its interactions with the atmosphere.

The well-being of human communities intrinsically depends on the availability of services that coastal and marine ecosystems provide. This is particularly important for the northern and northeastern regions of Tropical Brazil, which has, in some of its coastal municipalities, population densities that are among the highest in the country (Fig. 1.1). Understanding how different marine environments will react to climate change in the coming decades is therefore of strategic importance for the region.

1.2 The Tropical Marine Environments of Brazil

The main tropical marine environments of Brazil include (i) the wave-dominated deltas, (ii) the main coral reefs of the western South Atlantic, (iii) one of the most important mangrove forests on the planet, and (iv) a mostly narrow continental shelf bathed by oligotrophic waters, starved of sediments and therefore dominated by carbonate sedimentation. Additionally, this region plays an important role in biogeochemical cycles, CO_2 flux, and circulation in the Tropical Atlantic Ocean.

From a physiographic point of view, this area is divided into 3 sectors (Dominguez 2009): (i) the deltaic coast of eastern Brazil, (ii) the sediment-starved coast of northeastern Brazil, and (iii) the tidal embayment from the Amazon (Fig. 1.1).

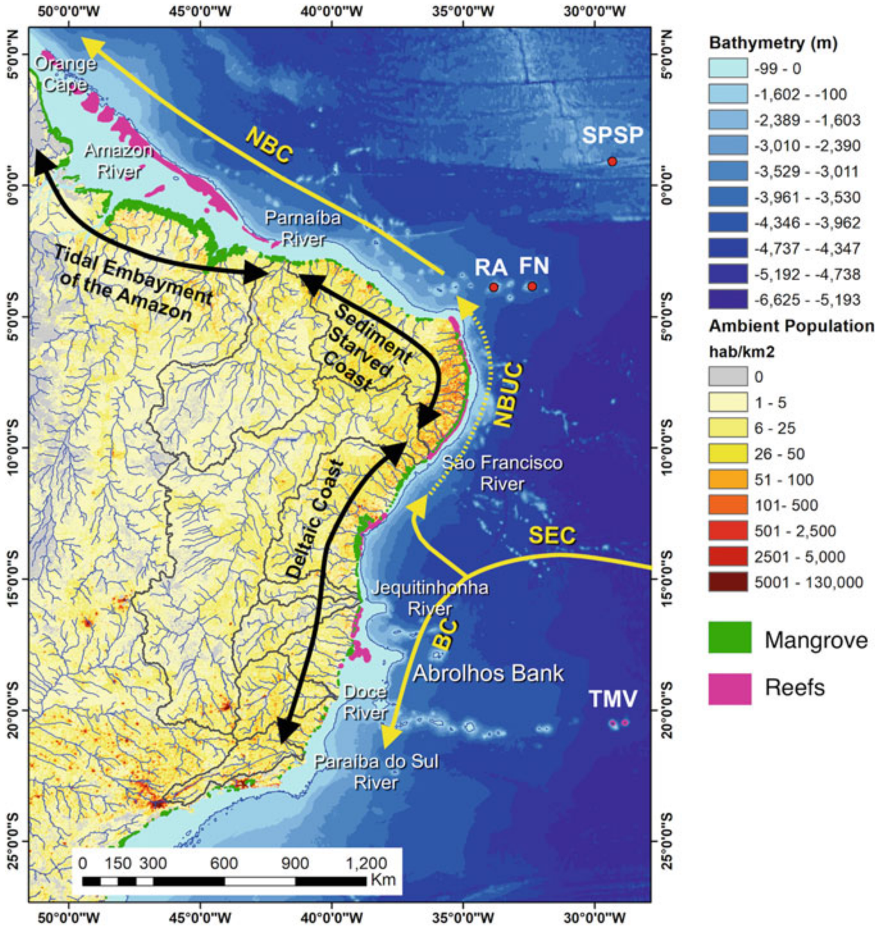

Fig. 1.1 Major tropical marine environments of Brazil. Ambient population refers to an average, or ambient, population that integrates diurnal movements and collective travel habits into a single measure (Dobson et al. 2000). *Source* Landscan Global Population Dataset. FNFernando de Noronha Archipelago; AR: Rocas Atoll; SPSP: Saint Peter and Saint Paul Archipelago; TMV: Trindade Martin Vaz islands; BC: Brazil Current; SEC: South Equatorial Current; and NBUC: North Brazil Undercurrent

1.2.1 The Deltaic Coast of Eastern Brazil

In this section of the coast, the major escarpment typical of rifted passive continental margins (Gilchrist and Summerfield 1994; Seidl et al. 1996; Matmon et al. 2002) retreated back from the coastal zone almost 500 km. All major rivers emptying into this section of the coast have their headwaters in this escarpment, except for the Paraíba do Sul and the São Francisco rivers.

A combination of large drainage basins with high intrabasin relief has resulted in large sediment yields in the major rivers emptying in this section of the coast of Brazil, resulting in classical examples of wave-dominated deltas (Parnaíba, Doce, Jequitinhonha-Pardo, and São Francisco) examined in detail in Chap. 4 (Fig. 1.1).

The continental shelf along this stretch varies from very large (south) to very narrow (north). The Abrolhos Bank, the widest portion of the shelf, has had its origin associated with volcanic activity that occurred between the Paleocene and the Eocene (Mohriak 2006). The narrowness of the shelf north of the Abrolhos Bank results from the presence of the São Francisco craton, a geotectonic unit of Archean-Paleoproterozoic age (Heilbron et al. 2017) that intercepts the shoreline in this stretch of the coastal zone. Overall, along this sector, the shelf break begins at the 50–60 m isobath. Shelf sedimentation away from major river mouths and along the outer shelf is carbonatic, having as a major constituent fragments of incrusting coralline algae and rhodoliths (Dominguez et al. 2013; Bastos et al. 2015) (see Chap. 6).

The most important coral reefs of the western South Atlantic have developed on the Abrolhos Bank in waters shallower than 20 m in a sediment-starved portion of the shelf located between the Jequitinhonha and Doce River deltas (Fig. 1.1). Chapter 5 presents a detailed characterization of the coral reefs present in this sector. Chapter 6 details the characteristics of two shelf areas of this sector (Abrolhos and Central Bahia).

1.2.2 The Sediment-Starved Coast of Northeastern Brazil

This section of the Brazilian coastline currently receives the smallest volume of sediment from the hinterland as a result of the small size of the drainage basins in association with low intrabasinal relief and low precipitation (Fig. 1.1). This coast is thus characterized by a long-term trend of shoreline retreat (Dominguez and Bittencourt 1996), displaying cemented upper shoreface sands ("beachrocks"), reef build-ups, and active sea cliffs carved into early-middle Miocene tablelands. The continental shelf is mostly narrow (< 20 km), a result of the combined effects of this region being the last to separate from Africa during the Mesozoic continental break-up (Rand and Mabesoone 1982), a dominance of transcurrent movements during separation and very limited sediment supply.

Sedimentation is dominantly carbonatic as a result of the very low terrigenous sediment influx. Additionally, because of the reduced sediment influx, most incised valleys carved into the shelf during the Quaternary lowstands are unfilled and have a morphological expression in the bathymetry. Two shelf sectors of this compartment are characterized in detail in Chap. 6.

This sector also contains most of the oceanic islands of Brazil, the Fernando de Noronha Archipelago (FN), the Rocas Atoll (RA), and Saint Peter and Saint Paul Archipelago (SPSP) (Fig. 1.1).

The shelf area is characterized by extreme oligotrophy, whose zoo- and ichthyoplankton communities are described in detail in Chap. 7. On the other hand, the presence of oceanic islands alters the oligotrophy of the typical tropical structure, which includes a strong, permanent thermocline. This alteration involves upwelling by local processes such as surface current divergence, winds, and interactions between the currents and submarine relief (Travassos et al. 1999; Araujo and Cintra 2009), providing nutrients to the photic zone (Neumann-Leitão et al. 1999). As a result, an increase in productivity occurs at numerous trophic levels, ensuring the maintenance and increase of the diversity of planktonic communities (Boltovskoy 1981; Melo et al. 2012) (see Chap. 7).

1.2.3 The Tidal Embayment of the Amazon

This sector extends approximately from the Parnaiba Delta to the Orange Cape, and it is characterized by a broad re-entrant in the coastal zone, which extends for more than 1000 km of shoreline. The combined flows of the Amazon and Tocantins/Pará Rivers bring to the coastal zone the largest sediment load in all of South America. This sector is also characterized by the highest tides in Brazil (Cartwright et al. 1991; Salles et al. 2000), with tidal ranges varying from 3 to 6 m. A combination of large sediment supply and tidal range has favored the development of extensive progradation of the shoreline under tidal dominated conditions, with shoreline progradation of up to 30 km (Souza-Filho et al. 2006) (see Chap. 3).

Two deltas occur in this sector: the tide-dominated delta of the Parnaíba (see Chap. 4) and the Amazon, which was the subject of a recent synthesis by Nittrouer et al. (2021) and therefore was not included in this book. On the shelf, sedimentation is mostly siliciclastic, although carbonate sedimentation dominates on the outer shelf. More recently, a major reef complex has been described for the outer shelf of this region (Moura et al. 2016).

In the coastal zone, the largest continuous mangrove belt of the world occurs occupying a total area of 7500 km^2 (see Chap. 3).

The large continental runoff with macrotidal mangroves originates from estuarine plumes on scales of dozens to hundreds of kilometres, which makes this region an extremely productive ecosystem. This region is among the most important fishing grounds in Brazil and may play an important role in regulating these North Brazilian shelf ecosystems. The zooplankton and ichthyoplankton communities along two transects in this compartment are presented in Chap. 7.

1.2.4 The Tropical Atlantic Ocean

The tropical Atlantic is characterized by permanent oligotrophic conditions outside the areas affected by river discharge (Da Cunha and Buitenhuis 2013) due to the relatively strong static stability with a well-marked thermocline, which is seasonally modulated by the meridional displacement of the ITCZ, controlling precipitation and trade wind regimes (Araujo et al. 2011; Assunção et al. 2020). The permanent thermocline restricts vertical mixing and nutrients up to photic layers and constrains biological productivity (Araujo et al. 2019).

Additionally, the tropical Atlantic is a complex region with two main current systems in play, the equatorial system and the western boundary system. The equatorward western boundary North Brazil Current and Undercurrent (NBC–NBUC) contributes to the upper Atlantic Meridional Overturning Circulation (AMOC) (Fig. 1.1). The currents, winds, precipitation, biogeochemical cycles, and CO_2 flux are seasonally regulated by the Intertropical Convergence Zone.

The tropical Atlantic is also the second-largest oceanic source of CO_2 to the atmosphere after the tropical Pacific (Lefèvre et al. 2010; Ibánhez et al. 2015; Araujo et al. 2019). Despite the net CO_2 outgassing registered in this region, zones of net atmospheric CO_2 uptake exist, which are mainly linked to the seasonal cycle of sea surface temperature (SST) and its associated thermodynamic effects on the partial pressure of CO_2 (pCO_2) (Ibánhez et al. 2015).

Under low discharge conditions, the spread of the Amazon plume acts as an atmospheric CO_2 sink of global relevance (Lefèvre et al. 2010; Ibánhez et al. 2015). In contrast, the northeastern Brazil region acts primarily as a CO_2 source to the atmosphere, with the highest CO_2 fluxes associated with periods of high SST in the area (Araujo et al. 2019). These aspects are discussed in detail in Chap. 8.

1.3 Climate Change Impacts

1.3.1 Deltas

In addition to the reduction in rainfall in the catchments, another major impact of climate change on deltas is sea-level rise and its implications for delta plain inundation and erosional shoreline retreat (Ibáñez et al. 2014). These aspects have been aggravated in recent decades by the construction of dams and artificial dikes that have reduced the ability of deltas to grow vertically (aggradation) and to feed the coastline with sediments (Vörösmarty et al. 2003; Syvitski et al. 2009; Day et al. 2016).

In the particular case of the Brazilian deltas, a few aspects must be considered when analyzing their vulnerability to climate change, since most of the delta plain is composed of beach dune deposits. The top of these beach-dune deposits is significantly higher than the mean sea level due to wave run-up (berm height is a function of the wave height at breaking) and Aeolian deposition (actually, most delta plain beach ridges were formed as dune ridges), which further contributes to increasing the average elevation of the terrain. Additionally, because they were built in a Glacial Isostatic Adjustment (GIA) far field region, the more internal beach deposits are approximately 3–4 m higher than those located in the outermost region of the delta plain (see Chap. 4). These factors contribute to increasing the resilience of these deltas to a rise in sea level.

Notwithstanding, the pristine tide-dominated delta of the Parnaíba has a vulnerability to sea-level rise much higher than the other wave-dominated deltas because most of this delta plain is occupied by mangrove swamps. The survivability of Parnaíba to current sea-level rise will depend on the capacity of these mangrove swamps to build up in response to a rising sea level.

For all Brazilian deltas, the results of climate models point to a reduction in precipitation in the watersheds, implying a reduction in river flows and, consequently, in the contribution of sediments to the mouth (Arias et al. 2021).

1.3.2 Mangroves

As detailed in Chap. 3, the response of the mangrove coasts to ongoing and future sea-level rise will depend on the environmental setting of the mangroves.

On open coasts, a rise in sea level will cause an increase in upstream penetration of the salt wedge and landward migration of mangroves along riverine and supratidal flats that are progressively converted to intertidal flats. However, erosive processes at the seaward front can result in mangrove loss along the shoreline (Allison et al. 2000; Anthony et al. 2010; Santos et al. 2016).

If sea level is rising over an open coast sheltered by barrier islands and densely colonized by mangroves and bounded landward by inactive cliffs, the muddy tidal flat will experience an elevation in water level and a sedimentary aggradation process. The landward retreat of the shoreline due to the rising sea level will result in barrier sand deposition over muddy flats and mangroves. This will cause coastal erosion, increased salinity, hydroperiod frequency, and inundation depth in mangrove forests (Souza-Filho and Paradella 2003; Souza-Filho et al. 2006).

Along deltaic coasts, the rise in sea level will result in increased salt wedge penetration and landward retreat of beach-dune ridges, occasionally burying tidal muddy flats colonized by mangroves.

Finally, tropical tidal flats fringing high gradient land regions or human-made obstacles such as seawalls and other shoreline protection structures will be the most threatened mangroves from sea-level rise. They will likely be drowned "in place" due to a lack of low-lying areas over which they can migrate (Lacerda et al. 2021).

1.3.3 Coral Reefs

Tropical southwestern Atlantic reefs are affected by a plethora of human stressors, including large-scale (global climate change-related processes, such as long-term warming, marine heatwaves, ocean acidification, and sea-level rise) or local but widespread impacts, such as mismanaged touristic and industrial activities, higher nutrient inputs, increased macro- and micro-plastic pollution, environmental disasters (e.g., oil spills and mining dam collapses), overfishing of reef species, and invasive species.

As detailed in Chap. 5, eastern-northeastern Brazil are reef areas that concentrate a higher diversity of habitats (reef forms) and major reef organisms, such as coral and fish communities. The Abrolhos Bank hosts one of the most important shallow water reef complexes of the western South Atlantic Ocean.

Shallow water coral richness is also higher in these regions, where *Mussismilia* species and milleporids are important constituents of the reef-building fauna. Global climate change shifts limit the control and survival of reef-building and dwelling organisms. Projections of future habitat suitability show that the most restricted species (*Mussismilia harttii* and *Mussismilia braziliensis*) can migrate north, a trend that can be enhanced by the increase in aridity and possibly an increase in temperature and salinity in the shallow shelf areas. On the other hand, turbidity might play an opposite role to these prognostications. *Mussismilia hispida*, on the other hand, might benefit from the tropicalization of the temperate realm and migrate south.

1.3.4 Continental Shelf

Important abiotic changes associated with climate change are expected to affect shelf areas. These include changes in atmospheric circulation that will lead to an increase in storm frequency; changes in precipitation affecting terrestrial-derived sediment, nutrients and pollutants; changes in salinity and temperature of the coastal ocean; and changes in ocean chemistry (pH). These changes will directly affect the shelf benthic communities (Holt et al. 2010). Although shelf seas comprise only 7% of the global ocean, they provide extremely important services for human society. The dominance of hard seabed substrates on the northeastern Brazil Shelf (NEBS) significantly increases the biodiversity of these regions. Changes in ocean chemistry can severely affect calcium carbonate-secreting organisms, such as corals and coralline algae, and impact their capacity to create reefs in some locations (Cornwall et al. 2019). In this respect, coralline algae, which are abundant on the NEBS, are considered one of the most crucial foundation taxa in the photic zone (Cornwall et al. 2019). Unfortunately, the NEBS region still lacks robust scientific data to allow a more in-depth evaluation of the impacts of climate change on its seabed and habitats. At the same time, there is a strong pressure for the use of the NEBS seabed, particularly from the energy and marine mineral industries, which creates new research opportunities to carry out mapping and characterization of the seabed.

1.3.5 Zoo- and Ichthyoplankton Communities

The results presented in Chap. 7 show considerable seasonal variability in the zoo- and ichthyoplankton communities, with large peaks in abundance and biomass, indicating that these planktonic systems are not stable at all but rather highly dynamic, with very strong responses to seasonal variations in climate and hydrography. Therefore, these systems are prone to show strong and exacerbated responses to climate variations in the near future, functioning as "amplifiers" of climate signals. Such responses may include drastic changes in the productivity of the ecosystem, but they may also manifest as unprecedented shifts in the timing of the peaks and blooms, leading to a deleterious disarrangement in the food webs, the "trophic mismatch" (Thackeray 2012).

The expected ecosystem responses are highly complex and totally different depending on the study area. In tropical oceanic ecosystems, the expected warming and deepening of the upper mixed layer (Roch et al. 2021) will most likely lead to increased stratification in layers above the permanent thermocline and thus to a reduction in primary (Gittings et al. 2018) and secondary productivity in the coming decades, with deleterious consequences for carbon sequestration, oceanic fish stocks (e.g., tuna and mackerels), seabirds, and other upper trophic levels.

For tropical pelagic ecosystems on the continental shelf, the situation is completely different, since they usually do not have a permanent thermocline. Tides and wind-driven turbulence usually break up any strong thermal stratification, except for areas with estuarine plumes. For the nearshore shelf, coastal and estuarine processes are very important, especially continental runoff. Extreme events, such as very strong rainfall, have drastic consequences for these nearshore ecosystems.

1.4 Book Organization

This book is arranged into 8 chapters.

This chapter provides a general overview of the subject.

Chapter 2 provides definitions of what climate variability and change are and an overview of observed and projected changes in climate in tropical South America. Temperature, rainfall, and drought projections are assessed from an ensemble of global and regional model projections under global warming scenarios of 1.5 and 4.0 °C for various regions of South America.

Chapter 3 presents a characterization of the mangrove swamps along the coast of Brazil and their subdivision based on geological, morphological, oceanographic, and climatic characteristics. It also discusses their spatiotemporal stability and changes in area from 1985 to 2020, sea-level changes and mangrove sedimentation evolution during the late Quaternary, and the impact of future sea-level rise.

Chapter 4 presents a synthesis of the wave-dominated deltas of Brazil, which are subject to different climatic zones, tidal regimes and wave climates, and different degrees of regulation and human occupation, ranging from pristine to human-influenced deltas. Vulnerability to climate change is also examined, particularly concerning the rise in sea level.

Chapter 5 synthesizes the main characteristics of the distribution and variability of reef and coralline ecosystems of the tropical southwestern Atlantic. These reefs are known as marginal reefs because they thrive in environmental conditions (high turbidity) far from those considered to be the optimal conditions for framework builders (calcareous skeleton-secreting organisms, such as corals). Additionally, three endemic coral species (*M. hispida*, *M. harttii*, and *M. braziliensis*) are used as proxies of the reef ecosystem to evaluate the trend of environmental suitability across the Brazilian Tropical Marine region in the RCP8.5 scenario.

Chapter 6 reviews the major characteristics of the continental shelves of northeastern Brazil, emphasizing seafloor morphology, its associated benthic ecosystems and the role of the eustatic variations in their late Quaternary evolution. Major human uses are also discussed.

Chapter 7 investigates zoo- and ichthyoplankton communities in seven Brazilian tropical marine environments that differ considerably in their abiotic and biological settings, ranging from the extremely wide continental shelf lined by mangroves off northern Brazil to the narrow oligotrophic shelf areas located in northeastern Brazil and three oceanic areas related to unique Brazilian island systems (Rocas Atoll, Fernando de Noronha, and St. Peter and St. Paul's Archipelagos).

Chapter 8 summarizes the main characteristics of the circulation, biogeochemical cycles, and CO_2 flux variability in the tropical Atlantic Ocean (TA). This is a very complex region where ocean–atmosphere interactions, oceanic currents, and phenomena such as wave propagations and mesoscale activities occur. The region is considered oligotrophic due to relatively strong static stability, with a well-marked thermocline. Additionally, the TA is the second-largest oceanic source of CO_2 to the atmosphere subject to equatorial upwelling, seasonal variations, and large river discharges, which drive the exchange of CO_2 between the sea and air.

1.5 Final Remarks

This book synthesizes the current knowledge about the major marine environments of tropical Brazil and how they might be impacted by ongoing climate change. Most results presented herein were derived from research conducted under the umbrella of the National Institute for Science and Technology in Tropical Marine Environments (inctAmbTropic) during the last 10 years. We hope this broad overview on this subject will be widely used by students, researchers, and managers interested in the subject and a source of inspiration for further studies on the topics discussed.

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