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Challenges and responses to sea level rise in the context of climate change: A case study of the Paranaguá Estuarine Complex

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ABSTRACT

Understanding the dynamics of sea surface variation and its direct effects on the coastal population has been a central issue of study for oceanography in conjunction with other areas of geosciences. One of the main challenges in a changing global ocean is continuously monitoring on an adequate scale that can detail locally varying phenomena. This study reviews the methods to obtain coastal topo-bathymetric data and the tools available to produce flood maps and coastal sea-level rise monitoring models. The advantages and limitations of the main tools are described, highlighting the difficulties related to implementation time and financial investment in contrast to the quality of the obtained data. A case study of the Paranaguá Estuarine Complex — of great environmental, economic, and tourism importance — is presented as its sea-level fluctuations have been poorly studied. For this reason, we describe the Paranaguá Estuarine Complex, highlighting and discussing the structural and methodological challenges and the lack of resources that limit the possibilities of a detailed study of the Paranaguá Estuarine Complex from the point of view of natural disasters, thus stimulating the debate on the necessary actions to address climate change at the local level.

Keywords: Sea level, Tidal flood, Vulnerable areas, Climate change

INTRODUCTION

Global warming and its induction of a rise in the global mean sea level (GMSL) has been constantly addressed by the world scientific community for years (Gornitz et al., 1982; Barnett, 1984; Pirazzoli, 1986; Gornitz and Lebedeff, 1987; Wigley and Raper, 1987; Douglas, 1997; Gregory and Oerlemans, 1998; Raper and Braithwaite, 2006; Domingues et al., 2008; Han et al., 2010; Leclercq et al., 2011; Meehl et al., 2012; Church and Clark, 2013; Mengel et al., 2016; Widlansky et al., 2020; Tebaldi et al., 2021). The GMSL showed a more significant increase in the 20th century than in the last 33 millennia, showing an average increase of 0.20 m from 1901 to 2018 (IPCC, 2021). Moreover, from the 1960s onward, the global mean sea level showed an acceleration in its elevation, with an average rate of 2.3 mm yr^{-1} from 1971 to 2018 and

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an average rate of 3.7 mm yr^{-1} from 2006 to 2018 (IPCC, 2021), with estimates of reaching 0.65 m by 2100 (Nerem et al., 2018). More specific estimates have been based on the emission of greenhouse gases into the atmosphere (IPCC, 2021).

- In a very low emission scenario, in which the concentration of greenhouse gases in the atmosphere is kept below 420 ppm (parts per million) CO_2 equivalent, sea level rise by the end of the 21st century is projected to be about 0.3 m (confidence interval of 0.2 to 0.4 m).

- In a low emission scenario, in which the concentration of greenhouse gases in the atmosphere is stabilized around 470 ppm CO_2 equivalent by the middle of the century, sea level rise by the end of the 21st century is projected to be about 0.5 m (confidence interval of 0.3 to 0.6 m).

- In a high emission scenario, in which the concentration of greenhouse gases in the atmosphere continues to increase throughout the 21st century, sea level rise by the end of the 21st century is projected to be about 1.0 m (confidence interval from 0.6 to 1.3 m).

Climate changes altering the behavior pattern of natural processes such as waves, tides, and winds across the globe will have consequences and effects on the entire world population and the environment (Allison and Bassett, 2015). Coastal zones, which are attractive for establishing diverse economic and recreational activities, provide livelihood resources and have valuable ecosystems essential for maintaining environmental quality and resilience to natural disasters (Branson and Nicholls, 1998; Nicholls et al., 2014a). However, they are among the most vulnerable areas to the impacts of climate change as they are influenced by oceanic, atmospheric, and continental agents in addition to suffering from increasing anthropization (McGranahan et al., 2007; Brecht et al., 2012; IPCC, 2014; Barbier, 2015a).

It is possible to minimize the impacts derived from climate change on the population and the environment. However, it is related to the ability of scientists to accurately survey affected populations and environments and those that may be affected in the future, which will enable the development of planning and damage mitigation tools. In this sense, in-depth knowledge of sea level rises (SLR) in the context of climate change is one of the priorities of scientists and decision-makers (GGOS, 2009; Oppenheimer and Alley, 2016; Angus and Hansom, 2021). By 2050, approximately 800 million people will live in coastal cities, where sea levels can rise by more than 0.5 meters, they will be potentially more vulnerable to the direct effects of the SLR (C40-Cities, 2018).

Rather than occurring homogeneously across the globe, SLR varies regionally due to characteristics of ocean circulation, water temperature and salinity, and vertical land movements, which, when added to anthropogenic factors, can also occur locally (Stammer et al., 2013a; Dahl et al., 2017a). Thus, the sea level depends on several factors over a given period. On a scale of 100 to 1,000 years, the sea level can be considered the sum of the GMSL, regional sea level changes due to meteo-oceanographic conditions, and the vertical movement of the physical surface of the Earth (Church et al., 2001; Kopp et al., 2015).

When assessing SLR impacts, local variation in the relative level is more important than determining the GMSL or the regional average level, which will be most effective in risk and vulnerability analyses (Klein and Nicholls, 1999). The term sea level used here refers to the relative sea level, which is the difference in elevation between the height of the sea surface (obtained by altimetry satellites) bound to a reference ellipsoid and the height of a solid surface of the Earth (the reference point of tide gauge altitudes) (Kopp et al., 2015). Therefore, when dealing with mean sea level, we consider the average of sea level values obtained over a long period, in which ocean tides are reduced, before calculating the average.

This study highlights the importance and the main difficulties encountered in developing SLR monitoring and modeling work in the face of climate change. As a case study, we describe the current situation of an estuarine complex of great economic and environmental importance on the coast of Paraná, in southern Brazil.

Sea level rise and economic losses

As mentioned, coastal regions tend to be highly populated, developed, and located at low altitudes. Thus, flood events affect society, the economy, and the local environment. For example, we can mention Hurricane Sandy, which hit the east coast of the United States in 2012, resulting in coastal flooding and totaling a loss of US$ 60 billion (De Moel et al., 2013). It is esteemed that about US$ 8.1 billion in damage stem from anthropogenic sea level rise (Strauss et al., 2021).

Studies have considered future economic expenditures that may occur according to estimates of sea level rise, such as Hallegatte et al. (2013), who estimated average annual flood losses in 136 large port cities, considering the structure and vulnerability of the population and assets, reaching a value of US$ 6 billion annually in 2005, which may reach US$ 52 billion in 2050. Prahl et al. (2018) analyzed the economic loss due to the height of coastal flooding in 600 European municipalities and estimated adaptation costs, developing damage and protection cost curves. Considering the worst SLR scenario added to extreme weather events on the Brazilian coast, the estimated material value at risk was around from US$ 83 to US$ 127 billion (Margulis and Dubeux, 2011). In Brazil, the main sectors susceptible to being affected by climate change include ports. The Brazilian port sector handles hundreds of millions of tons of various goods annually. In 2021, for example, it reached 1.21 billion tons (Anuário Estatístico, 2022).

Regional and local scale studies can add specific variables that result in more accurate analyses, such as losses of ecosystem services in raw material and food supply. For a coastal portion of Bangladesh, these losses could vary from US$ 0-1 million and US$ 16.5-20 million, respectively, in different SLR scenarios by 2100 (Mehvar et al., 2019). For the coastal region of Kuwait, in SLR scenarios from 0.5 to 1.5 meters, economic losses in the residential sector could range from US$ 612.4 million to US$ 2.3 billion in the capital of Kuwait alone, and other provinces could be more or less affected than the capital (Al-Mutairi et al., 2021).

Importance of mapping vulnerable areas

To increase resilience and provide the possibility of mitigating damages, broad knowledge about the specific problem and its risks is essential. Thus, accurate knowledge of the SLR elevation trends and the possibly affected areas can determine risk management capacity and, thus, guarantee minimum impacts on human well-being, natural and cultural heritage, freshwater supply, biodiversity, agriculture, and fisheries (Almeida and Mostafavi, 2016; Van Dongeren et al., 2018; Allen et al., 2021).

Modeling practices can assess the socioeconomic impacts caused by climate change and adaptation to SLR and extreme coastal events (Bosello and Di Cian, 2014). These methodologies can vary in scales, most of which are on global scales. The negative aspect of applying global modeling at regional and local levels without considering the specificities of landforms and bathymetry, land use and occupation, ocean circulation, among others, is the increase in uncertainties in results, which can lead to erroneous analyses (Bars et al., 2017; Sweet et al., 2017; Cross, 2019). More specific studies have been published recently, although still in small numbers (Vital et al., 2010; Alizad et al., 2016; Araújo et al., 2021a; De Figueiredo et al., 2020; Khojasteh et al., 2021; Hauer et al., 2021; Olsen et al., 2022). However, they mainly stem from large economic centers and developed countries (Mitsova et al., 2012).

Brazil is among the most vulnerable countries to SLR-related impacts due to its size and the low altitudes of its coastline (Kirezci et al., 2020). However, due to the low occupation of the coast (given its length), studies on modeling and assessing the risk of floods in the face of climate change focus on highly populated coastal cities (Muehe, 2010). Thus, some areas of great ecological, biological, and economic relevance, such as the Estuarine Complex of Paranaguá, are deprived of specific studies to carry out projections for the following decades, which are essential to prepare and plan responses to the growing threat related to the level of the sea. Below, we present (Figure 1) the variables necessary for an effective mapping, modeling, and monitoring of areas that are vulnerable to flooding, the ways in which they are obtained, and their current stage of development.

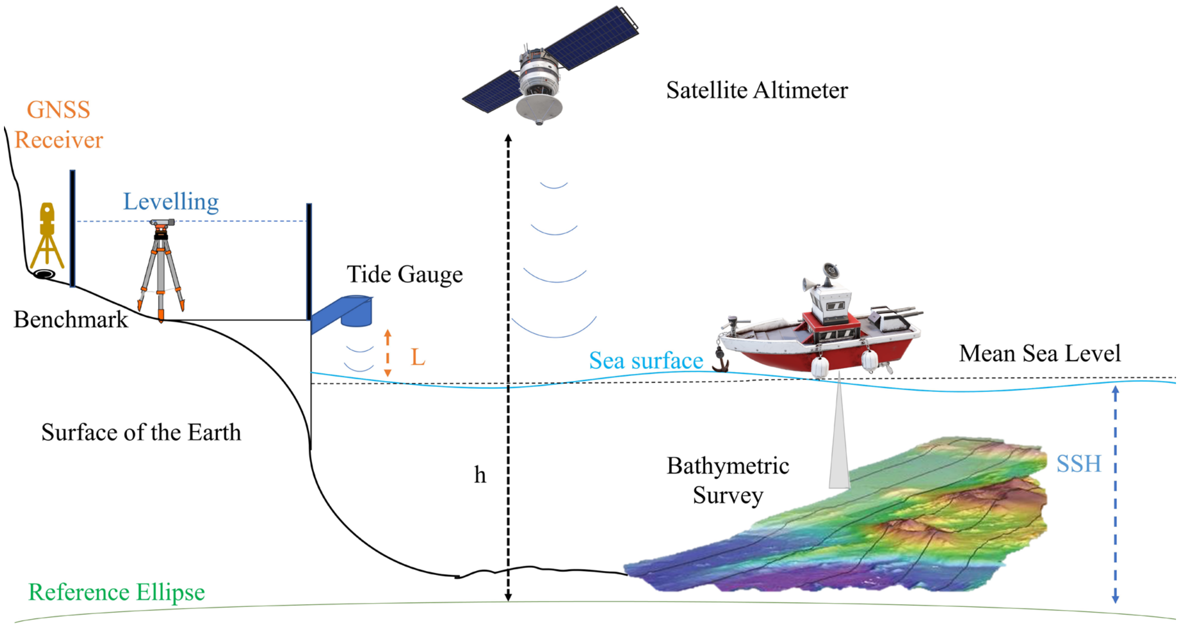

Figure 1. Representation of different data sources and methodologies to map and monitor areas susceptible to flooding, in which the sea surface height (SSH) and the information derived from artificial satellites (h) are relative to a reference ellipse and the tide gauge data (L) are referenced to an arbitrary position on the ground where it was installed.

ALTIMETRY

Studying and monitoring the consequences of sea level rise highly depend on representing the natural relief altimetry by digital elevation models (DEM) (Amante, 2018; Almeida et al., 2019; Tsatsaris et al., 2021). Thus, a specific resolution and accuracy are required for each type of DEM application, and several data sources are currently available.

Data sources include: I) points obtained by surveys with electronic distance meters (Nelson et al., 2009); II) surveys based on global navigation satellite systems (GNSS) (Ferreira et al., 2014; Silva et al., 2020); III) satellite-derived photogrammetry (Shean et al., 2016; Almeida et al., 2019); IV) photogrammetry derived from autonomous unmanned aerial vehicles (UAV) (Mancini et al., 2013; Martínez-Carricondo et al., 2018; Araújo et al. 2021b); V) range interferometry and radio detection and ranging (RADAR) (Rahman and Di, 2017; Oh et al., 2019); VI) range interferometry and airborne light detection and ranging (LIDAR) (Horritt et al., 2003; Zhou, 2009; Werbrouck et al., 2011; Joyce et al., 2014); and VII) map digitization (Amoura and Dahmani, 2022).

Surveys by electronic distance meters, GNSS positioning, and terrestrial laser scanners provide accurate data but are limited to applications in large areas as they require long periods of field survey and data processing (Kizil and Tisor, 2011; Gallay et al., 2013; Puente et al., 2013). Therefore, they are more applicable in local studies in regions of easy human access, requiring measurements with millimetric precision.

Data derived from remote sensing have been widely applied to DEM because they have a lower cost and greater spatial coverage and meet the resolution and accuracy required for applications of global and, in some cases, regional scales. The most used data are SRTM-1 DEM, ALOS World 3D, and ASTER GDEM v2, which have a 30-m spatial resolution (Tadono et al., 2015; Caglar et al., 2018; Florinsky et al., 2018; González-Moradas and Viveen, 2020; Nikolakopoulos, 2020).

Shuttle radar topographic mission (SRTM) data are freely available, with wide spatial coverage but low vertical accuracy (up to 16 m) at the local level (Smith and Sandwell, 2003). The SRTM mission was planned to obtain an absolute altimetric error of around 16 m and a spatial resolution of 90 m

(Rabus et al., 2003a), but research has shown that in some locations, this error has been reduced to about 6 m, such as the South American coastal region (Rodriguez et al., 2005a). SRTM data were updated by reprocessing the original SRTM data with data from the ASTER GDEM. This reprocessing corrected flaws and voids and are known as NASADEM.

For the entire Brazilian territory, SRTM data were refined to obtain a spatial resolution of 30 m and corrections for spurious values (Valeriano and Rossetti, 2012). This refinement, carried out by the National Institute for Space Research, gave rise to the database called Topodata (Polidori et al., 2014).

The advanced spaceborne thermal emission and reflection radiometer – global digital elevation model (ASTER model GDEM), launched in 2011, is a global scope DEM derived from the stereoscopic processing of about 1.2 million images from the visible and near-infrared bands, with a vertical accuracy that varies from 6 to 15 m, depending on the slope and ground cover (Abrams et al., 2010; Tachikawa et al., 2011). Made available in 2014 by the Japanese Aerospace Exploration Agency, the DEM ALOS World 3D-30m (AW3D30) has 30 m of spatial resolution and vertical accuracy better than 5 m (Tadono et al., 2015; Santillan and Makinano-Santillan, 2016).

Despite new available sources of information, SRTM data with a horizontal resolution of 30 m still offer greater altimetric accuracy (Bonfietti Marini et al., 2017; Silva et al., 2022). However, applying data from remote sensing for coastal flooding analysis becomes difficult since their altimetry uncertainty can exceed the vertical flooding range (Yamazaki et al., 2017). For example, most flood waves have amplitudes of a few meters (Yamazaki et al., 2014) and can reach 10 m when considering storm waves (Tang et al., 2009).

A widely applied technology with satisfactory results refers to UAVs. The advantages of using UAVs are their portability, the possibility of self-designing and modifying the integrated sensors, the collection of data in areas of difficult access, and their relatively low cost in the case of basic UAVs (Gindraux et al., 2017). UAVs, which operate at low altitudes, have a much higher spatial resolution than satellites, are not limited in temporal resolution, and significantly increase their accuracy when used with the aid of ground control points (GCPs) (Samboko et al., 2022).

With a more innovative technology, LIDAR has obtained DEM with a vertical accuracy of up to 0.15 m. LIDAR technology determines the distance between the objects and the emission source by the emission and reception of an optical laser, obtaining an accurate 3D structure of the imaged objects. However, despite its ability to explore significantly large areas, its use is expensive, and its results fail to provide data with spatial and vertical accuracy when compared to electronic distance meters and GNSS (Xiaoye, 2011; Kucharczyk et al., 2018).

In Brazil, considerable financial investment is required to obtain LIDAR data as they are not freely available. LIDAR surveys in national territory are carried out by specialized companies in the aerial surveys sector and commonly cover specific areas of road structures under construction, dam structures, or areas that will make up a real estate registry (Ribeiro et al., 2016; Mendonça and Portugal, 2018; Magalhães and Moura, 2021; Pacheco et al., 2022).

The choice and application of the altimetric model for hydraulic and hydrodynamic studies must be careful regarding its vertical accuracy. For example, the use of lower accuracy altimetric data may underestimate the risk of coastal flooding, and a prior DEM assessment is essential to develop robust flood maps, minimizing bias in the final product (Bales and Wagner, 2009; Gesch, 2009; Sande et al., 2012; Tate et al., 2015; Xu et al., 2021). Table 1 (Lakshmi and Yarrakula, 2018; Toth and Jóźków, 2016) summarizes the methods to obtain data for generating digital elevation models, followed by their capabilities and limitations.

Table 1. Capabilities and limitations of topographic data collection methods.

Methods	Capabilities	Limitations
Land surveys	Provides high-resolution and accurate data. Low cost relative to aerophotogrammetric methods.	Unapplicable to large areas. GNSS operates unreliably under vegetation. Long data collection.
Laser scanners and aerophotogrammetry	Provides high-resolution and accurate data.	High cost. Problems with steep slopes and areas with dense vegetation. Requires homogeneously distributed ground control points.
Stereoscopic satellite imaging	Covers large areas. Available for free.	Limited spatial resolution and accuracy for local and regional studies. Sight must be clear of clouds and depends on the lighting.
LIDAR satellite imagery	Covers large areas. Available for free.	Unable to penetrate areas of dense vegetation. Suffers interference from the atmosphere.
Satellite RADAR imaging	Available for free. Acquires images under any weather conditions.	Problems with steep slopes and areas with dense vegetation. Limited spatial resolution and accuracy for local and regional studies.

Bathymetry

Hydrographic surveys are commonly intended for making or updating nautical charts and bathymetric maps, scientific investigations, or as a basis for developing specific engineering work (IHO, 2005, 2020). In Brazilian jurisdictional waters, the institution responsible for developing and updating nautical charts is the Directorate of Hydrography and Navigation of the Navy Hydrography Center.

The importance of knowledge of the bathymetric surface beyond navigation is evinced by research developed to improve knowledge about oceanographic and meteorological phenomena by numerical hydrodynamic modeling (Harari and Camargo, 1998; Camargo and Harari, 2003; Franz et al., 2016; Lacasce, 2017), underwater geomorphological phenomena (Finkl et al., 2005; Banks et al., 2007; Klemas, 2011; Cea and French, 2012; Mandlburger et al., 2015), and hydraulic analysis (McKean et al., 2014; Mandlburger et al. 2015; Naumenko, 2020; Awadallah et al., 2022). Thus, it is necessary to have bathymetric information with a wide spatial coverage and an accuracy compatible with each research goal.

Advances in the knowledge of the bottom topography of water bodies have contributed to improving the accuracy of hydrodynamic modeling. For example, Cea and French (2012) found that the bathymetric uncertainty could be a more appropriate and effective parameter than the friction coefficient in the bed of medium-depth estuaries. Moreover, bathymetry is an essential variable in investigating tidal responses to SLR elevation (Du et al., 2018) since bathymetric variations significantly influence the dynamics of coastal flooding events (Mj and Dutykh, 2020).

However, obtaining bathymetric data in coastal regions and estuaries is expensive due to the need for technological instruments, highly trained technicians, and long data collection and processing periods. Some cases need combining bathymetric data from different sources and resolutions to obtain the totality of data from the areas to be studied (Wang et al., 2009).

The depth can be measured directly (by a hand plumb, sounding machine, and stadia) or indirectly (by acoustic sensors — such as single-beam or multi-beam echo sounders —, space or airborne electromagnetic sensors, and optical sensors). However, applying direct methods in coastal regions and estuaries becomes difficult due to the extensive dimensions to be surveyed and the depths to be measured.

Traditionally, onboard echo sounding is used in bathymetry surveys to record sound signals returned at a fixed time interval for extensive water depth measurements (Li et al., 2004). This advanced approach can accurately represent underwater terrain, providing bathymetry that suits hydrodynamic modeling, ship engineering design, and construction, but its high cost makes it less affordable.

Bathymetry by aerial optical sensing has been frequently used for diverse bodies of water, including inland lakes, shallow estuaries, coastal areas, and the open sea. This method can be analytically or empirically implemented. Several empirical methods have been proposed for bathymetry recovery, in which the relation between the radiance of the water body and the water depth at sampled locations has been empirically established (Lyzenga, 1978, 1985; Lyzenga et al., 2006). Other analytical methods consider the propagation of light in the water and are applicable in shallow water bodies with a bottom composed of reflective material, requiring the input of a series of optical properties of water, such as the attenuation coefficient and backscattering of light (Spitzer and Dirks, 1986). A wider range of parameters is required for cases of greater depths and turbid waters (Ji et al., 1992).

For the surf zone, in which it is unfeasible to use large and small vessels for bathymetric surveys (influenced by depth and breaking waves, respectively), an adaptation of procedures is necessary to estimate the bathymetry in this region. For this, remote sensors are being used to record the behavior of sea waves and then determine the bathymetry by applying image processing algorithms (Lyzenga, 1985; Lippmann and Holman, 1989; Holman et al., 2013; Bergsma et al., 2016).

Optical sensors fixed on land and UAVs have been suitable for calculating water depth based on the celerity of long waves estimated from photogrammetric images (Liu et al., 2012; Matsuba et al., 2017). This methodology has achieved the bathymetric representation with reasonable accuracy but it still has specific issues to be improved, such as higher wave height, non-linearity of waves on the coast, sunlight in the images, cloud noise, and raindrops on its lenses.

In LIDAR bathymetry, a laser pulse is emitted from a scanner mounted on an aerial platform (plane, helicopter, UAV), travels through the atmosphere, and reaches the water surface, in which a part of the signal is scattered back. The remaining signal is reflected at the bottom of the water and returns to the sensor. Based on the time-of-flight principle, the depths are estimated from the time between the emission and arrival of the backscattered pulse at the sensor (Mandlburger et al., 2015a; 2015b; 2020).

Although the use of LIDAR technology returns highly accurate data, the water body must have a depth of up to 70 m and clear water, and its accuracy depends on the material and composition of the bottom (Gao, 2009). In estuaries, in which these conditions are absent, conventional methods are still used for bathymetric surveys. Furthermore, costs become unfeasible for most surveys if it is necessary to use aircraft. Table 2 (Gao, 2009) summarizes the available methods with their respective qualities and operating restrictions.

Table 2. Capabilities and limitations of imaging methods.

Methods	Capabilities	Limitations
Optical imaging (Video)	Provides high-resolution accurate data. Lower cost than aerophotogrammetric methods.	Limited coverage area and depends on the camera resolution and environmental conditions.
Optical imaging (image) Empirical methods	Covers great lengths great depths.	Low accuracy.
Optical imaging (image) Analytical methods	High accuracy up to 30-m depth.	Complex and needs many input parameters. It depends on atmospheric conditions and the liquid surface.
LIDAR satellite imaging	Penetrates depths up to 70 m and returns high accuracy.	High cost. Limited to clear water and a calm liquid surface.
Satellite microwave imaging	Available for free. Acquires images under any weather conditions.	Low accuracy. It depends on the conditions of the liquid surface.
Acoustic and sonar methods	High accuracy and independence of water optics.	High cost and time-consuming for large extensions, unfeasible for rough surfaces.

ABSOLUTE AND RELATIVE SEA LEVEL

Changes in the surface of the sea can occur due to changes in the mass or volume of the oceans or by changes in the solid surface of the land in relation to the surface of the sea. In the first case, sea level change is defined as eustatic, and in the second case, as relative sea level change (Bosence et al., 2003). Thus, distinguishing variations in the position of the physical surface of the Earth from variations on the surface of the oceans is a challenge and requires an initial understanding of the involved processes. Moreover, understanding the eustatic sea level on different time scales leads us to understand the melting of the polar ice caps and the variation in the temperature of water masses. Relative sea level variation also enables us to know active regional and local processes.

Absolute sea or eustatic level means the position of the sea surface in relation to the center of the Earth. Eustatic sea levels mainly vary as a function of (Gornitz, 2005):

I) Tectono – Eustasy – in which variations in the volume of ocean basins occur in addition to the expansion of the seabed. The sedimentation process that changes the volume of ocean basins can also be considered here (Rovere et al., 2016);

II) Glacio-Eustasy – in which the volume of masses change due to the variation in the volume of ice;

III) Geoidal-Eustasy – in which the variation of the sea surface occurs as a function of the gravitational field variation;

IV) Thermal Expansion of the Oceans – increase in the volume of the oceans due to temperature variation.

The relative sea level, referenced to a point on the physical surface of the Earth, considers the absolute (eustatic) sea level and the isostatic and tectonic processes of the physical surface. Eustatic and tectonic/isostatic cycles overlap and result in cyclic successions of transgressions and regressions on passive continental margins. On continental margins, this process produces a succession of sedimentary packages related to relative sea level variation in the past millions of years (Simmons et al., 2012).

Sequence stratigraphy focuses on the stacking patterns of stratigraphic units and bounding surfaces and configures an approach to stratigraphy. The patterns make it possible to identify and correlate stratigraphic units in different locations and to reconstruct the environmental conditions that led to their formation. Thus, sequence stratigraphy is exclusively focused on analyzing changes in the facies and geometric character of strata and identifying key surfaces to determine the chronological order of basin filling and erosion events (Catuneanu, 2019, 2002, 2020). Variations in sea level can be observed on different time scales and with different data collection techniques, and no observation can record purely eustatic changes in sea level regardless of the technique applied for data collection (Rovere et al., 2016). Altimetry techniques (satellite gravimetry) and tide gauges have been used to reconstruct sea level on multidecadal time scales, which is the time scale that enables us to make inferences about sea level variation for the following decades. Longer time scales (hundreds to millions of years) have no instrumental observation of sea level. Thus, to obtain information about eustatic changes on longer time scales, it is necessary to reconstruct paleo changes in sea level using proxies, for example ^{18}O, which represents a signal of ocean mass and variations in sea temperature. The notation is a measure of the abundance of the ^{18}O isotope relative to a chosen standard, in this case, the standard mean ocean water (Stokes et al., 2015; Batchelor et al., 2019; Dalton et al., 2022).

SEA SURFACE MEASUREMENT

Since the 1990s, it has been possible to obtain sea level information derived from satellite altimetry, with near-global coverage (Ablain et al., 2017). However, proximity to the continent and the influence of the seafloor on coastal dynamics hampered the direct extraction of useful information from altimeter waveforms, making data for the coastal region unreliable (Vignudelli et al., 2011; Cipollini et al., 2017).

Recently, an increasing number of studies have pointed out that the synthetic aperture radar of CryoSat-2 and, now globally, of Sentinel-3A and Sentinel-3B has obtained excellent results in the monitoring of the sea level in the coastal zone due to the higher resolution along the track and lower noise when compared to conventional altimetry when the terrestrial path of the satellite is perpendicular to the coastline (Cipollini et al., 2014; Gómez-Enri et al., 2018). For more details, see Vignudelli et al. (2019), who studied the increasing use of coastal altimetry datasets in coastal sea level surveys and applications, such as high-frequency studies (tides and storms) and long-term sea level change studies.

Despite advances in satellite altimetry, the main instrument for obtaining tide data in coastal areas is still tide gauges. There currently exist several tide gauges along coastal areas around the world. However, only one sparse network has a sufficiently long series — despite its considerable gaps, especially in developing countries or remote places, in which access is difficult or costly to implement measuring instruments (Woodworth et al., 2016).

The heterogeneous spatial and temporal distribution of tide gauge records and, in particular, the scarcity of data until the beginning of the 20th century are the main obstacles to the scaling and complete understanding of long-term regional changes in mean sea level and their consequences (Dangendorf et al., 2017).

Regarding sea level information, the international program global sea level observing system, established by the Intergovernmental Oceanographic Commission, overviews and coordinates global and regional sea level networks, supporting and guiding the oceanographic and climate research communities.

Tide gauges measure the SLR in relation to the surface on which they are attached. Thus, to ensure the continuity of sea level recording, tide gauge measurements must refer to a properly defined datum, usually a fixed point on the ground (benchmark). Continuity can be achieved by systematically measuring the stability of the tide gauge benchmark by high-precision leveling to nearby GCPs that are ideally linked to the corresponding national geodesic network. Furthermore, neither benchmark height nor sea levels are constant, changing on different spatial and time scales. Therefore, accurate estimates of long-term vertical land movement are required to separate terrestrial and oceanic contributions in the tide gauge records.

As important as the current monitoring of the sea surface by tide gauges and altimetric satellites, knowledge of the behavior of the sea surface in past centuries and millennia is also necessary. Thus, another important source of information on ocean basin changes by inferences derived from relative sea level variations from sequence stratigraphy (Vail et al., 1977).

Sequence stratigraphy uses diverse sedimentological and paleontological data to divide the sedimentary succession into genetically related strata units separated superiorly and inferiorly by discordant boundaries representing periods of readjustment of sedimentary systems related to eustatic sea level variation. It aims to subdivide sedimentary sequences into packages of different scales within sedimentary basins and relate to relative sea level changes (Posarnentier and Allen, 1999; Simmons et al., 2012).

The main factors responsible for the architecture of the depositional sequence refer to changes in relative sea level and sediment supply rates. These two factors inevitably relate to global, regional, or local processes. Thus, the structure of the stratigraphic sequence can vary depending on time, scale, and composition (Catuneanu, 2002; Coe, 2003). Sequence stratigraphic studies highlight the stratigraphic cyclicity that develops in response to changes in relative sea (accommodation) and base levels (sedimentation). The resulting transgression floods the shoreline, moving the shoreline inland and forming a nearshore transgressive surface (Abbott and Carter, 2007). When the rate of sea level rise reaches its highest rise, the accumulation of sediments along the coast is reduced, whereas pelagic and benthic fossils and organic matter continue to accumulate in the open sea, forming the maximum inundation surface (Mitchum Jr, 1977).

Following the higher position of the sea, a drop in sea level can cause coastal and nearshore erosion, forming an erosion unconformity and its correlative conformities or sequence boundaries (Catuneanu, 2002).

Figure 2 (modified from Catuneanu, 2019) presents an overview of the processes and scale of observation. However, we can cite other processes that generate stratal units and boundary surfaces at sub-stratigraphic scales, including tidal cycles, storm cycles, seasonal changes in river discharge and sediment load (allogeneic), the migration of bedforms and macro forms, and the lateral displacements of channels, without changes in the total energy and sediment balance of the depositional environment (autogenous) (Catuneanu, 2019).

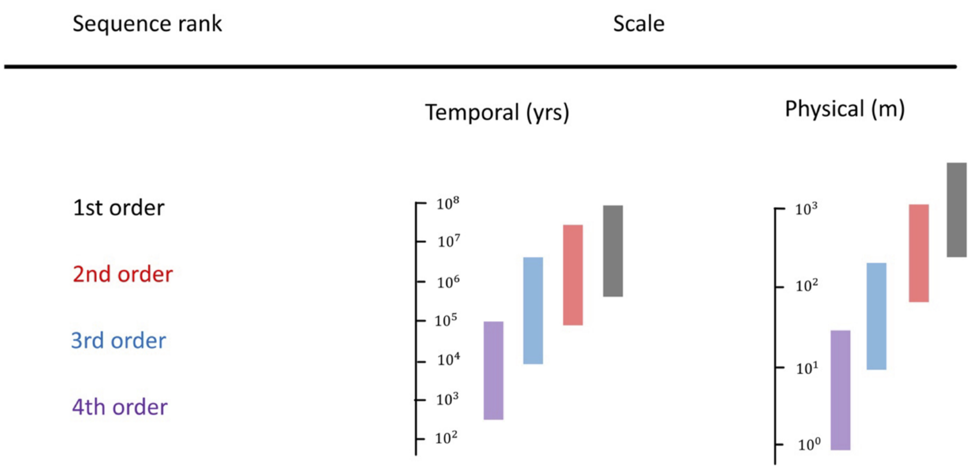

Figure 2. (Modified from Catuneanu (2019)) first-order sequences are called mega-sequences; second-order sequences, as composite sequences; third-order sequences, as mesothems; and fourth-order sequences, as cyclothemes. For allogenic processes, on the time scale of 10^6 to 10^8 years, long-term climate variations occur, such as the greenhouse-icehouse cycle, formation of tectonic basins, and eustasy related to seafloor expansion; From 10^4 to 10^5 years, glacial-interglacial cycles occur, which are short-term eustasy derived from orbital forcing; On smaller time scales (> 10^4 years), dynamics of ice layers, atmospheric and thermohaline circulation induced by cycles of solar radiation, and activation of sedimentary faults in sedimentary basins delimited by faults occur. For autogenic processes, on a 10^3-to-10^5-year time scale, autogenic change processes occur in alluvial channel belts or submarine fans and from 10^0 to 10^3, canal avulsion and delta lobe switching.

Vertical ground movements

Vertical movements of the physical surface of the Earth, such as the uplift or subsidence of the ground due to natural and anthropogenic processes, can attenuate variations in sea level in relation to its physical surface (Peltier, 2004; Ballu et al., 2011; Wöppelmann and Marcos, 2016). Thus, the vertical movement of the Earth affects the tide gauge records, leading to discrepant relative observations when compared to those occurring at geocentric sea level (Church and Clark, 2013; Denys et al., 2020). The glacial isostatic adjustment, one of the phenomena contributing to the vertical movement of the surface of the Earth, has a global model (Peltier, 2004; Peltier et al., 2015). However, other phenomena occur regionally — such as ocean thermal expansion and salinity variations (Lombard et al., 2005; Levitus et al., 2012) — and locally — especially those derived from human actions (Nicholls et al., 2021).

When obtaining data for coastal management, the most appropriate variable refers to the total variation in relative sea level, which is composed of the sum of three components: I) global mean elevation and regional variability; II) static effects, which cause regional changes; and III) the local component of vertical ground movement (Holgate et al., 2013; Wöppelmann and Marcos, 2016).

Ideally, it would be necessary to install a GNSS station for continuous monitoring in the vicinity of tide gauges to quantify the vertical movement (Teferle et al., 2009; IOC, 2012), with standard errors of a lower order than the estimated increase in the global mean level, varying from 1 to 3 mm yr^{-1} (Wöppelmann et al., 2007; Pfeffer and Allemand, 2016; Wöppelmann and Marcos, 2016; Kleinherenbrink et al., 2018). It would require long-term monitoring, which could last more than a decade, depending on the station and the type of noise in the GNSS signal (Santamaría-Gómez et al., 2011).

Using GPS-based accurate positioning, Ballu et al. (2011) found that a coastal area on the Torres Islands, in northern Vanuatu and the southwestern Pacific, underwent a subsidence of approximately 12 cm from 2007 to 2009 due to seismic events, which erroneously contributed to the calculation of the uplift trend at sea level. For a broader estimate (also applying GPS-based accurate positioning), Kleinherenbrink et al. (2018) estimated the trend of vertical surface movement at 570 tide gauge stations with an uncertainty of less than 1 mm yr^{-1} at up to 50 km.

A low percentage of tide gauge stations have GNSS antennas attached to them (PSMSL, 2022). For example, only five stations on the Brazilian coast make up its permanent service for mean sea level (with geodetic monitoring stations). Other forms of vertical control are applied in the absence of monitoring stations (Woodworth et al., 2017). Despite the need to be performed frequently and for long periods, traditional leveling methods can minimize errors in the vertical displacement of the tide gauges if geodetic control points lie close to tide gauges. The first-order quality standard of leveling (a standard deviation of 1 mm per $\sqrt{k}$, iin which k is the leveled distance in km) must be achieved.

For example, the trigonometric leveling method by the leap-frog technique can return fair values when correcting distance measurements for temperature, pressure, and relative humidity and minimize refraction errors by standard field procedures of sights equal to and less than 50 m (Deo et al., 2013).

The difference between data derived from satellite altimetry and tide gauges is worth noting. As mentioned, tide data have a local reference, i.e., the site of the equipment deployment. On the other hand, sea-level altimetry data from satellites have a global reference, a reference ellipsoid. Thus, the leveling of the tide gauge using traditional and geodetic methods is necessary to compare altimetry and absolute sea levels, in addition to linking data from different tide gauges to the same reference system.

Sediment redistribution

The non-climate components of the SLR have received less attention than its climatic ones as they are considered a local issue (Nicholls and Cazenave, 2010). When addressing SLR, an important variable must be considered is the local sedimentation rate of the studied area. Coastal regions composed of wetlands, such as mangroves and salt marshes, will decline unless they have sufficient sediment supply to keep up with the SLR (Nicholls and Cazenave, 2010). The world's largest deltas are at risk of becoming submerged due to SLR projections, and the variable that can offset local SLR refers from the deposition of fluvial sediments (Darby et al., 2020).

Mangroves — which are dynamic systems capable of expansion, contraction, and vertical growth — serve as barriers for extreme events in coastal regions and can mitigate the impacts of SLR. The maintenance and sustainability of these coastal wetlands will depend on flooding duration, plant submergence, salinity variation resulting from SLR, and the concentration of its suspended sediments and sediment accretion rate (Ganju et al., 2015). According to the spatiotemporal variability of sediment transport, sediment input will be critical in maintaining the geomorphic shape of wetlands under SLR (Chant et al., 2021), and, depending on the sedimentation rate in coastal wetlands, may vertically grow or decrease, thus responding positively or negatively to SLR (Weston, 2014).

It is understood that bio-geomorphic feedback will improve wetland survival by higher biomass productivity, enhanced by higher temperatures and higher carbon dioxide concentrations (Mudd et al., 2009). Increased sedimentation rates are less likely due to lower-than-expected suspended sediment concentrations (Breda et al., 2021). Most wetland loss today is due to wave-induced edge erosion, which beneficially adds sediment to the system (Grigs, 2021)

Modeling

Robust and accurate coastal forecasts require models to represent the relevant processes in this highly dynamic environment. Currently through computational tools for prediction and reliable computational resources, the complexity of coastal circulation can be better understood by applying hydrodynamic models.

If provided with accurate input data, hydrodynamic models enable good analyses of coastal hydrodynamics, morphology, wave, tidal current, and other oceanic processes (Ji et al., 2007; Belibassakis and Karathanasi, 2017; Fairchild et al., 2021; Harrison et al., 2022).

From 2011 to 2019, a model developed by the University of Cambria in Spain was introduced on the Brazilian coast due to its simplicity and feasibility of application when compared to other hydrodynamic models. Databases from the Brazilian coast were incorporated into this model to create a coastal modeling system in Brazil and make it available to a network of public managers and researchers in coastal management.

Currently, an operational hydrodynamic modeling system is available for the southeastern Brazilian shelf, focusing on the coastal regions of Paraná and Santa Catarina. The Brazilian Sea Observatory project was implemented to provide hydrodynamic forecasts with high spatial resolution and particle trajectory simulations at defined locations on demand. The Brazilian Sea Observatory can also predict oil dispersion in accidents and assist emergency actions. A complete overview of the current moment in Brazil concerning observation systems and modeling of coastal oceans can be obtained in Franz et al. (2021).

Regional and local models can be nested to simulate processes at different spatial scales, such as storms mainly generated by wind action over thousands of kilometers or friction and shoreline influence on flow, which need numerical grids of higher resolution to be appropriately solved (Franz et al., 2016). Numerical models are also used to reconstruct past events as they have been applied to predict the conditions of coastal dynamics and project potential consequences of climate change. (Klingbeil et al. 2018). We describe, in the Table S1, the research carried out in Brazil that addressed the modeling of relative sea level elevation.

Discussion

For discussion, we bring, as a case study, the Paranaguá Estuarine Complex (PEC), on the coast of the state of Paraná in southern Brazil (Figures 3 and 4). The location was chosen after the authors carried out an extensive bibliographic survey of studies that address physical processes and found that the PEC is insufficiently studied concerning SLR. Studies in the literature focused on sea-land flows (Marone et al., 2012; Spier et al., 2016) and tidal analyses (Polli et al., 2021), and only one article analyzed the impact on the system due to SLR projections (Marone et al., 2015).

The assessment of coastal risks and impacts lacks information from the SLR at the regional level due to the pattern of spatial variation of some phenomena. Despite the uncertainty about the value of the SLR, minimizing the inaccuracies contained in the modeling input variables is essential for the effectiveness of adaptation measures.

PEC, up to the conclusion of this research, only show global altimetric data (SRTM, ALOS, ASTER). Because this dataset has an error that can cause a strong bias in the results of its application, an alternative would involve reducing errors to an acceptable level within the purpose of this study. An alternative to improving the quality of the SRTM elevation data has been proposed by calibrating the original DEM by geodetic and statistical methods. This calibration consists of applying GCPs with high vertical precision acquired by geodetic methods (Araújo et al., 2018). The method improved by about 25% the resulting altimetry and its dependence on the general morphology of the studied region.

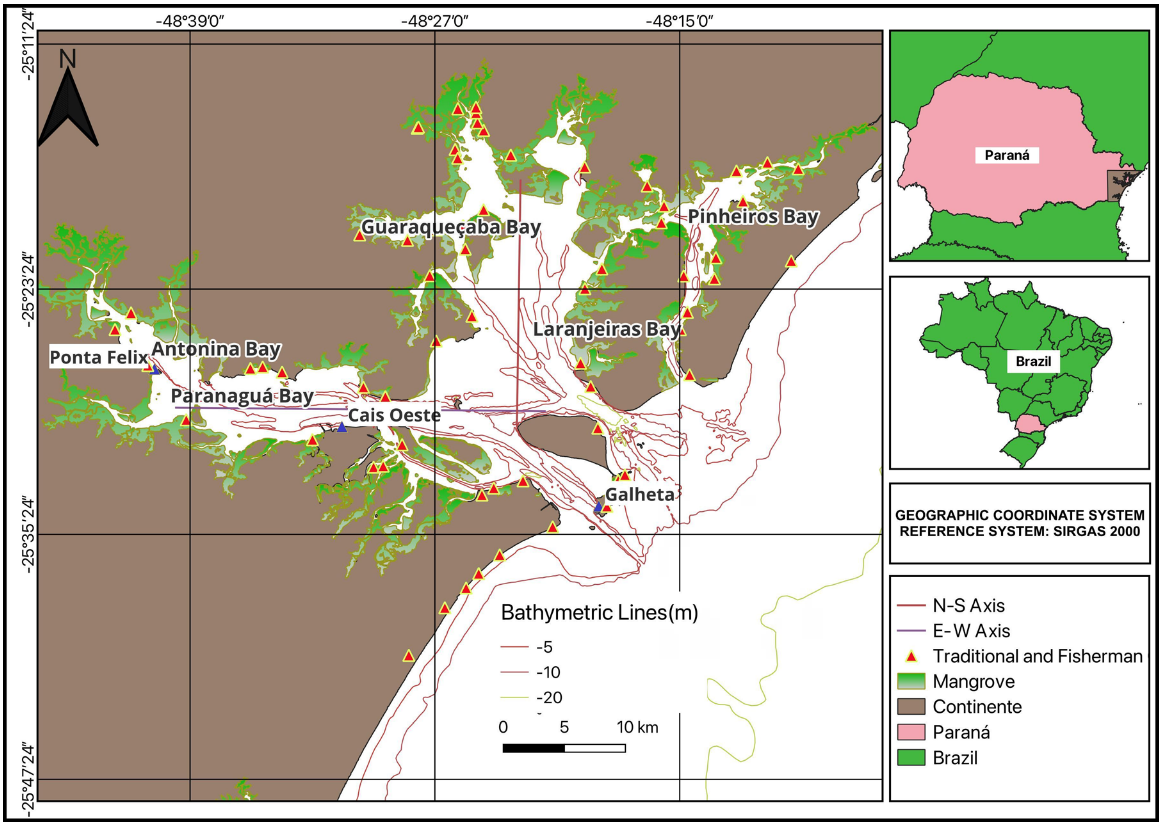

Figure 3. Location map of the Paranaguá Estuarine Complex (PEC), on the coast of the state of Paraná – Brazil, and the arrangement of resident communities and tide gauge stations.

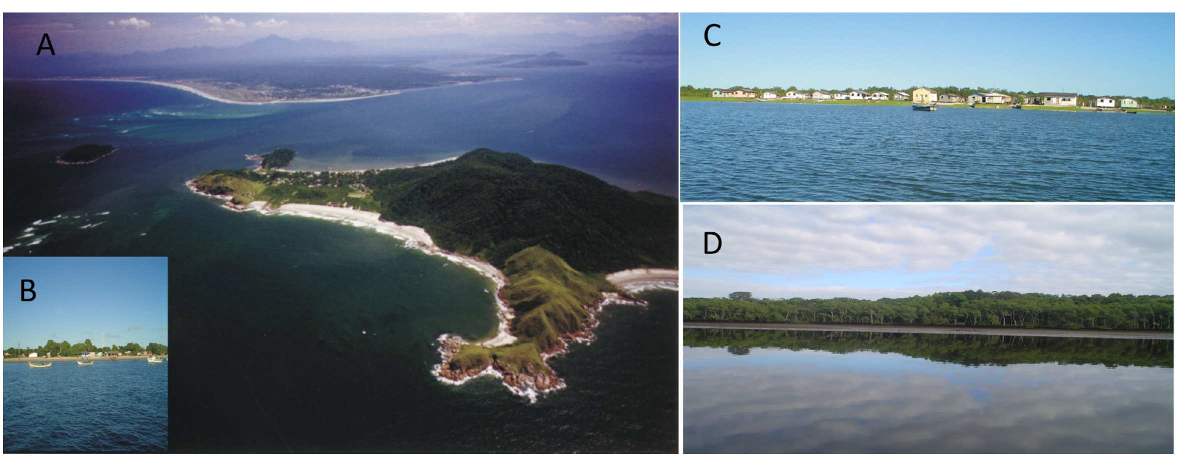

Figure 4. View of Ilha do Mel and Galheta channel at the southern mouth of the PEC. B) and C) Traditional communities who live on the banks of the PEC D) View of a mangrove area that covers large areas of the PEC.

Calibration quality depends on the quality and quantity of GCPs. However, with the enormous PEC area and the difficulty accessing some places (possible only by boat and favorable weather conditions), the geodetic survey with high point distribution becomes unfeasible. On the other hand, the low-altitude regions show a slight variation in their surface slope, enabling the collection of a sufficient number of GCPs for an adequate calibration.

The astronomical tides in the PEC have an average range of 1.5 m at their mouth. Its tidal amplitude increases toward the head of the bay, being amplified and reaching around 2.7 m inside the estuary (Marone and Camargo, 1995). Its tidal wave propagates in a mixed way, with a progressive form in the outer part of the bay and in a stationary form in the upper part of the bay (Marone et al., 2012). Storm surges can raise the water levels in the PEC to 0.8 m above astronomical tides (Marone and Camargo, 1995)

The available bathymetric information for the PEC mainly stems from bathymetric surveys around ports and the accesses channel on the E-W axis, approximately 56 km long. However, the bathymetric surveys are sparse and outdated in the north portion of the PEC, composed of Laranjeiras, Pinheiros, and Guaraqueçaba bays. As the area lacks a large structure of added economic value, the last bathymetric survey in the northern PEC dates back to 1970 (Diretoria de Hidrografia da Marinha do Brasil, 2022).

The tide gauge information for the PEC is mainly derived from the gauges implemented and managed by the company Paranaguá Pilots Serviços de Praticagem Ltda. in the Galheta Channel and Paranaguá (Cais Oeste) and Antonina (Ponta Felix) ports. As bathymetric information, tide information is available only for the E-W axis of the estuary (Figure 3).

The Paranaguá and Antonina tide stations use radar-type tide gauges and have five and seven benchmarks installed in their vicinity to monitor possible displacements. The Galheta station is the daily hydrography type, with seven benchmarks to check stability nearby. Descriptions and reference levels of these tide gauge stations can be founded on their identification sheets (F41) on the Brazilian Navy website. Among the tide gauge stations that make up the global sea level observing system network in Brazil, none are located on the coast of Paraná.

The distribution of bathymetry and SLR data in the PEC makes it challenging to understand the wave propagation throughout the estuary since the calibration and validation of hydrodynamic models depend on *in situ* data. On the other hand, long sea level records along the port access channel are available. It is also worth noting that the northern portion, which lacks more data, is inhabited by traditional coastal communities that live on fishing and tourism. Such communities tend to be more vulnerable to SLR.

The PEC encompasses approximately 295 km^2 of mangroves (Figure 3) (Faraco et al., 2010). The sediments composing the coastal plain of the PEC (Figure 5) are mostly composed of sand and fine silt in the areas surrounding the river mouth and very fine sand in the PEC estuary outlets. In the internal region, in which mixing processes predominate, sediments are characterized as mud (Angulo et al., 2006). The sediment transport by tidal currents is normal along the coast, with high-energy offshore waves being the main responsible for sediment movement in the region, regardless of tides. Ebb currents are stronger than flood currents on the surface and at the bottom (Noernberg et al., 2007).

Anthropogenic processes in estuaries tend to increase the local sedimentation rate and consequently increase siltation (Angulo et al., 2006; Angulo et al., 2020). The L-W Axis, due to the ports of Antonina and Paranaguá (Figure 5), undergoes constant dredging processes that interfere with the natural sediment transport in the PEC, resulting in morphological changes and erosion processes on the Paraná coast (Angulo et al., 2006). Deposition rates (2.6 cm yr^{-1}) have been determined in the region near the head of the PEC, in which a volume of 60×106 m^3 of sediment was deposited from 1901 to 1979 (Odreski et al., 2003).

The PEC is a tidal-dominated estuary, with the Serra do Mar as its main source of sediment. The residual circulation of the PEC points to the great influence of bathymetry on the sediment transport capacity, and the dredging that constantly occurs in navigation channels changes the direction of transport and spatial distribution of deposition (Paladino et al., 2022). The input of fluvial sediments at the Estuary Head (EHE) results in high values (65.9 mg L^{-1}) of suspended particulate matter (Noernberg, 2001). Additionally, it shows a high concentration of particulate matter in the maximum turbidity zone, in which regions prone to both siltation and erosion were identified in an analysis spanning 39 years (Carilho, 2003). At the mouth of the estuary, in which submerged and semi-submerged sandbanks occur, siltation rates of 19288.8 m^3 mo^{-1} were determined in a study based on a nine-month time series (Lamour et al., 2007; Cruz and Noernberg, 2020).

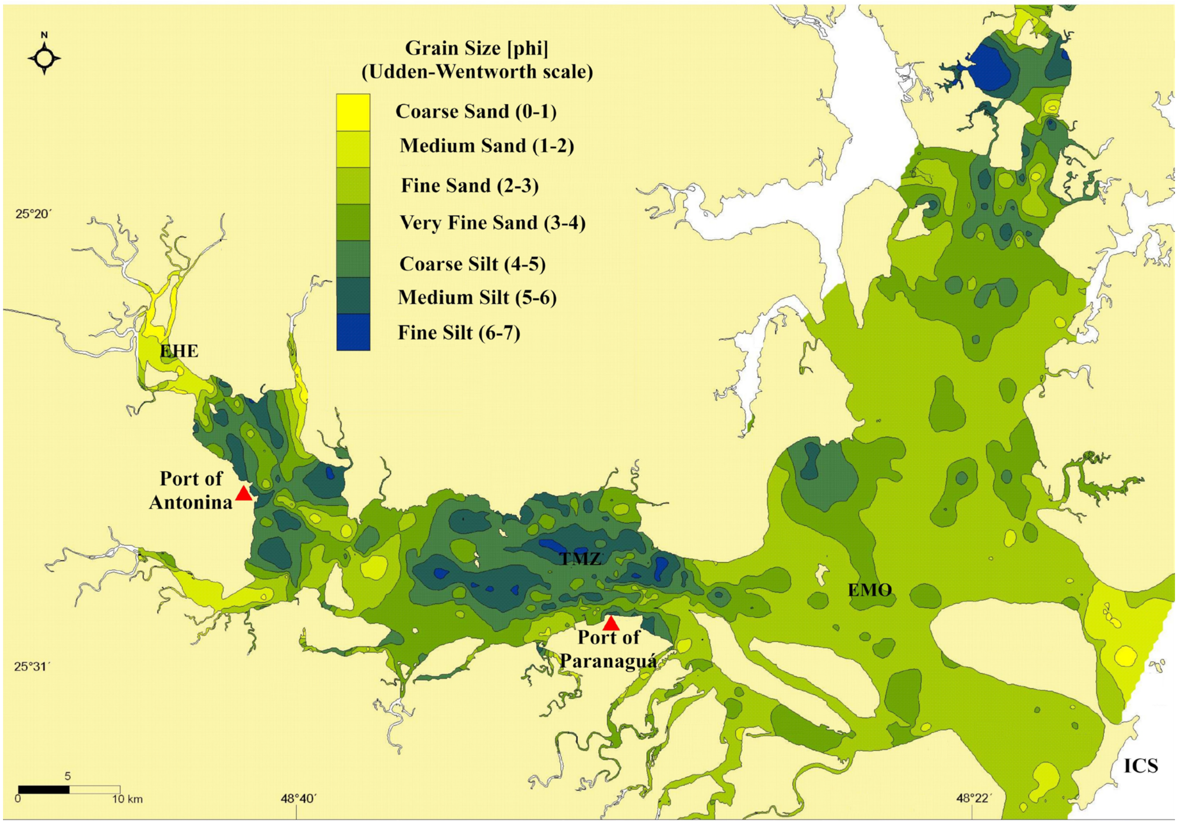

Figure 5. Sediment size distribution in the PEC (Adapted from Lamour et al. (2004)). Along the E-W axis of the PEC, the division of different environments of sedimentation: Inner Continental Shelf (ICS), the Estuary Mouth (EMO), the Turbidity Maximum zone (TMZ), and the Estuary Head (EHE).

As well as bathymetric and tide gauge data, knowledge of sediment transport in the PEC (Port and Coastal Engineering) is more extensive in the L-W axis due to maritime routes leading to the ports. This whole axis shows a sedimentation process that results in constant dredging to maintain a safe depth for the navigation of cargo vessels. A more advanced visualization of the sedimentation process in the L-W axis can be obtained by comparing the sedimentation rates produced by the hydrological units of the PEC (Port and Coastal Engineering) and the volumes dredged in this region, as presented by (Rutyna et al., 2021). Moreover, adding to the understanding of the residual circulation process at the southern mouth of the PEC shown by (Cruz and Noernberg, 2020) indicates an inward flow of both bottom transport and residual currents into the estuary. However, it is still necessary to understand the sedimentation process in the PEC as a whole, especially concerning the mangrove areas.

Despite no GNSS stations for continuous monitoring in the vicinity of the PEC (the nearest is located 100 km away in the municipality of Curitiba), the provision of benchmarks in the vicinity of the tide gauge stations enables the control of the vertical movement of the ground, with the application of leveling of the first order and geodetic positioning (Kontny and Bogusz, 2012; Hao et al., 2016). It is noteworthy that the control would possibly be unable to be performed at equal intervals given the difficulties performing the leveling continuously. It implies considering the constant vertical movement (if any) of the study region and adopting a dynamic linear fit of the leveling data using the least squares method (Hao et al., 2014).

The National Cartography Commission and its Committee for the Integration of Vertical Land and Sea Components have sought to systematize the methodology to integrate vertical references in coastal regions, aiming at the correct assessment of coastal flood risks resulting from climate changes (PAF-ZC – IV, 2017). Studies indicate that the answer will come by a Geodetic Coastal Reference Network, materialized by robust geodetic landmarks, leveled in circuits by the first-order geometric leveling method, a dense gravimetric mesh, and the installation of GNSS stations coupled to tide gauge stations (Alves and Dalazoana, 2020; Dalazoana and De Freitas, 2020).

The development of the Geodesic Network of the Paraná coast began in the PEC, with a methodology that covers the requirements of first-order leveling and gravimetric surveys (Prunzel, 2022) and the creation of a local database (De Vargas et al., 2020). It significantly reduces the tide gauge stations tying uncertainties and improves hydrodynamic model calibration.

Several studies still use static models to determine areas exposed to SLR. These valid applications can lead to estimates about the degree of exposure and vulnerability of coastal regions. However, static models better suit global applications, indicating areas vulnerable to coastal flooding. In the case of local studies, such as in estuaries, the application of numerical models is more suitable for a more accurate determination of the extent of flooding (Ramirez et al., 2016; Didier et al., 2018; Kumbier et al., 2018).

The ideal is to rely on robust statistical approaches combining probabilistic SLR estimates with other impact factors such as waves, storms, and tides. These approaches are fundamental to defining the appropriate boundary conditions for the models. An example involves the dynamic approach, in which the individual forcings of all extreme sea level components (i.e., regional SLR and water levels driven by waves, storms, and tides) are obtained and combined using a Monte Carlo simulation (Vousdoukas et al., 2016).

CONCLUSION

It is essential to use efficient tools to characterize and predict the dynamics of coastal systems, especially nowadays due to the climate changes effects at different spatial scales in oceanic and coastal processes. Although it is a concern and a recurring need for the coastal and the global populations, studies on the impacts from sea level rise on a regional and local scale still face the lack of financial investment for the acquisition of data collection technologies with a high degree of refinement.

Land surface, bathymetric, and sea level variation information, associated with a single altimetric reference system by the currently available modeling methodologies, contributes to understanding SLR and estimating its future behavior. Thus, in addition to a first identification of the danger of flooding in coastal areas, it is possible to plan interventions for future disasters.

Altimetric data that is available for free, despite gradually improving its positional and altimetric quality to meet different research areas and work scales, still have application restrictions. In terms of modeling the SLR, the estimates of which indicate that the variable under study can obtain values of a few meters (from 0.5 to 2.5 m). Local scale modeling must be performed with more accurate representations of the elevation, in which the vertical error of the product is lower than the values to be represented on it. Therefore, adaptations of techniques are necessary to overcome the obstacles related to acquiring accurate data or their complete absence.

The advancement of coastal altimetry observation and data processing techniques tends to minimize the lack of information on sea level in poorly sampled regions and is essential for the continuity of research in SLR monitoring. However, applying tide gauges is still essential for studies that need information on high-frequency tide phenomena since data derived from altimeters have a review frequency of a few days, thus greatly necessitating complementing sea level data from tide gauges and satellite altimetry. Furthermore, homogenizing the current network of tide gauges with stable reference and the connection with geodetic receivers are relevant for the continuity and improvement of sea surface observations.

The current computational development can implement models that join and compile data in large, quite diversified volumes. Thus, hydrodynamic models have significantly advanced climatological spatial resolution and physical perception, improving the description of the interactions between meteo-oceanographic processes on a regional scale and coastal dynamics on a local scale. However, models depend entirely on the quality of the input variables. Therefore, the more accurate and refined data are obtained, the more faithfully the modeled phenomena will represent reality.

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AUTHOR CONTRIBUTIONS

R.M.S.; M.A.N.: Conceptualization; Investigation; Writing – original draft; Writing – review & editing.

A.B.L.: Conceptualization; Investigation; Writing – original draft.

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