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CLIMATE CHANGE AND RISING SEA LEVELS AND THEIR IMPACT ON URBAN AREAS ALONG THE NE/E COAST OF SANTA CATARINA

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Abstract:

Objective of the study: To present the results of research into climate change and the impact of sea level rise in urban areas along the northeastern and eastern coastal regions of the state of Santa Catarina in Brazil.
Methodology/approach: This work presents primary data and a bibliometric survey of digital collections, published in scientific journals, analyzed by specialists and published between 2005 and 2022.
Originality/relevance: There are currently hundreds of bibliographies regarding climate change on both an international and national level. On a regional level, given the economic, ecological and demographic importance of the urban areas along the coast of Santa Catarina, there is a lack of studies presented in a systematic and integrated manner.
Theoretical/methodological contributions: Current studies using georeferenced projections make it possible to understand the causes and worsening effects of human activities on natural systems.
Main results: Climate change and the impact of rising sea levels on areas of high urban concentration along the Santa Catarina coast, added to the susceptibility of natural conditions, aggravated by the disorderly use and occupation of space, still lack the integrated mapping and information necessary for urban planning to mitigate the effects of climate change.
Conclusion: The impacts on economic growth and land occupation also represent an opportunity for the collective exploration of the adaptive capacity and resilience of urban ecosystems in the face of current climate change.

Key words: climate change, sea level rise, environmental vulnerability, urban planning, brazilian coastline.

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AS MUDANÇAS CLIMÁTICAS E O AUMENTO DO NÍVEL DOS OCEANOS E SEUS IMPACTOS NAS ÁREAS URBANAS DA ORLA NE/E DE SANTA CATARINA

Resumo:

Objetivo do estudo: Apresentar os resultados das pesquisas sobre as mudanças climáticas e o impacto da elevação do nível do mar nas áreas urbanas da orla nordeste e leste do estado de Santa Catarina, no Brasil.
Metodologia / abordagem: Este trabalho apresenta dados primários e um levantamento bibliométrico em acervo digital, publicados em periódicos científicos, analisados por especialistas e publicados entre 2005 e 2022.
Originalidade/relevância: Atualmente existem centenas de bibliografias sobre as mudanças climáticas em níveis internacional e nacional. No âmbito regional, tendo em vista a relevância econômica, ecológica e demográfica das áreas urbanas da orla catarinense, há carência de estudos apresentados de forma sistemática e integrada.
Contribuições teóricas / metodológicas: Os estudos atuais com projeções georreferenciadas permitem entender os efeitos e agravamento provocados pelas atividades humanas sobre o sistema natural.
Principais resultados: As mudanças climáticas e o impacto da elevação do nível do mar nas áreas de elevada concentração urbana da orla catarinense, somados à suscetibilidade das condições naturais, agravada pelo uso e ocupação desordenados do espaço, ainda carecem de mapeamentos e informações integrados necessários para o planejamento urbano para mitigar os efeitos das mudanças climáticas.
Conclusão: Os impactos no crescimento econômico e a ocupação do território também representam uma oportunidade para a prospecção coletiva da capacidade adaptativa e resiliência dos ecossistemas urbanos diante das mudanças climáticas atuais.

Palavras chaves: mudanças climáticas, elevação do nível do mar, vulnerabilidade ambiental, planejamento urbano, litoral brasileiro.

EL CAMBIO CLIMÁTICO Y LA SUBIDA DEL NIVEL DEL MAR Y SU IMPACTO EN LAS ZONAS URBANAS DE LA COSTA NE/E DE SANTA CATARINA

Resumen

Objetivo del estudio: Presentar los resultados de la investigación sobre el cambio climático y el impacto del aumento del nivel del mar en las zonas urbanas de las costas nordeste y este del estado de Santa Catarina en Brasil.
Metodología / enfoque: Este trabajo presenta datos primarios y una encuesta bibliométrica en colecciones digitales, publicadas en revistas científicas, analizadas por expertos y publicadas entre 2005 y 2022.
Originalidad / relevancia: En la actualidad existen cientos de bibliografías sobre el cambio climático a nivel internacional y nacional. A nivel regional, dada la importancia económica, ecológica y demográfica de las áreas urbanas del litoral catarinense, faltan estudios presentados de forma sistemática e integrada.
Contribuciones teóricas / metodológicas: Los estudios actuales que utilizan proyecciones georreferenciadas permiten comprender los efectos y empeoramientos causados por las actividades humanas sobre el sistema natural.
Principales resultados: El cambio climático y el impacto de la elevación del nivel del mar en áreas de alta concentración urbana del litoral catarinense, sumados a la susceptibilidad de las condiciones naturales, agravada por el uso y ocupación desordenada del espacio, aún carecen de la cartografía integrada y de la información necesaria para que la planificación urbana mitigue los efectos del cambio climático.
Conclusión: Los impactos sobre el crecimiento económico y la ocupación del suelo también representan una oportunidad para la exploración colectiva de la capacidad de adaptación y resiliencia de los ecosistemas urbanos frente al cambio climático actual.

Palabras clave: cambio climático, subida del nivel del mar, vulnerabilidad ambiental, planificación urbana, litoral brasileño.

Introduction

Climate change is the result of natural processes that have been occurring throughout the Earth's history. However, current studies reveal the impact of human activities on the climate, and have identified the causes of climate change, whether natural or man-made. These changes have affected various elements of the climate system and may be detected through evidence and calibrated information. Thus, the most recent period of the Earth's history, known as the Anthropocene, is characterized by the significant influence of human activities on the global landscape and the evolution of the planet.

Forecasts by the Intergovernmental Panel on Climate Change (IPCC) have indicated an increase in global temperatures by the year 2100, mainly due to greenhouse gas emissions resulting from human activities. It is estimated that 17% of these emissions are caused by changes in land use and forestry. There is consensus among the IPCC reports (2007, 2014 and 2020) that climate change is predominantly anthropogenic in origin. The effects of climate change are evident from the frequency and intensity of extreme weather and climate events, such as hurricanes, tropical storms, the melting poles and prolonged droughts. These events are related to ongoing climate change and have brought about destructive impacts all over the world, including Brazil.

Climate variations make short-term projections increasingly irregular, thereby replacing temporal and spatial linearity with meteorological disorganization. Population and economic growth increase the demand for natural resources, which affects the economy and thus implies investments in agriculture, urban infrastructure and industries. Environmental disasters result from the interaction between natural environmental conditions and anthropogenic and social changes, which intensify the vulnerability and risk of regions.

The research has been structured so as to comprehensively address all the relevant aspects related to the impacts of rising sea levels along the coastal regions of the state of Santa Catarina in South Brazil. Initially, a detailed bibliographical review was carried out, seeking to gather state-of-the-art information on previous studies conducted in the field, as well as the main concepts and theories related to the topic. Primary data was then collected through field surveys, including sea level measurements, projection analyses and mapping to identify the areas most vulnerable to flooding. In addition, interviews were held and questionnaires applied with the local affected communities in order to understand the challenges faced by these populations, as well as their perceptions of the need for adaptive measures. Lastly, the results were critically analyzed and interpreted, taking into account the different perspectives and contributions of the existing literature. This methodological framework enabled a comprehensive approach to the topic, bringing together quantitative and qualitative data to provide a more complete understanding of the impacts of sea level rise in

this specific region.

Rising sea levels in coastal regions are an extremely relevant and topical phenomenon, with direct implications for the lives of millions of people worldwide. However, despite widespread awareness of the risks associated with this process, there are still significant gaps in understanding the specific impacts that occur in certain coastal areas, such as in the state of Santa Catarina. Therefore, this article aims to fill this gap by providing a comprehensive, state-of-the-art analysis of the results of research carried out over two decades in this region. By bringing together information on the impacts of sea level rise, as well as the adaptive measures needed to address these challenges, this study seeks to contribute to informed decision-making and to the implementation of effective adaptation policies in coastal communities.

Bibliographical review

Climatic changes

Climate change is the result of natural processes that have been occurring throughout the Earth's geological history (Salgado-Labouriau, 1998). However, studies carried out both in the past and the present have made it possible to understand the effects of human activities on the climate, as well as to identify the causes of climate change, whether natural or anthropogenic. Salgado-Labouriau (1998) defined climate change as an intense alteration involving various elements of the climate system. In order to detect climate variations that have occurred in the past, it is possible to use methods that enable the calibration of evidence and records of climate change, as reported by Oliveira (2008) and Oliveira et al. (2015).

According to Aumond and Silva (2018), the Anthropocene refers to the most recent period of the Earth's history, in which human influence became a significant geological force, thereby shaping the global landscape and interfering with the evolution of the planet. Human activity has triggered dramatic effects on the Earth, including a rapid disruption in the unstable balance of landscape morphology, and an increase and intensification in the erosion and sedimentation processes that cause climate change (Aumond & Silva, 2018). Future climate forecasts by the Intergovernmental Panel on Climate Change (IPCC) indicate an increase in the average global temperature of between 1.8º C and 4º C by the year 2100, considering the most “pessimistic” scenarios. It is thought that around 17% of global greenhouse gas (GHG) emissions will be caused by changes in the land use and forestry. The IPCC, in its reports (published in 1990, 1997, 2001, 2007, 2014 and 2021), highlights with 98% confidence that the predicted climate changes are predominantly anthropogenic in origin, resulting from the capacity of human beings to disturb the climate system, in addition to the natural dynamics of

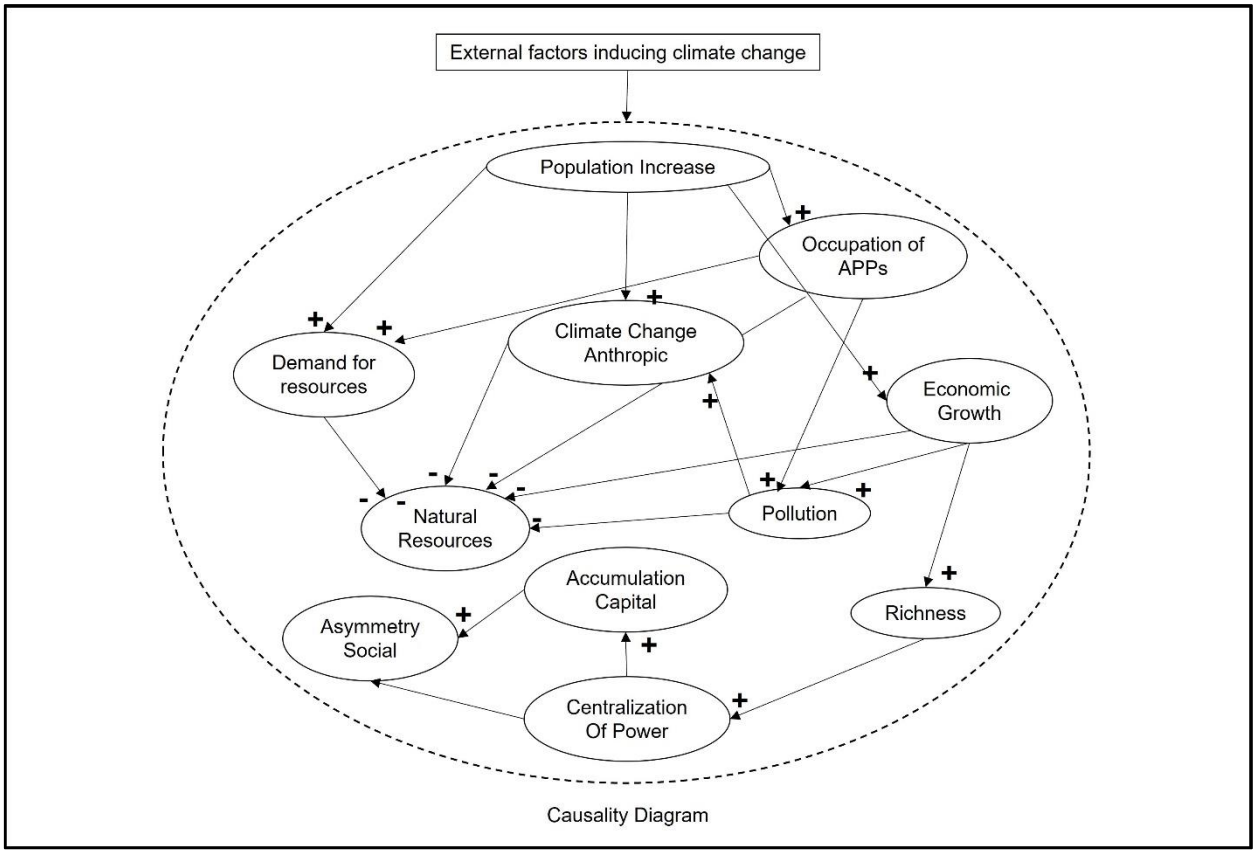
the planet (IPCC, 2021).

Due to global climate change, extreme weather and climate events are becoming increasingly frequent and intense, thereby causing disastrous effects (Aumond and Bacca, 2018) with their destructive impacts being observed all over the world (including Brazil), with hurricanes, typhoons, tropical storms, polar masses, unexpected snowfalls, accelerated melting of the poles and glaciers, together with particularly prolonged periods of extremely intense droughts. Moreover, the spatial and temporal variation of climatic conditions has also altered weather and climate patterns, affecting the frequency of rainfall and winds.

These variations have caused short-term climate projections, which until this point have been relatively predictable, to become increasingly irregular and the temporal and spatial linearity of variables seems to have been replaced by meteorological disorganization (Aumond, 2017). Figure 1 presents a diagram of the external and internal causes of climate change as indicated by Aumond (2017), in which he demonstrates that population and economic growth will increase the demand for natural resources, which in turn will directly affect the economy (through heavy investments in agriculture and urban infrastructure, with a growing need for natural resources to serve industries, among others). It should be noted that the greater the population growth, the greater the occupation of Permanent Preservation Areas (APPs) and the demand for natural resources.

Figure 1

Diagram of the causalities of climate change and their consequences
b



Own elaboration: adapted from Aumond (2017).

According to Aumond and Silva (2018), environmental disasters are made up of two interconnected aspects. First, the natural conditions of the environment, which are affected by temporal changes in surface dynamics, geological and geomorphological conditions of the region. Then, anthropogenic and social changes, which are influenced by the human presence and accentuate the condition of risk and vulnerability.

Impacts of sea level rise

Sea level rise as a result of climate change has significant impacts on natural resources and socio-economic issues, especially in coastal areas. It also intensifies the impacts of extreme events and coastal hazards, leading to various adverse effects on marine ecosystems and ecosystem services (Moftakhari et al., 2017; Fagherazzi et al., 2020; Masson-Delmotte et al., 2021; Martyr-Koller et al., 2021). Model experiments have shown that the rising sea levels during the twentieth century may not be explained by natural processes alone. Anthropogenic human activities have become a dominant cause of the recent sea level changes (Nicholls, 2018; IPCC, 2021).

The components that contribute to understanding sea level rise have improved

significantly, i.e. studies in this field of science have expanded the methodologies of physics to model the dynamics of ocean systems (involving glaciers, warm water currents, among others). Although there are no complete studies with simulations of regional changes in ocean temperature, Church et al. (2013) discussed various publications that have enabled an assessment of the likely range of sea level rises for the twenty-first century. For Becker and Karpytchev (2023), adaptation to future sea level rise is based on continuously improved climate model projections, but which are however, accompanied by inherent uncertainties, including those due to internal climate variability. Thus, neglecting this uncertainty may lead to an underestimation of future rises in sea level, since its estimation and impacts have not yet been fully explored (Becker & Karpytchev, 2023).

Global sea level rise has the potential to cause a range of impacts, such as flooding, coastal erosion and the salinization of both surface and groundwater (Nicholls, 2018), which pose a threat to the degradation or loss of large coastal areas, and to the associated economic assets and activities, resulting in the displacement of millions of people and a significant degradation of the coastal habitat. It should also be noted that coastal zones are the main drivers of the global economy and sites of significant urbanization, home to 65% of the world's largest cities. If current trends continue, the coastal population will almost double by 2060 (Neumann et al., 2015).

Methods

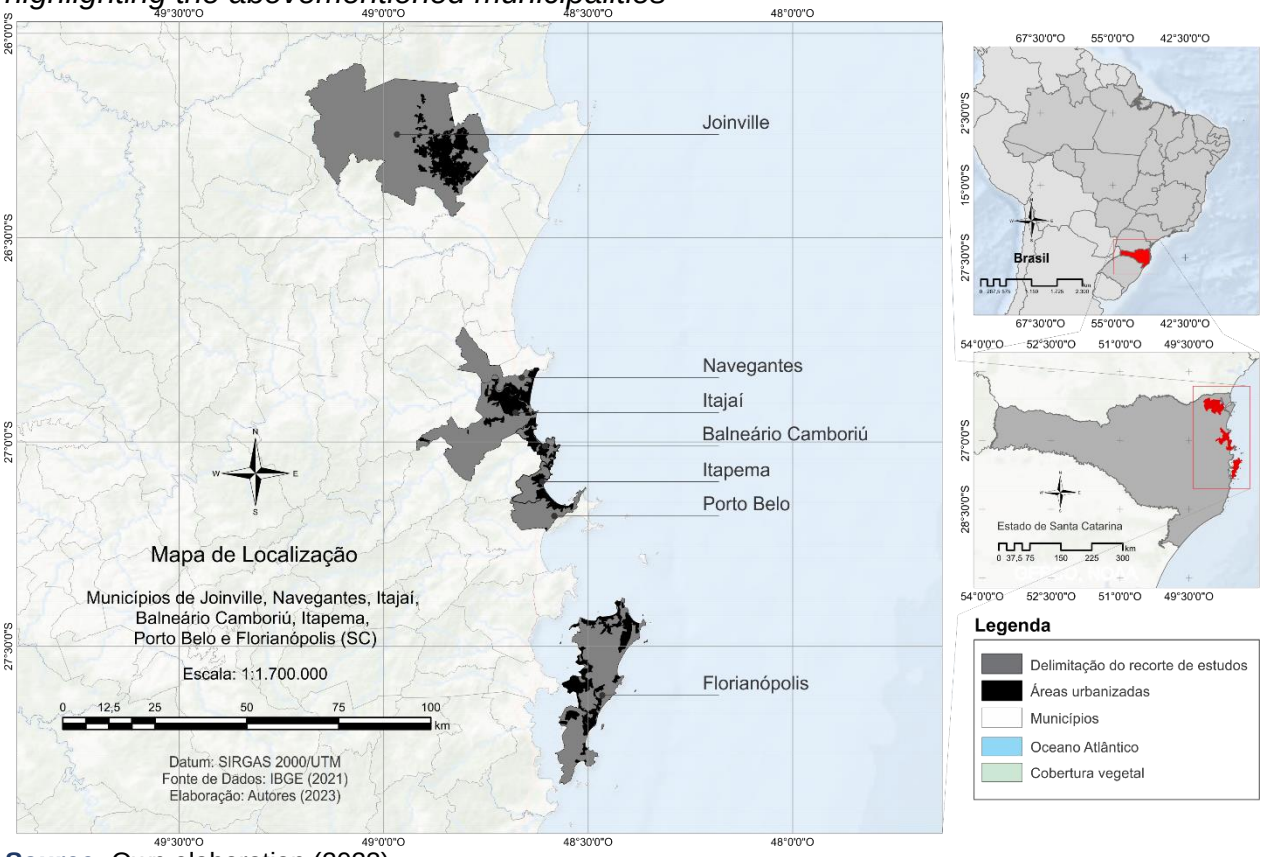
This research covers the eastern and northeastern coastline of Santa Catarina, including the municipalities of Itajaí (Hodecker & Aumond, 2016), Navegantes (Hodecker & Aumond, 2016), Balneário Camboriú (Gomes, 2018), Itapema (Jandrey, 2019), Joinville (Braun, 2017), Florianópolis (Montanari, 2015; Montanari & Pollete, 2015) and Porto Belo (Moura, 2005). The most prominent areas are located near the mouth of the Itajaí River, as may be seen in Figure 2. The Itajaí River estuary is of great economic importance to the region, since it is home to the ports of Itajaí and Navegantes, which are the main maritime trade routes of the state. In addition, there are a large number of fishing industries along the banks, making it the region with the largest fishing landings in Brazil (Schettini, 2002). The Port of Itajaí is currently Brazil's largest exporter of refrigerated products, which attracts companies to set up business within its territory and the surrounding region.

The towns of Itajaí and Navegantes play a key role in the economic development of Santa Catarina thanks to their port activities, which together, handle a large amount of containerized cargo. According to 2021 data, Itajaí presents the 34th largest economy in Brazil and the third largest gross domestic product (GDP) in Santa Catarina. The GDP data, issued by the Brazilian Institute of Geography and Statistics (IBGE, 2021), also indicated that the urban concentration of municipalities in the Itajaí-Balneário Camboriú region (along with seven

other nearby cities) has the largest share of GDP at current prices in Santa Catarina. Together, they represent an amount of 44.4 billion BRL per year, making this region the sixth largest economy in Brazil, surpassing the urban concentration of Florianópolis, which, in 2018, occupied first place in the state.

Figure 2

Location map of the study area, which covers the northeastern coast of Santa Catarina, highlighting the abovementioned municipalities



Source: Own elaboration (2023).

For the data and analysis selection, criteria were established which included documentary texts (dissertations and theses) published in journals in academic libraries in the region between 2005 and 2022. The search was carried out using the keywords "climate change", "marine transgression" and "Itajaí Valley". ArcGIS - Esri (2015) software was used to prepare scenarios for the rise in mean sea level (MSL), together with digital terrain model (DTM) files. The cartographic information was processed in raster format and then converted into vector files to facilitate intersection and calculations with other cartographic bases.

The scenarios selected for this research were based on the IPCC (2014), following the projections for the years 2030, 2060 and 2100, as described in the IPCC Report (2013), for the standards in Representative Concentration Pathways - RCP 2.6 and RCP 8.5. The first scenario, RCP 2.6, is considered the most "optimistic", showing lower levels of sea level rise,

according to IPCC data (2014). The RCP 8.5 scenario, determined as "pessimistic", has the highest projected levels. The selection of these scenarios seeks to take into account a longer time interval and an increase in sea level (in meters), as presented in Table 1.

Table 1

Average values for the global rise in mean sea level

Anos	RCP 2.6	RCP 8.5
2030	0,13m	0,13m
2060	0,26m	0,33m
2100	0,44m	Mínimo 0,74m – Máximo 0,98m

Note: The table presents the prognosis of mean global sea level rise (in meters) based on IPCC data (2014), including the forecasts for the future scenarios chosen in this research. RCP 2.6 - optimistic scenario and RCP 8.5 - pessimistic scenario. Source: Own elaboration, adapted from IPCC (2014).

Results and discussions

The results of this article describe each of the areas surveyed, which cover the urban areas along the northeast and east coasts of Santa Catarina (Brazil), including the towns of Itajaí, Navegantes, Balneário Camboriú, Itapema, Joinville, Florianópolis and Porto Belo.

Itajaí

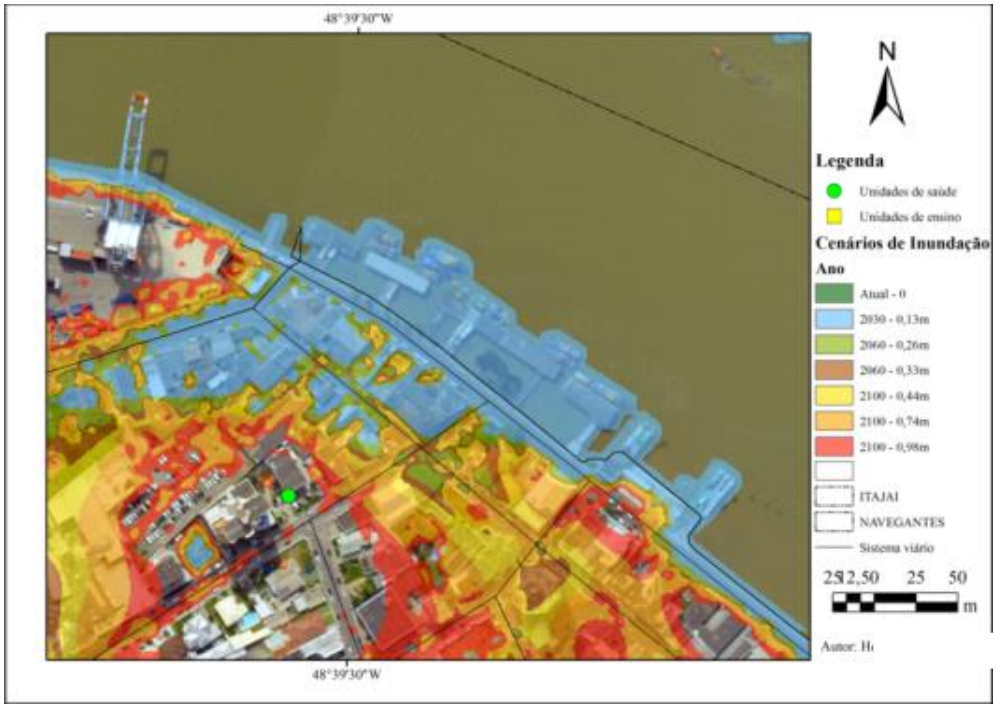
The maps (Figures 3 and 4) generated in the research by Hodecker and Aumond (2016) are based on the scenarios published by the IPCC (2014) for the northeastern region of Santa Catarina. According to the IPCC (2014), by 2030 the sea level is expected to rise by 0.13m, reaching the entire area up to the level indicated in blue in Figure 3. Between 2030 and 2060, the sea level will reach the entire area up to the level indicated in green with a rise of 0.26m, an optimistic scenario (RCP 2.6), and up to 0.33m in the pessimistic scenario (RCP 8.5) represented in brown. For the time interval between 2060 and 2100, the representation of the scope of the area affected by sea level rise is based on a minimum of 0.44m represented in yellow, and in the pessimistic scenario of 0.74m represented in orange, and may reach a maximum of 0.98m, represented in red. Thus, the analysis of certain future scenario(s) is based on the premise that the representation of the colors is equivalent to the sum of the area(s) of the previous scenario(s). In the pessimistic scenario of 2100, for example, all areas in red will be flooded by 2100, as well as all the colors that represent flooding in the lower elevations.

The area analyzed is located in the central part of the municipality and includes the important ferry terminal, which provides intercity transport between Itajaí and Navegantes. In detail (Figure 3), it may be observed that in the most optimistic scenario (2030), the flooding

will take over the entire port structure together with the streets with the oldest houses in the municipality (historic center). It may be stated that the impacts will be felt over the next few years.

Figure 3

Detail of area 2, in Itajaí, comprising urban areas, with shops, educational and health institutions, including the ferry boat structure



Source: Elaborated by Hodecker (2016).

For area 2 (Figure 3), located in Itajaí, the effects of flooding will be significant in the first scenario (2030). The entire length of Prefeito Paulo Bauer Avenue will be affected, along with the first block of Doutor Pedro Ferreira Street. This area is mainly made up of industries, the fish trade and old houses of historical and cultural value. In addition, fishing vessels along the Itajaí River will also be affected. According to the authors (Hodecker & Aumond, 2016), the rise in sea level in the first scenario (2030) will also affect a natural area made up of remnants of restinga and mangroves. However, the presence of this ecosystem will help minimize the impacts caused by sea level rise, acting as a natural risk containment. Restinga and mangrove vegetation will reduce impacts such as erosion on public spaces, including the avenue, square and sports court. Nonetheless, in the 2100 scenario, with a level of 0.74m, flooding will invade the entire ecosystem area, representing a greater risk for this region.

In contrast to other areas, this region has a significantly larger natural area of ecosystems. However, it has recently become occupied with urban interventions and engineering works. With the scenario projected for 2030, these ecosystems, including

mangroves and estuaries, already suffering from urban pressure and real estate speculation, will become highly vulnerable. There is even a risk that some species of flora and fauna that depend on this environment will become extinct (Tognella et al., 2009; Zimmermann & Branco, 2009).

Coastal ecosystems play a crucial role in minimizing climate change by sequestering and fixing carbon. In addition, they contribute significantly to the adaptive capacity of the coastal system and are therefore an important part of climate change adaptation measures (Duarte et al., 2013). It is essential to recognize the importance of these ecosystems and implement conservation policies to ensure their long-term sustainability.

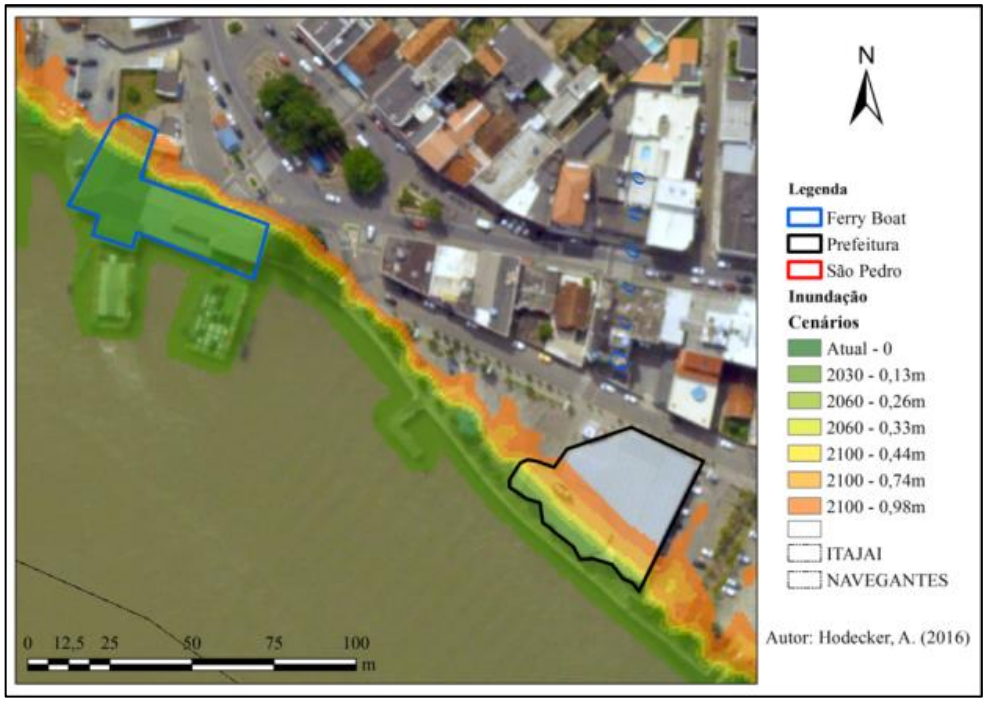
Navegantes

Based on the modeling projections of the research by Hodecker and Aumond (2016), the restinga area located in the coastal zone of the municipality of Navegantes will not be directly impacted by rising sea levels. It should be noted that the worst-case flooding scenario will also affect the Navegantes Town Hall, as well as urban areas with shops, educational and health institutions, even compromising the ferry boat structure located near the town hall (Figure 4). The São Pedro neighborhood in Navegantes will also be heavily impacted by rising sea levels. In the most optimistic scenario, with a rise of 0.13m, flooding will affect all the homes located closest to the mouth of the Itajaí River. The predicted rises by the year 2060 will flood a significant area of this urban neighborhood.

Due to its location and anthropogenic drift, the artisanal fishermen of the São Pedro neighborhood will be the most economically affected by the flooding, in terms of homes and commercial structures. The homes are mostly small and simple, many still made of wood, and located close to the riverbank. Although it is not clear from the mapping, it is possible to state that this population will face serious problems in the coming years as a result of the flooding.

Figure 2

Area close to the São Pedro neighborhood, comprising urban areas, with shops, educational and health institutions, even affecting the ferry boat structure, located next to the town hall. Both structures are highlighted in the image



Source: Elaborated by Hodecker (2016).

Itapema

The studies by Jandrey (2019) demonstrated that the northernmost areas of the municipality of Itapema would be less impacted, even when projecting the scenario for the year 2100. Coincidentally, this is where the restinga vegetation has been preserved and there is less real estate development. It is assumed that by preserving the vegetation and the consequent height of the naturally created small dunes in these places would constitute a competent barrier to the advance of the ocean. However, it is important to bear in mind that the natural features would undergo major changes. According to the author, it is possible to observe that in the Meia Praia neighbourhood, urbanization is intensifying along the waterfront, thereby causing a narrowing of the strip of sand in these areas, a fact that has been proven where the sandbank has been removed. In the projected sea level rise scenario for 2030, the concealment of the sand strip is noticeable and, for 2100, the marine transgression is even more impactful, since it would exceed the limitations of the Calçadão Linear Park (Jandrey, 2019).

Figure 3

Projection of the Future Scenario in the Meia Praia Clipping Area

Source: Elaborated by Jandrey, (2019).

Jandrey (2019) mentioned that the impacts of climate change will be most severe in places where the natural environment - such as sandbanks and mangroves – has been replaced by buildings. However, as previously mentioned, Itapema has experienced a disorderly growth driven by the interests of construction and real estate companies, without considering susceptibility to flooding or environmentally fragile areas. Unfortunately, the urban zoning policies adopted by the municipality of Itapema have not been effective in mitigating the impacts of rising sea levels caused by climate change in the areas analyzed. On the contrary, these policies have encouraged the occupation of vulnerable areas, which are of interest to developers and real estate agents. It is therefore, crucial to review these policies and implement adaptation measures to protect local communities and the environment.

Balneário Camboriú

According to Gomes (2018), projections for the municipality of Balneário Camboriú

indicate that sea level rise will have a significant impact on the beachfront, especially in the most pessimistic scenario (RCP 8.5). Even before the artificial extension of the beach, the author discovered that there would be a tendency for the strip of sand to shrink significantly in the scenarios for 2030, with the marine transgression reaching the roadway of Avenida Atlântica adjacent to the beach, as may be observed in Figure 4. It is important to note that these projections do not take into account the dynamics of tides and sea surges, which could extend the area even further. As this is a very commercial area and has many real estate developments, the impacts will be significant.

Figure 4

Projection of the marine invasion area with the rise in sea level in the municipality of Balneário Camboriú

Fonte: Elaborado pelo autor a partir da Cartografia em *Shapefile* no site do SIG SC, 2017.

Source: Elaborated by Gomes (2018).

Gomes (2018) demonstrated that the area in question is susceptible to marine

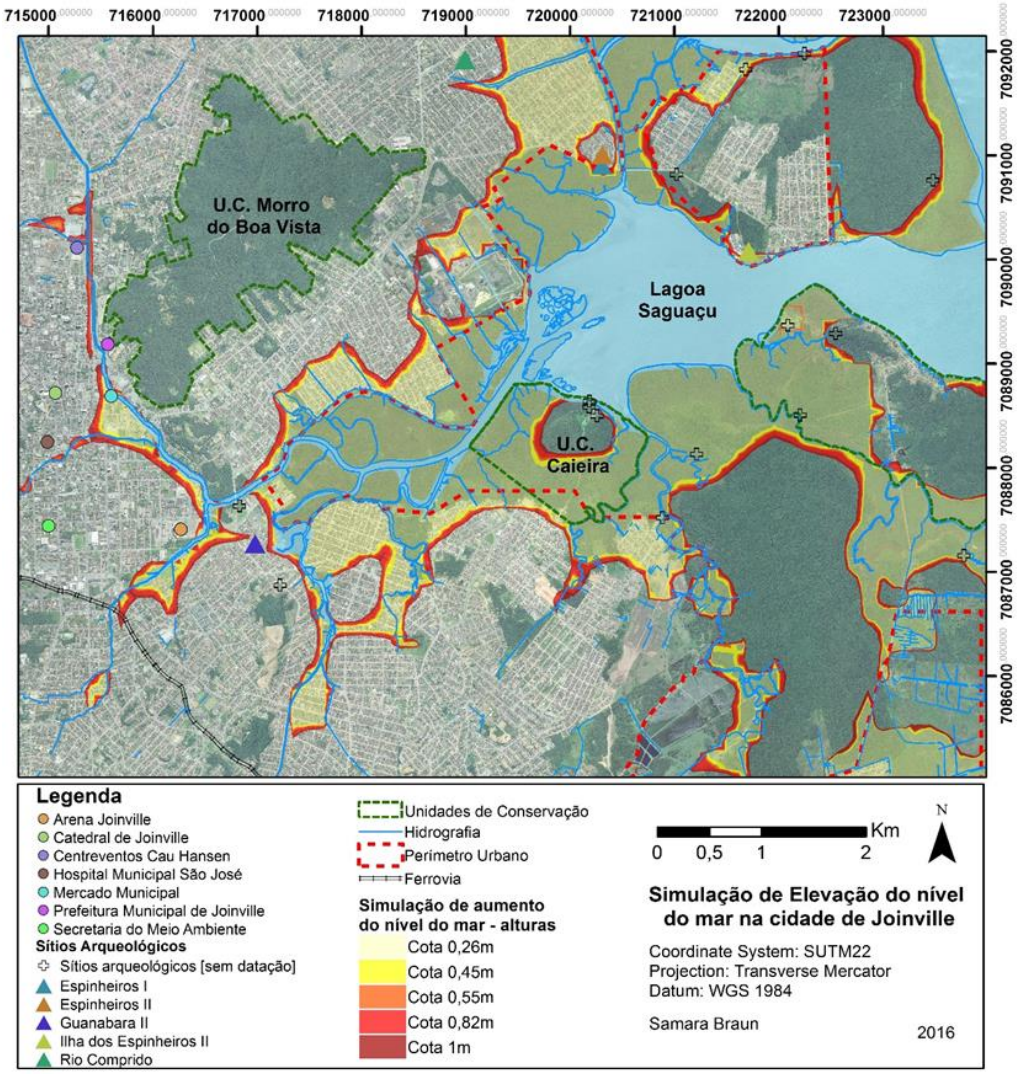
transgression, even considering the lower eustatic sea level. The analysis also revealed that the region is vulnerable in all IPCC scenarios, both for 2030 and 2100. In the most pessimistic scenario (RCP 8.5), the roadway on Avenida Atlântica will be subject to marine transgression. Even in the 2030 scenarios, before the beach development works, the strip of sand would be invaded by the waters, increasing the impacts of the transgression. It is important to note that the dynamics of tides and sea surges were not taken into account in the analysis, which could signify that the situation will be even worse. Given the commercial activity and the large number of real estate developments in the area, the impacts will be significant.

Joinville

Braun (2017) found that Joinville's coastal plain will be affected by flooding due to climate change. This plain is made up of recent sediments, mainly sands and silts, on which the municipality is situated and also has secondary river channels, such as those of the Cachoeira and Mathias rivers. According to the author, these secondary river channels will be reached even in the central region of the municipality in the highest elevation scenarios, as presented in Figure 5, which highlights the presence of the "U. C. Morro da Boa Vista", an important conservation unit. These units are protected areas (PAs) created by legislation, in accordance with Federal Law No. 9.985 of July 18, 2000 (Brasil, 2000), whose main objective is to preserve biological diversity, as well as natural and environmental resources in their various ecosystems. It is important to note that the PAs will play a crucial role in guaranteeing natural resources such as water and food, and in climate change scenarios, they will become even more relevant in conserving ecosystems and combating the negative impacts of these changes.

Figure 5

Simulation of flooding in the in the central region of the municipality of Joinville caused by the sea level rise



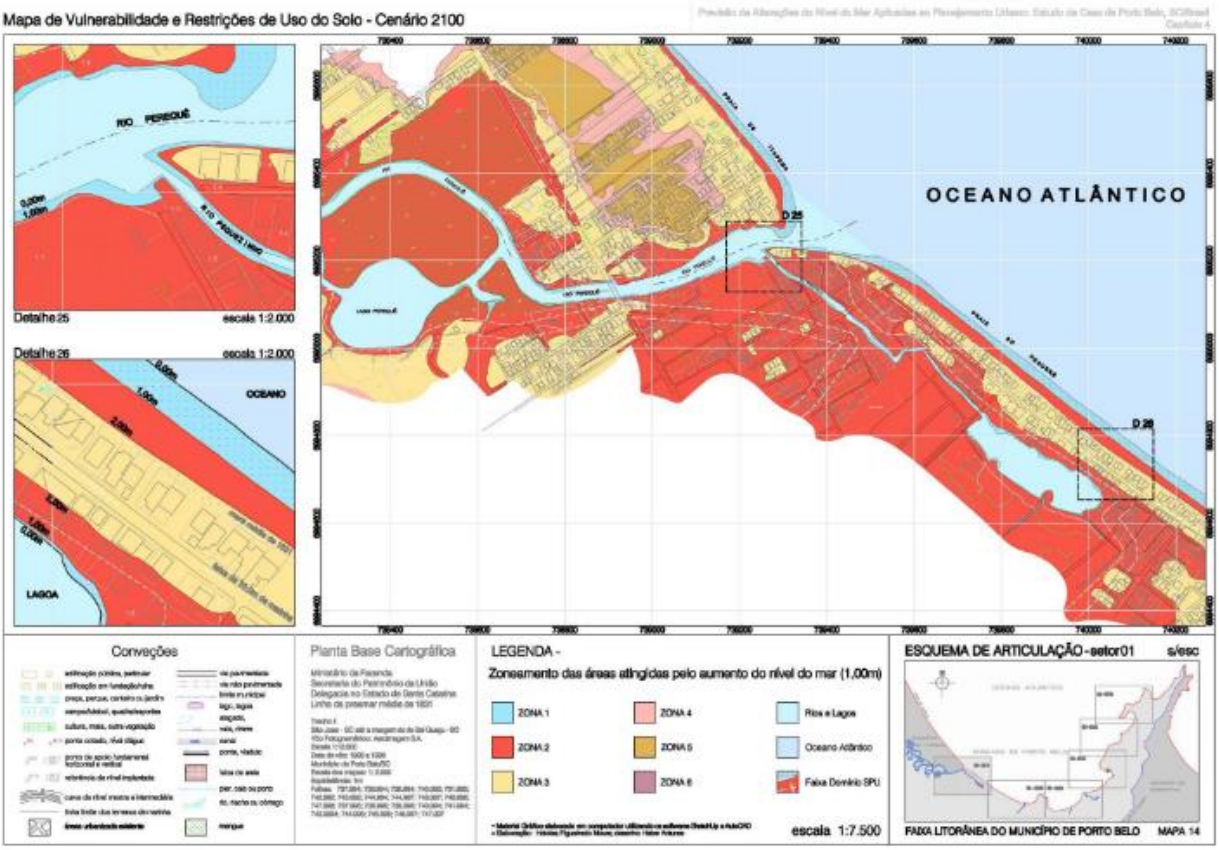
Source: Elaborated by Braun (2017).

Porto Belo

In the analysis of rising sea levels carried out by Moura (2005), it was found that almost the entire length of the right bank of the Perequê River will be flooded. In addition, both banks of the Perequezinho River and the Perequê Lagoon could become wetlands due to the influence of monthly high tides, as may be observed in Figure 6 (detail 25). According to Moura (2005), the absence of adequate systems for collecting and treating urban effluents aggravates the level of pollution, compromising the quality of river and sea water.

Figure 6

Vulnerability map and land use restrictions in Porto Belo in a 2100 scenario



Source: Elaborated by Moura (2005).

Moura (2005) notes that rising sea levels could result in the formation of dunes and sandbanks over areas currently occupied by walls, fences and other similar structures, as well as some buildings, as indicated by the real estate registry provided by the city council (Figure 6, detail 26). The author emphasized that the effects on these areas will be influenced by the landscape units into which they are inserted and by the period analyzed, and will be enhanced by the way the sea progressively occupies natural or currently urbanized spaces. The scenario projected for 2100 indicates a greater impact upstream of the areas affected by the sea compared to the current scenario.

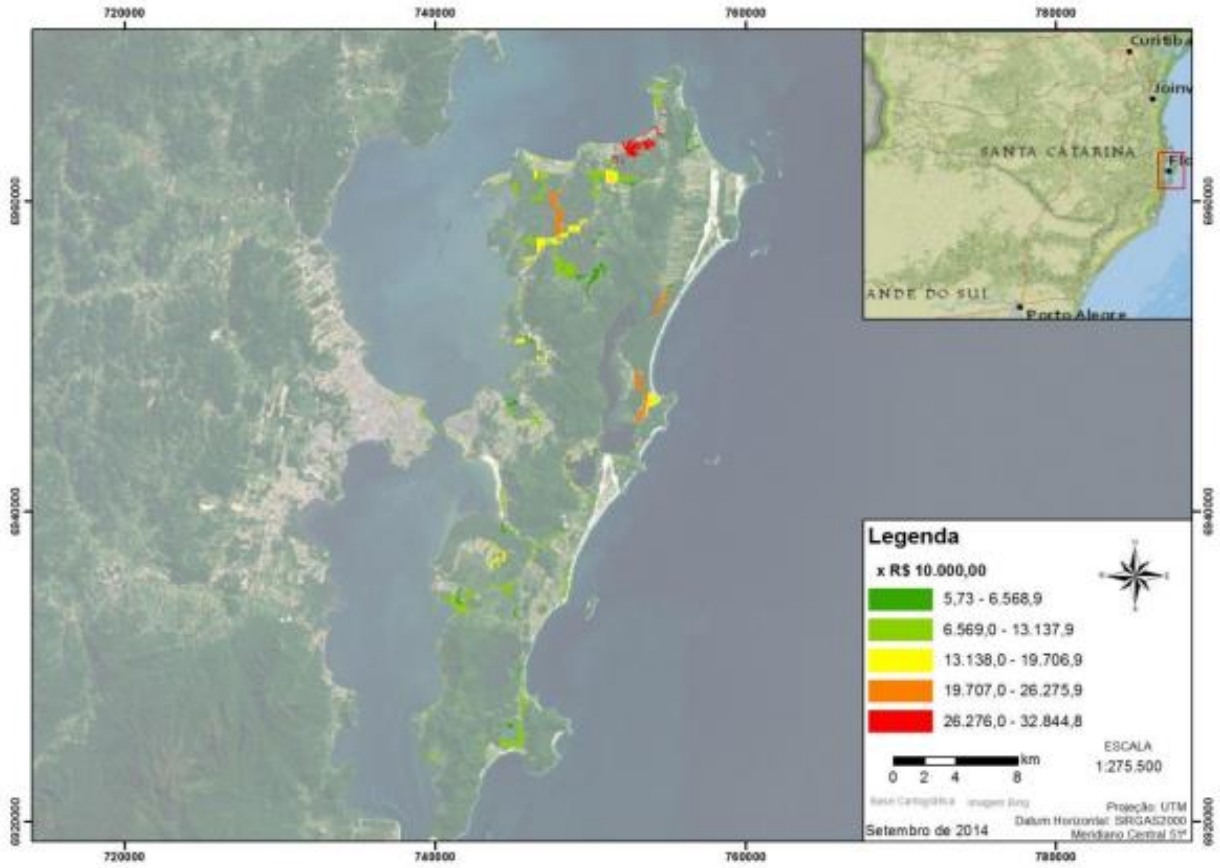
Among the most common problems detected by the author are constructions too close to the beach, on marine land, the obstruction of sanitary strips along waterways, residential pressure on mangrove areas, the privatization and obstruction of the seascape, as well as the de-characterization of the environmental heritage. In addition, the poor accessibility of the waterfront must be adapted to the changing landscape. Moura (2005) also indicates that one of the direct consequences of this process is the need to vacate and demolish vulnerable areas that will be impacted by the waterfront.

Florianópolis

Montanari (2015) conducted an analysis of the economic impacts that could occur in Florianópolis if climate change predictions come true. The data was obtained by cross-referencing information from the IBGE land use map, and the population and economic census. The study revealed that 27% of the territory of the Ratones River basin would be affected by rising sea levels, in which the most affected classes of land use would be lowland vegetation (14.28 km²) and mangroves (6.31 km²). The number of inhabitants affected would be 32,355, and the total number of households affected would be 10,990 (Figure 7).

Figure 7

Map of the estimated direct cost of the scenarios proposed by the author in Florianópolis due to the rise in sea level modeled for 2100



Source: Elaborated Prepared by Montanari, 2015.

It has been estimated that the costs of measures to mitigate the direct impacts of a rise in mean sea level in Florianópolis could reach around 13 billion BRL (in values from the current year of the research) (Montanari, 2015; Montanari & Pollete, 2015). The immediate damage would result from the direct contact of floodwater due to coastal erosion, which would affect the beach infrastructure and the pavements along the waterfront. This damage would include

the cost of relocating the damaged buildings. According to Hallegatte et al. (2011), assessing the impacts of changes in average conditions and extreme changes should be undertaken differently, as their forecasts require different methodologies and therefore demand different adaptation strategies.

Montanari (2015) also found that urban expansion in Florianópolis is limited and that there is a tendency for densification in central areas, which may lead the low-income population to seek out peripheral areas, many of which are Environmental Preservation Areas (APPs) such as steep slopes, creeks, lagoons, dunes and mangroves. According to the author, the mangrove areas in Florianópolis will be affected by rising sea levels by 2100, and although the mangroves located in the south and north may migrate to other areas, for those located in the central region of the city, surrounded by urban areas, this will not be possible.

Discussion

The results of all the research carried out in the coastal regions of Santa Catarina over the last 20 years have provided valuable information regarding the impacts of rising sea levels in the region. This information is of considerable importance, since it provides an understanding of the challenges faced by local communities and of the need to implement adaptive measures in the face of climate change.

The maps and projections demonstrate that rising sea levels will result in significant flooding in different areas of the region. The optimistic and pessimistic scenarios indicate different levels of sea rise, but in all cases, it is expected that urban areas and important infrastructure will be affected. For example, in the most optimistic scenario for 2030, flooding will affect the ferry terminal and historic center in Itajaí. The impacts will be felt over the next few years and will mainly affect industrial and commercial centers, homes and Permanent Preservation Areas (APPs).

Thus, coastal ecosystems, such as mangroves and sandbanks, play a fundamental role in minimizing climate change, contributing to the adaptive capacity of the coastal system. They act as a natural containment of risks, reducing the impacts of rising sea levels, such as erosion and flooding, which have also been observed in dozens of studies in various parts of the world, such as Nicolodi & Petermann (2010), Moftakhari et al. (2017), Fagherazzi et al. (2020), Masson-Delmotte et al. (2021) and Martyr-Koller et al. (2021). However, the disorderly occupation and suppression of these ecosystems jeopardizes their ability to mitigate the effects of climate change. It is essential to recognize the importance of these ecosystems and implement conservation policies to ensure their long-term sustainability.

Urban areas - especially those where the natural environment has been replaced by buildings - will be most severely affected by rising sea levels. Local communities, such as artisanal fishermen and residents of vulnerable neighborhoods, will be hit hardest both

economically and in terms of infrastructure. Housing in these areas is often simple and located close to riverbanks, making them even more susceptible to flooding. Furthermore, urban interventions and disorderly occupation have increased the vulnerability of these areas, as discussed by Neumann et al. (2015).

There is a need to review the urban zoning policies adopted by municipalities such as Itajaí, Itapema and Balneário Camboriú, which have not been effective in mitigating the impacts of rising sea levels. As discussed by Becker and Karpytchev (2023) and Roy et al. (2023), these policies have so far encouraged the occupation of vulnerable areas, of particular interest to construction and real estate companies, without considering the risks associated with climate change. It is essential to implement adaptation and conservation measures to protect local communities and the environment.

Final considerations

With the aim of compiling research results on climate change and its impact on sea level rise in the urban areas of the northeastern and eastern coastal regions of the state of Santa Catarina, a comprehensive approach was employed. In order to achieve this goal, relevant climatic and oceanographic data was collected. In each section of the results, statistical analysis and modeling were presented to assess the patterns of climate change and sea level rise in the specific regions in question. Through these methodologies, it has been possible to obtain results that provide valuable information on the impacts of climate change and sea level rise in the coastal urban areas of Santa Catarina, which has contributed to the advancement of scientific knowledge in this area. It has also provided relevant data for planning and decision-making related to the adaptation and mitigation of these effects.

This article contributes to urban studies since the rise in ocean levels will cause significant impacts on the northeastern and eastern coastline of Santa Catarina, as evidenced by various studies analyzed herein. Some areas, such as the São Pedro neighborhood in Navegantes, have already been affected by tides and storm surges, against whiche, local fishermen are implementing barriers to protect their homes. The future scenarios (up to 2100) analyzed in this study show how the coastline will be transformed by the progressive rise in sea level, which may also cause significant damage to fishing activities, due to the possible salinization process of the waters. This could further reduce the quantity of fish, which is the main source of income for local artisanal fishermen. The lack of basic sanitation and sewage collection systems is also a serious problem in the area, and it is believed that this situation will worsen with the abovementioned scenarios.

As sea levels rise, so does the risk of spreading infectious diseases and exposure to toxic chemicals in floodwater, and of the potential indirect effects of climate change, such as disruptions to water and energy supplies. Ongoing climate change, intensified by human

activities, will have significant negative environmental, social and economic impacts. The replacement of natural environments, such as sandbanks and mangroves, by informal settlements will further increase these impacts. Current urban zoning policies are proving to be ineffective in reducing the impacts of sea level rise in the areas analyzed.

This study also contributes to the practice of urban managers and planners, as well as public policy managers, since the projections of the analyzed sea level rise could cause socio-environmental disasters in the coastal region. It will therefore be useful for planning land use and occupation in urban areas, as well as for managing natural resources. Identifying and characterizing the most vulnerable areas will help in implementing preventive measures in order to minimize the impact of sea level rise on natural environments, which could be achieved through biodiversity conservation management and conservation of the subsistence resources of artisanal fishing communities.

Although results have been presented on climate change and the rise in sea level, it is important to recognize that these phenomena are complex, and are influenced by a variety of interconnected factors. Therefore, it is necessary to consider that other elements such as coastal dynamics, human occupation and adaptation policies also play a significant role in the observed impacts. Furthermore, it is important to mention that this study was based on data and information available up to the date of the research, and new scientific developments and future events may bring additional contributions and updates to the understanding of climate change and its effects on sea level rise. It is therefore essential to continue with more comprehensive research and studies to broaden our knowledge on these issues and their implications for coastal areas.

Lastly, the sustainable development goals (SDGs) 11, 13 and 14 are linked to the importance of promoting sustainable communities, mitigating climate change and conserving marine ecosystems, and represent a way forward in meeting the challenges of climate change, seeking to ensure a safe, resilient future for all. Sustainable development goal 11 aims to promote the resilience of coastal communities, empowering them to cope with the impacts of rising sea levels and build sustainable human settlements. Achieving SDG 13 contributes to mitigating the effects of climate change and protecting coastal communities vulnerable to sea level rise. The link between SDG 14 and sea level rise is clear, as it poses a direct threat to biodiversity and the sustainability of marine and coastal ecosystems. To tackle this issue, it is essential to adopt measures that protect and restore these ecosystems, ensuring the conservation of oceans, seas and marine resources in a sustainable manner. This involves implementing sustainable coastal management strategies, protecting sensitive coastal areas and promoting sustainable fishing, among other actions.

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