COASTAL VULNERABILITY ASSESSMENT: AN INTEGRATED FRAMEWORK TO ANALYZE LOCAL DECISION MAKING AND ADAPTATION TO SEA-LEVEL RISE IN SANTOS, SAO PAULO-BRAZIL

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The METROPOLE Project is an international collaboration between Brazil, the United Kingdom, and the United States designed to evaluate local decision making processes and to provide feedback to local urban managers on possible actions toward adaption to sea level rise (SLR). The goal of the project is to help coastal communities better understand factors that facilitate or hinder their intrinsic, local decision-making processes related to planning for adaptation to risk. The test used case sea level rise to develop case studies on long-term planning by local government and society as a means to gauge the of municipalities in different settings to address possible future risks. The framework was designed by an interdisciplinary team that incorporated social and natural scientists from these three nations, and which included local government officials. This paper focuses on some of the factors that affect decision-making in the coastal city of Santos, in the state of Sao Paulo in southeastern Brazil, and provides insight on possible actions that a coastal city, such as Santos, can do to prepare for impacts of SLR.

Key words: *Sea level rise, climate change, adaptation, coastal vulnerability*

I. INTRODUCTION

One of the clear signals of present climate change is sea level rise (SLR). There is mounting evidence of other changes, including warmer temperatures in many localities, and changes in the intensity and frequency of extreme meteorological events, including wind, rain, and waves. A rising sea level combined with these factors and tides is expected to affect coastal communities through a number of processes, including increased risk of flooding and contamination of water sources. Extremes in meteorological events can also lead to erosion of coastal areas, landslides, and floods or droughts. These can have direct impacts on human communities, but also important indirect impacts through changes in biodiversity and other ecosystem services [1], [2], [3], [4].

Most of the world's 60 million poor people living in low elevation areas reside in just 15 countries, including Brazil [5]. Urban low elevation coastal zones are expanding faster than elsewhere and this trend is expected to continue into the future [6]. Globally, between 660,000 and 1,200,000 km^2 of land, 93-310 million inhabitants and 3,100–11,000 billion USD of built capital are currently located at elevations less than the present 100-year sea level flooding event [7], but by mid-century there could be an increase in global flood losses for the 136 largest coastal cities. The Brazilian coastal zone is home to ~27% of the population of Brazil (ca. 51 million people). These communities are vulnerable to the hazards outlined above. Between 5 and 8% of the population living in coastal areas could be disastrously affected by climate warming of the order of 2-4ºC by the end of the 21th century.

To improve resilience, policymakers need to understand current adaptation processes and obstacles, and plan accordingly to be effective. These processes depend in great measure on how decision-makers and the public perceive and respond to changes and the perception of risk. In order to evaluate how local government may respond to risks associated with sea level rise projections, a group of natural and social scientists from the United States (US), United Kingdom (UK), and Brazil developed the *METROPOLE Project.* The goal was to combine expertise from diverse scientific backgrounds to develop an integrated framework to analyze local decision-making and the adaptive capacity to local environmental change driven by large-scale processes like climate. The team sought to understand the perception of risks associated with climate change by co-developing an evaluation of adaptation capacity that given a particular social, political, and cultural context in a region. The study developed case studies in three coastal areas, each representing one of the three countries involved, specifically the city of Santos (São Paulo, Brazil), Selsey/Chichester (West Sussex, United Kingdom), and Broward County (Florida, United States).

This paper focuses on the Brazilian case study. We describe the reaction of local stakeholders to scenarios under SLR projections for 2050 and 2100, including potential consequences to no action and to a range of possible adaptation measures. The study was an active, participatory engagement of the civil society of Santos in which scientists and stakeholders explored options and the factors that hindered or facilitated action. Most of the results presented here come from the study by [8] that described the METROPOLE project and the results for Santos.

II. SEA LEVEL RISE IN BRAZIL AND THE SANTOS CASE STUDY

For the Latin America and the Caribbean Atlantic coast, SLR between 1950-2008 rose ~2 mm yr^{-1} [9] and the Brazilian coastal areas are being affected by coastal erosion and coastal inundation [10], [11], with the southern part of the State of São Paulo and Rio de Janeiro seeing rates of between 1.8 and 4.2 mm yr^{-1} since the 1950's [12], [13]. According to [14], the mean sea level in Santos has risen at a rate of 1.2 mm yr^{-1} since 1940's, with an increasing trend in the past decade. This rate is slower than the global mean sea level rise rate. This suggests that additional factors such as estuarine circulation patterns, land subsidence and/or anthropogenic interferences like dredging may be affecting local sea level rate.

Founded in 1546, Santos is one of the oldest settlements of Brazil. It occupies an area of 281 km^2, of which 39.4 km^2 lies in the insular domain (São Vicente Island) and 231.6 km^2 correspond to the mainland part of the municipality (Figure 1). Around 99.3% of the Santos population live in the insular domain (Gasparro et al., 2008). The Port of Santos alone is responsible for the transport of products from the largest industrial park in Brazil, handling around 25% of Brazil's foreign trade [15].

The municipality of Santos is also a portrait of the social asymmetry of the country, featuring upscale neighborhoods especially closer to the shoreline and poor neighborhoods concentrated at the Northwestern Zone of the island, on the hill-slopes and the wet lowlands. The irregular occupation of the hill-slopes and mangroves, the pollution generated by industries located around the area, and deforestation of the Atlantic Rainforest, which reduced the water retention capacity of the soil and increased the continental runoff, accelerated common processes in the area such as landslides, mudslides and floods, putting a large contingent of the population under constant threat. The region is affected by tropical, subtropical and mid-latitude weather systems. During summer, when convective activity is greater, the SACZ (South Atlantic Convective Zone) influences the rainfall regime, with a cloud band and rainfall remaining semi-stationary for several days. Frontal systems are common in the area, mainly during autumn-winter. Storm surges have historically affected this region. Nowadays, storm surges typically cause destruction or urban infrastructure and damages related to traffic interruption at the southeastern ending of the Santos coastline [15].

Flooding events normally occur in two main areas of Santos: at the Northwestern Zone (NW) and at the Southeastern Zone (SE). The latter is closer to the mouth of the Santos estuarine channel, along the seafront (Figure 1). At the NW zone, flooding is caused by the combination of heavy rainfall and high tides, so that the waters from the watersheds discharges summed to the superficial continental runoff flowing down towards the estuarine channel are blocked by the tidal waters rising into the existing drainage system. At the SE zone, flooding is caused by coastal inundation related to storm and tidal surges, in general associated to extra-tropical cyclones passage.

The Port of Santos, the key economic asset for the municipality, may be affected by SLR. Most sections are built to withstand water level increases of as much as 3 m above the current mean sea level (ICF-GHK, 2012). The interaction between SLR and flood frequency may be of greatest concern.

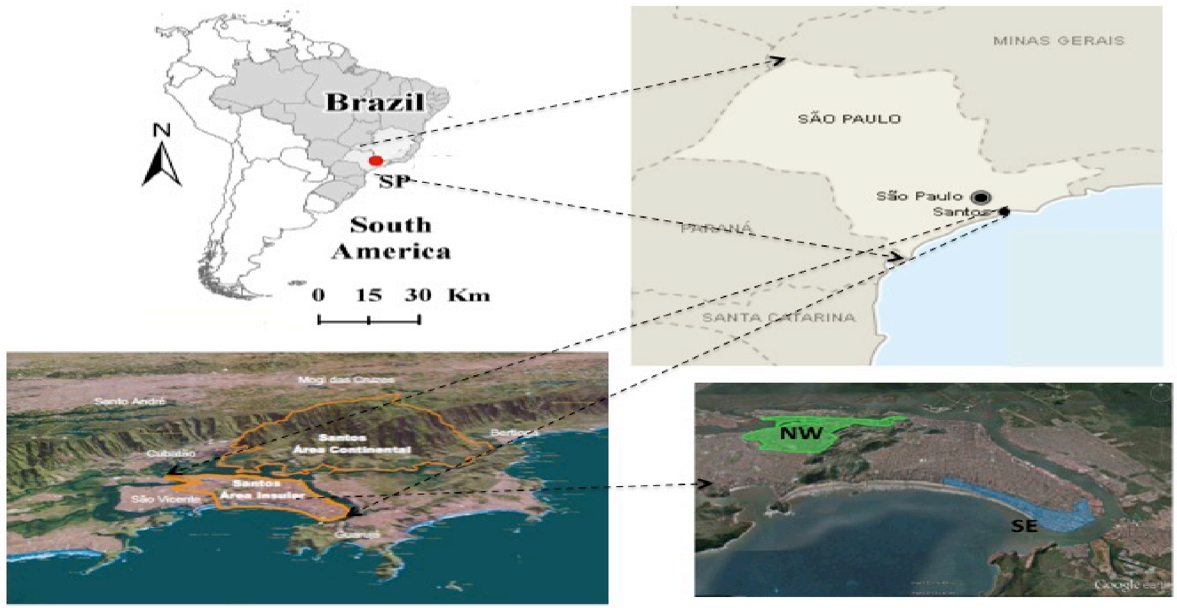

Fig. 1 Location of the study area [8]

III. Methods and the COAST Platform

The METROPOLE project incorporated an evaluation of risks and impacts of SLR and tested the city's Adaptive capacity. SLR risks were estimated using the COAST (COastal Adaptation to Sea level rise Tool) platform [16]. The METROPOLE project incorporated an evaluation of risks and impacts of SLR and tested the city's Adaptive capacity. SLR risks were estimated using the COAST (COastal Adaptation to Sea level rise Tool) platform.

COAST estimates SLR and storm surge impacts by calculating damage from storm surge events cumulatively over time, given a changing base water level. It then calculates relative benefits of various adaptation scenarios in terms of cumulative *avoided* damages over time. The model is intended to be used by municipalities, state agencies and other groups interested in benefit-cost analysis for adaptation strategies aimed at reducing damages from SLR and storm surge. COAST allows users to (a) calculate how much building damage may be avoided over time if such strategies are implemented; (b) confirm whether the projected benefits outweigh the costs; and (c) evaluate which strategies seem the most cost-effective. The process includes creation of data projections for coastal changes and potential economic and environment consequences of flooding scenarios resulting from a rise in sea level and extreme storm surge events. Financial ramifications are calculated using inputs from local stakeholders and confirmed by expert engineering review. Use of the tool in public process also allows stakeholders to articulate and modify potential adaptation strategies. Figure 2 shows the conceptual model developed for application of COAST in the two zones affected by hydro-meteorological risks in Santos: the NW and SE zones (see Figure 1).

Data required to run COAST for the two case studies (district, land area, construction area, assessed value of the land, value of construction and value of the property) was obtained from the

Municipaliuy of Santos. The City of Santos identifies the property through a primary key called "Lançamento Fiscal" containing 11 digits Sector/Court/Parcel/Sub Parcel, where the final sheet was modeled in level Parcel x Venal Value of the Property. These data were associated line by line / parcel-to-parcel, as the software that the Secretariat for Finances of Santos uses was not geo-referenced. This information allowed generating a map containing all layers of geo-referenced information with the orthoimages, adopting the scale 1: 1,000.

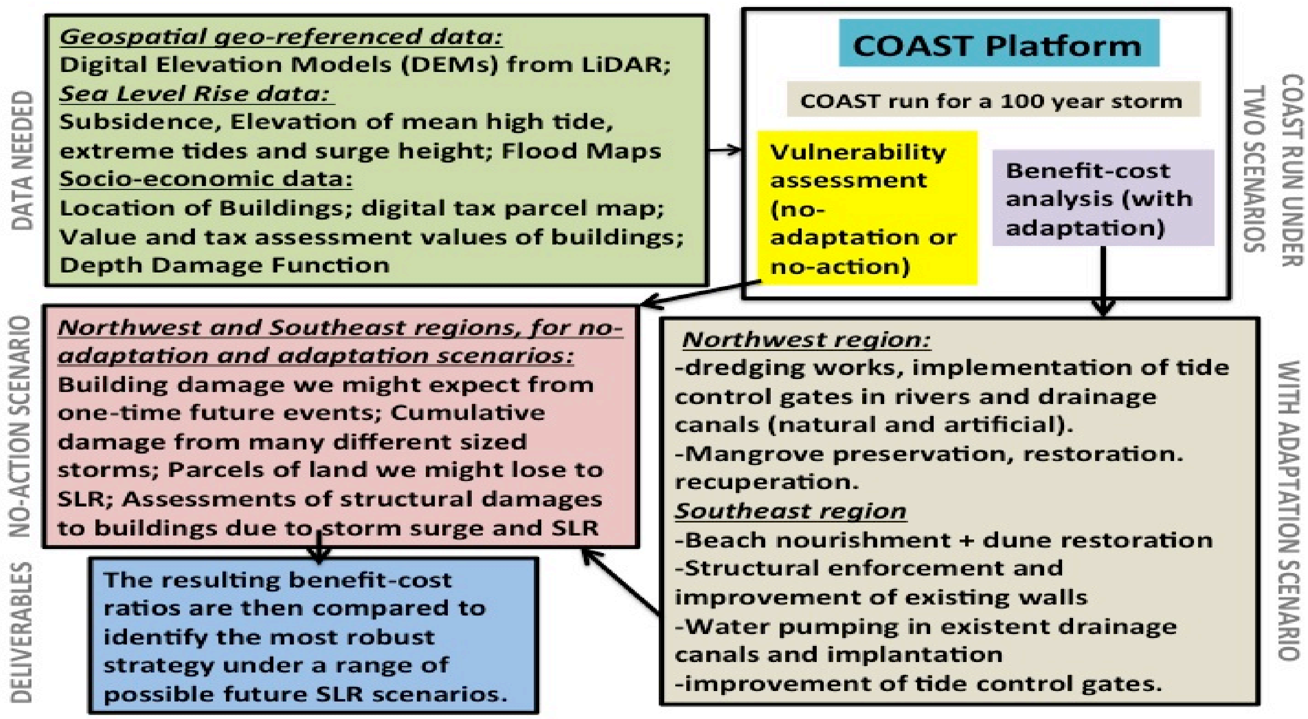

Fig. 2. Conceptual model developed for the application of the COAST tool in Santos [8]

IV. MAIN RESULTS

Table 1 presents projections of SL considering several trends for Santos, as computed by J. Harari=IO/USP using altimetric data in the period 1993 - 2014. When considering separately the first and second decades, three rates of mean sea level trend were obtained. A rate of 2.7 mm y^{-1} (optimistic scenario or low SLR, from the first decade), a rate of 3.6 mm y^{-1} (moderate scenario or mean SLR, from the second decade) and an additional rate of 4.5 mm y^{-1} (pessimist scenario or high SLR, when keeping the observed sea level acceleration from on decade to the next). These rates would lead to an increase of sea level, in 2100, of 27.0 cm, 36.0 cm or 45.0 cm above the mean sea level of the year 2000 (using a hypothesis that no additional acceleration would occur). Finally, one last SLR was also considered in COAST simulations, based on the estimation of IPCC analysis, which considers a global and uniform SLR of 1.0 meter at the year of 2100. Besides this information, COAST platform also needed an estimate of maximum levels reached for return periods of 50 and 100 years, based on actual data, not considering any future sea level rise. By applying the generalized extreme value distribution, this estimation gave the values of 1.60 m and 1.66 m above the mean sea level, for 50 and 100 years of return periods respectively. Important to note that the mean level of maximum spring tides is 0.61 m and the presently observed maximum level is 1.45 m (above the mean sea level).

Table 2 shows cumulative damage estimates for real estate in Brazilian currency (Reais, R$). The asset modeled by COAST corresponds to structural value of buildings. If no adaptation action is taken, and considering as scenario year 2100, low SLR (between 0-0.36 cm) for a 100-year storm, losses of R$ 870.093.165 in the SE Zone and of R$1 66.933.832 in the NW Zone are expected. In a high SLR scenario (between 0.36-0.45 cm) losses of R$ 1.043.498.249 in the SE Zone and of R$ 236.406.111 in the NW zone are expected.

Table 1. Projections of SLR increase under several trends (Source: J. Harari, IO-USP). [8]

Years	SLR increase (cm) – Trends 0.27 ± 0.06 cm/year	SLR increase (cm) – Trends 0.36 ± 0.18 cm/year	Sea level increase (cm) - Trends 0.45 cm/year
2000	0	0	0
2015	4.05 cm	5.40 cm	6.75 cm
2025	6.75 cm	9.00 cm	11.25 cm
2050	13.50 cm	18.00 cm	22.50 cm
2075	20.25 cm	27.00 cm	33.75 cm
2100	27.00 cm	36.00 cm	45.00 cm

Table 2. Cumulative damages for two scenarios of SLR (low and high) in different time slices (no action scenario). Values are in Brazilian currency Reais R$. (As a reference 1 US dollar=3.7 R$) [8]

Period	SLR	Southeast Zone	Northwest Zone
2010-2050	Low (0 m-0.18 m)	R$ 268.616.063	R$ 38.741.161
2010-2050	High (0 m-0.23 m)	R$ 304.751.652	R$ 49.577.392
2051-2100	Low (0.18 m-0.36 m)	R$ 601.477.102	R$ 128.192.671
2051-2100	High (0.23 m-0.45 m)	R$ 738.746.597	R$ 186.828.719
2010-2100	Low (0 m-0.36 m)	R$ 870.093.165	R$ 166.933.832
2010-2100	High (0 m-0.45 m)	R$ 1.043.498.249	R$ 236.406.111

Using 3D visualizations, the information on the location of the risk and damages was presented to Workshop participants. For example Figures 3a-d show results for 2050 and 2100n considering a high SLR (0.18 m+1.60 m) and (0.45 m + 1.66 m) inundation scenario and lost asset value, respectively. Similar maps for the NW zone (not presented) were also and shown to participants and discussed in the Workshops.

To advance the understanding of connections between stakeholder beliefs, values and preferences regarding adaptation options and funding choices, as well as to improve understanding of barriers to adaptation in Santos, decision makers, citizens, representatives of public and private sectors and of NGOs of Santos were engaged with the METROPOLE process through two stakeholder workshops. As a result of these workshops, participants coming from various sectors of society living in Santos proposed some adaptation measures, that were later on incorporated in the COAST model:

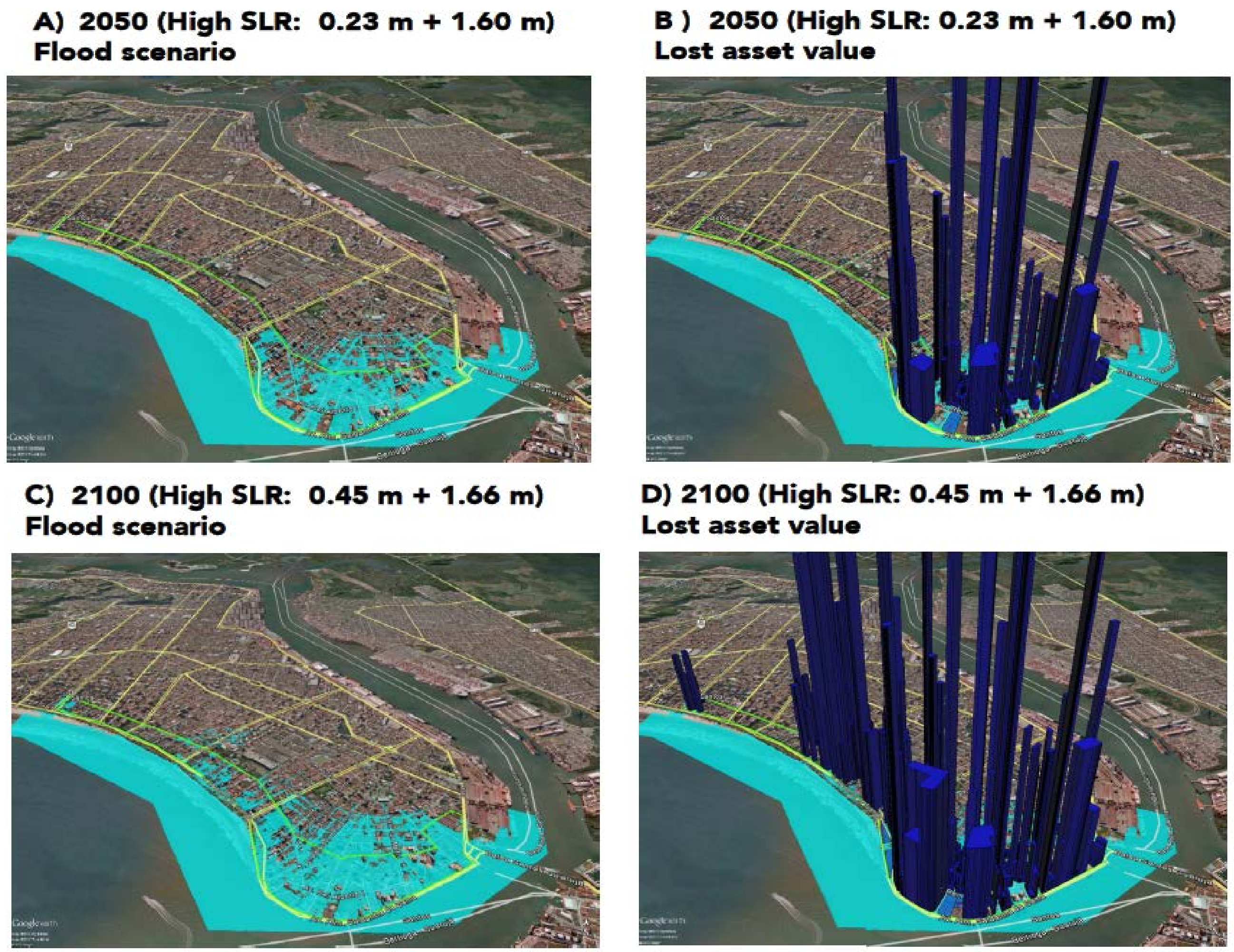

Fig. 3. Flood scenario expected for 2050, high SLR (0.23 m+1.60m) and 2100 (0.45 m + 1.66 m) [8]

(a) SE zone: fortification (beach nourishment + dune restoration, structural enforcement/improvement of existing sea-walls, water pumping and implementation/improvement of tide control gates in existing drainage canals); and

(b) NW zone: fortification (improvement of existing measures such as dredging works and construction of tide control gates in rivers and drainage canals, natural and artificial, and implementation of tide control gates in rivers and drainage canals) and accommodation (mangrove preservation, restoration, and recuperation). Relocation of vulnerable assets was not among the most favored options for either region.

Results suggest that for the SE zone the chosen measure (fortification) would be cost effective (benefit-cost ratio = 28.58), while in the NW zone the measures modeled (fortification and accommodation) would not be as beneficial (benefit-cost ratio = 0.32 (Table 3). However avoided damages for the NW Zone might be greater than was modeled because of challenges encountered in obtaining accurate real estate valuation data from the Municipality of Santos. According to the Municipality of Santos, the venal value (value of properties) for commerce activities is estimated in about R$ 1.450.003.838,00 in the NW region, while in the SE zone this value is about R$ 859.681.820,07. The NW zone is mostly residential, with buildings up to 4 floors, and there are a lot of commerce activities (stores, supermarkets, restaurants, offices). The SE zone is mostly residential with apartment buildings, hotels and shops that can reach up to 20 floors or more on the seaside.

Table 3. Avoided damages in both sites and Cost/Benefit rates. Values are in Brazilian currency Reais R$. As a reference, 1 US dollar=3.7 R$ [8]

	SE-Low elevation	SE-High elevation	NW-Low elevation	NW-High elevation
Damages without adaptation actions	R$870,093,165	R$1,043,498,249	R$166,933,832	R$236,406,111
Damages with adaptation actions	R$0	R$0	R$ 123,647,994	R$171,429,478
Avoidable Damages	R$870,093,165	R$1,043,498,249	R$43,285,839	R$64,976,633
Costs	R$ 36,514,212	R$ 36,514,212	R$201,999,540	R$201,999,540
Cost-Benefit Rate	23.83	28.58	0.21	0.32

The COAST tool presents some gaps and represent conservative estimates of benefit that are limited by factors such as: (a) the model does not consider beach processes over time (i.e., results represent cumulative effects as if geomorphological conditions remained static); (b) it does not consider natural sedimentary processes in tidal flats and the probable expansion and/or retraction of mangroves into the estuarine system, or the resilience of these ecosystems; (c) it does not consider impacts to public services, urban infrastructure, or business interruptions or clean-up costs after extreme weather events; (d) it does not consider changes in local ocean circulation, salinity, etc. that may affect local sea level; (e) it does not include damage from winds, erosive forces and rainwater drainage backups that might also cause building damage during the surge events modeled; (f) it does not reflect the value of commercial properties, leading to an underestimation of total damages; (g) modeled damages reflect structural damage only and not damage to building contents, adjacent automobiles that belong to property owners, or other site-specific vulnerable assets. Data from commercial properties are not geo-referenced and could not be included in the COAST running.

V Conclusions and Final remarks

Projections of SLR impacts from the COAST model under the no-action scenarios provided an initial estimate of the possible cost of SLR and storm surge through 2100 for some key regions of Santos. Model runs with adaptation options in place indicated the possible efficiency of these means

of addressing the challenges of SLR and storm surge in the city. Model results provide useful information for the MRBS, a strategic area of the country, and especially for the Port of Santos, the most important coastal economic resource in Brazil. However more research is be needed to better understand possible impacts the adaptation options evaluated may have on local revenue over time.
As in the other regions where COAST has been used, in Santos, evaluations about priorities and community values were particularly meaningful and useful outcomes from the study. In recognition that the municipality of Santos needs to be creative about its future, most attendees wanted to explore feasible possibilities using structural and ecological options.

Like for many other coastal areas of the world, in Santos, the threat of SLR appears to be an issue when combined with the threat of extreme rainfall events and storm surges. Model results for this important Brazilian coastal seaport city, center of the Metropolitan Region of Baixada Santista, regional leader on economic development and also one of the oldest settlements of the country (Santos was founded in 1540) showed that SLR alone is not likely to inundate buildings, but the Santos Municipality should consider SLR when planning for protection from large flood events. The benefit-cost ratio for elevation was highly positive for the SE Zone. Although these benefits could theoretically be obtained immediately, decisions around most adaptation strategies require substantial public support and will take years or decades to develop and implement. The institutional arrangement articulated in the document involves city and state government, civil society, the private sector, and universities and research institutes in Santos. It is an important step towards efficient multilevel governance processes aiming to cope with risks associated with climate change. The METROPOLE project has helped Santos demonstrate innovation in governance issues and provide valuable lessons to other coastal locations in Brazil.

IV. Acknowledgment

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