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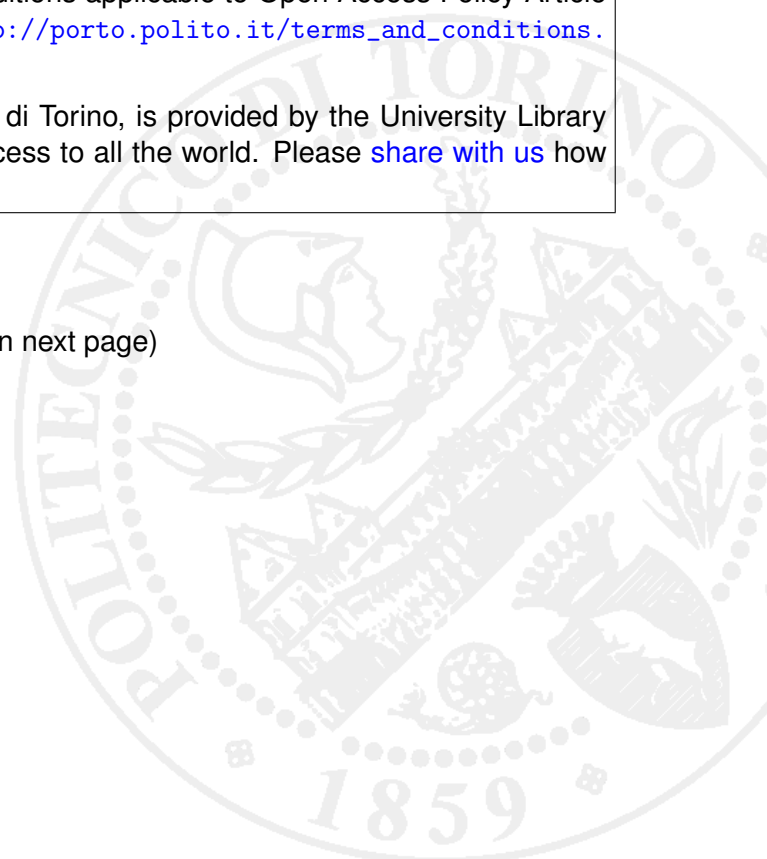
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Impact of climate changes on the Santos Harbor, São Paulo State (Brazil)

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ABSTRACT: Santos Harbor Area (SHA) in Sao Paulo Coastline (Brazil) is the most important marine cargo transfer terminal in the Southern Hemisphere. A long term relative tidal level variability assessment shows a consistent response to relative sea level rise. A wave data base Wave Watch III was compared with a long term wave data-base generated by the ERA40-ECMWF (2003), both local validated. The current bed level of SHA Outer Channel is -15.00 m (Chart Datum or, in abbreviation, CD), maintained by dredging. According to the cargo throughput forecast, in 2025, the Access Channel will have to be deepened to level of -17.00 m. The feasibility of that choice is discussed from a technical, economical and conceptual navigation point of view in that context. A data set found from a scale model of the whole area of Santos Bay, Estuary and nearby beaches, showed the impact of maritime climate changes upon the coastal area. In the previous researches developed by the authors, it was demonstrated that the wave climate, the tides and tidal currents affect harbor and coastal structures maintenance, beaches stability, tidal inlet, sediment transport, saline intrusion and wetlands. Considering the increasing of the sea hazards and the high values of the infrastructures in that coastline, it is necessary to mitigate the risks. Hence, based on the results obtained by the authors, are highlighted guidelines strategies suggested for Access Channels dimensions, wharves free-board, jetties dimensions, dredging rates, rigid and flexible littoral defenses and land protection against flooding (including wetlands).

1 INTRODUCTION

As well know the climate change affect the human activity, the agriculture and the industry as well as the tourism business (Pezzoli et al. 2013a). However a less bibliography was developed on the effect of the climate change on the maritime navigation. In fact, also if some studies were conducted about the effect of the climate change on the wind conditions and the wave action, the studies about the management and the policies are focused principally about the mitigation of the greenhouse gas emissions (GHG) generate by the navigation (Pezzoli et al. 2013a).

Nevertheless it is evident an inadequate bibliography about the effect of the climate change on the maritime navigation. For this reason a less literature is present about the management policy that the Government and the Organizations responsible for the port control can apply to sustain the shipping business due to the climate change effects.

There is the awareness that conditions of bathymetry, tides, winds, currents and waves for next decades shall have climate changes impacts on maritime navigation. The risk is understood, but only in a qualitative way, as composed by Hazard, Exposure and Vulnerability (Pezzoli et al. 2013a).

A study of 136 maritime cities with over 1 million of inhabitants showed that large populations are already exposed to coastal flooding in ports areas, with approximately 40 million people exposed to a 1 in 100-year coastal flood event (Nicholls et al. 2008). Other study (Becker et al. 2012) identified that climate change will disproportionately affect ports and port based economies.

For harbors, the most important change is likely to be sea level rise but others factors, including changes to precipitation (both yearly averages and heavy extreme weather events), will lead to a variety of impacts. In fact the climate changes generate storm surges, inundations and coastal flooding as well as the increasing of coastal hardening, coastal runoff and siltation requiring more frequent dredging on the harbors that it generates the increased greenhouse gas emissions (Nursey-Bray et al. 2012).

The São Paulo State (Brazil) Coastline (Fig. 1) has around 450 km. Santos Harbor is the most important in the Southern Hemisphere and the first in Latin America. In the last decade important oil and gas reserves were discovered in the Santos Offshore Basin and São Paulo Coastline received a great demand for supplier boats harbors for the petroleum industry (Arasaki et al. 2011). Santos Metropolitan Urban Region is one of the most important of Brazilian Coastline, also considering the tourism. For that great economic growth scenario it is very important to have well known the main maritime hydrodynamics forcing processes including climate changes in tidal

levels, currents and waves, considering the sea extreme events hazards influence in vessel operations, coastal erosion, land flooding and estuarine mangrove wetlands survival as marine ecosystem (Alfredini et al. 2012).

The understanding of these aspects can avoid damages and potential impacts on coastal areas, minimizing future costs, making decisions in mitigation and adaptation and also show the most dangerous and costly impacts (Neumann et al. 2010).

According to Osthorst and Manz (2012), Pezzoli et al (2013b) developed an in-depth study about the joint effect of rain and tides on the coastal area were found that the “coastal locations are supposed to be particularly vulnerable to effects of climate change. As a consequence of the high concentration of infrastructures and sensitive values, potential losses due to destructive weather events are also very significant.”

The goal of this paper is to overcome the contraposition that it emerges between the defense against the hydraulic risk and the management to preserve the environmental protection for nautical purposes. Moreover, basing on the results obtained by the authors in the previous published researches, the highlighted guidelines strategies are suggested for access channels dimensions, wharves free-board, jetties and breakwaters dimensions, dredging rates, rigid and flexible littoral defenses, saline intrusion and land protection against flooding (including wetlands).

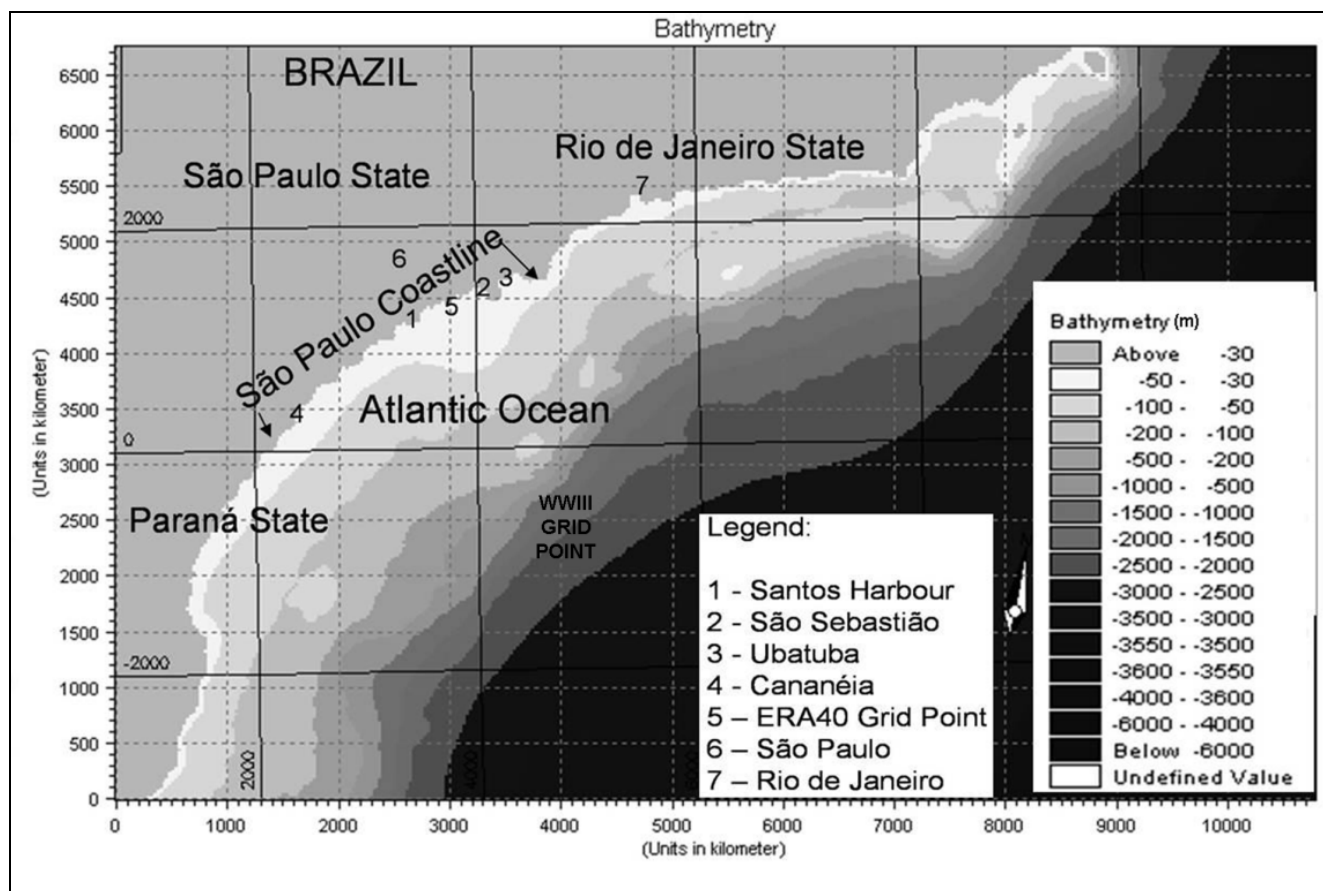


Figure 1. Site location

2 MATERIAL AND METHODS

The IPCC and PIANC recommendations (Pezzoli et al. 2013a), about the study of the impact on the climate change on the maritime navigation, are to focus on the met ocean variables such as wind, waves, sea level and ice.

Although large-scale climatic processes are driven by the ocean-atmosphere exchange system, very few studies are available on maritime impacts compared to continental impacts due to shorter data series and fewer human consequences (Pezzoli et al. 2013a and Pezzoli et al. 2013b).

Some analysis about the increasing of the sea level was conducted by Bindoff et al. (2007). The authors indicates that the global mean sea level increased at an average rate of about 1.7 ± 0.5 mm/year during the twentieth century and that the rate has been slightly higher over the period 1961 to 2003.

In other the climate model prediction elaborated by the IPCC panel (Pezzoli et al. 2013a) shows that the global average rate of rise over the Twenty First century will be 25 mm/year, implying that mean sea level will be $0.2 \div 0.5$ m higher in the 2100 than 2000.

In the same time the waves conditions could be affected by climate changes in a number of aspect. Threnberth et al. (2007) reports a statistically significant trend of increasing annual mean and winter mean significant wave height (Hs) for the mid-latitude North Atlantic and North Pacific, western subtropical South Atlantic, eastern equatorial Indian Ocean, and the East China and South China Seas. They, also, report statistically significant decreases in Hs for western Pacific tropics, the Tasman Sea and the south Indian Ocean. Similar trends are found for the 99% extreme Hs with a maximum increase of winter extreme Hs of 0.4 m per decade in the North Atlantic. The worsening of wave conditions in the north-eastern North Atlantic is most likely connected to a northward displacement of the storm tracks, with decreasing wave heights in the southern North Atlantic.

Following these indications, Pezzoli et al (2013a) showed how the regional analysis of the sea level and the wave climate become important as demonstrated by Debernard and Roed (2008) and by Sterl et al. (2009).

Considering the lack of bibliography and researches developed in this topic in the South Atlantic and in particular along the coastal line of the South of the Brazil, it was activated in 2010 a joint project called "Rede Litoral" (<http://www.redelitoral.ita.br/>).

The Research Unit, based in the São Paulo University – Polytechnic School, has the goal of the research focused on the study of wave and tidal level analysis, maritime climate change, navigation's strategy and impact on the coastal defenses along the São Paulo Coastline Harbor Areas (Brazil).

As well indicated in the Introduction, this paper summarizes the research developed by the Research Unit of the São Paulo University (Alfredini et al. 2012, Alfredini et al. 2013, Arasaki et al. 2011, COASTLAB08 2008, Dovetta 2012, Pezzoli et al. 2013a and Pezzoli et al. 2013b) concentrating on the management policies.

This study was developed analyzing three different aspects of the problems (sea level, wave climate and sediments transport), apparently distant from each other, but, in fact, coordinated as well shows by the PIANC (Pezzoli et al. 2013a).

The long term tidal level variability (high tide, mean sea level and low tide) assessment considering the Santos Dock Company (CDS) tidal variability (Highest High Water or HHW, Mean Sea Level or MSL and Lowest Low Water or LLW) for the last six decades, comprising three moon nodal cycles (58 years), shows a consistent response of relative sea level rise. Those figures were of similar magnitude than the other long term tidal series recorded in São Paulo Coastline, at the tidal gauges of Cananeia (1955 - 1992), according to Franco et al. (2007), 200 km southward, and at Ubatuba (1954 - 2003), 200 km northward (see Fig. 1).

A long term wave data-base (1957-2002) was made by a comparison between wave's data modeled by the European deep water data base meteorological model ERA-40 Project (2003) and measured wave's data in the years 1982-1984 by a coastal buoy in Santos littoral (São Paulo State, Brazil). Calibration coefficients according to angular sectors of wave's direction were obtained by the comparison of the instrument data with the modeled ones, and applied to the original scenarios. Validation checking procedures with instrumental measurements of storm surges made in other years than 1982-1984 shows high level of confidence. Finally the significant height (Hs) and the peak period (Tp), obtained by the "virtually" data-base (1957-2002), were analyzed to evaluate the possible effect of the climate change on the sea state in point S 23.5°; W 45.5° for a water depth of 18 m (Dovetta 2012).

In other a long term (Jan 1st 1980 to August 6th 2012) deep water wave climate database was employed (<http://www.ondasdobrasil.com>) to develop an assessment of the characteristics and historical frequency of extreme storm events (point S 26°; W 45°, water depth 1,521 m). The database includes definitions of significant wave height (Hm0), spectral peak wave period (Tp) and spectral directions (Alfredini et al. 2013). The deepwater hindcast was developed with the aid of the WaveWatch III model (Tolman 2009) calibrated with Topex Satellite data along Brazilian coastline and, subsequently, validated with a directional sea buoy. Finally a scale model representing the area included between the Santos Bay, Estuary, Santos Harbor and nearby beaches of Santos (COASTLAB 2006), modeling tidal cycles and wave climate (Fig. 2), was used to evaluate beach erosion and the land and mangrove wetlands flooding (Fig. 3).

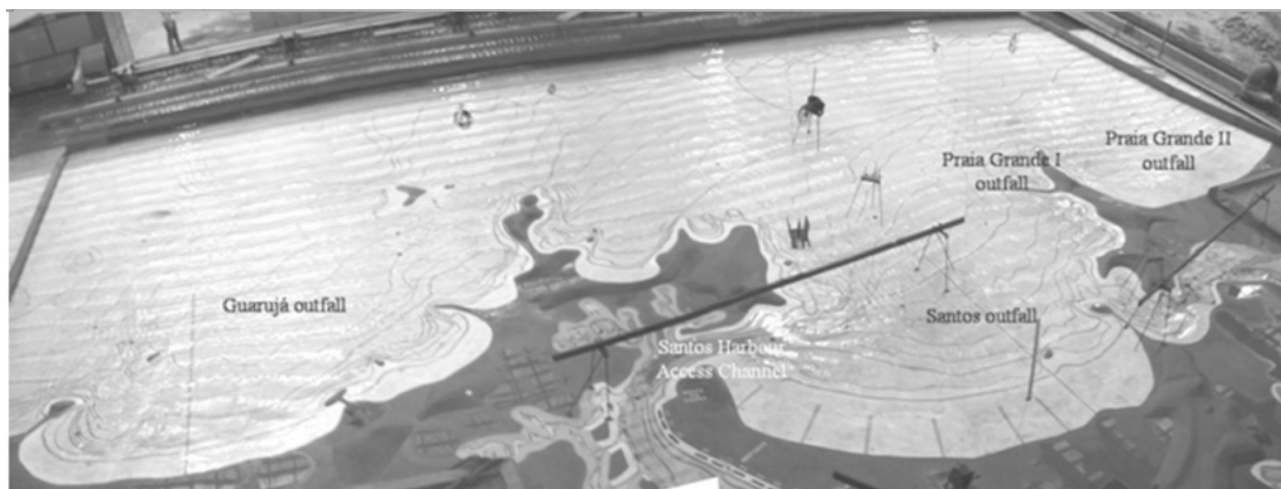


Figure 2. Scale model of Santos Bay, Estuary and Harbor and nearby beaches

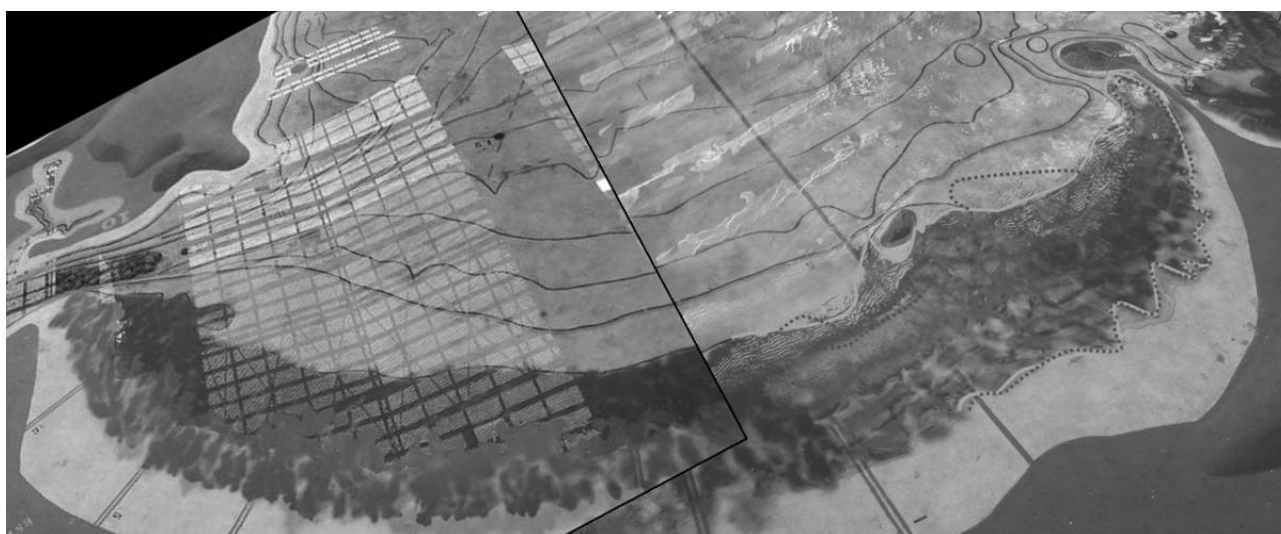


Figure 3. Scale model storm surge test: view of the beach scour

3 RESULTS AND DISCUSSION

The long term tidal level data variability assessment of the Santos Dock Company tidal gauge, which measured water level fluctuations from 1944 using the same Vertical Datum, provided the possibility to have at least 3 lunar declination periods of 18.61 years each one. The forecasting trends of HHW and LLW depend largely upon meteorological forcing, beyond sea level rise (Alfredini et al. 2013). The use of 19 years mobile average fittings, from 1970 to 2007 and from 1989 to 2007, are consistent showing impressive increasing gradients of relative sea level rise, with century gradient rates shown in Table 1 and Fig. 4.

According to that scenario, the scale model study showed the flooding of around 50% of the Santos Estuary mangroves (COASTLAB 2006) and around 100 m of the beaches (Fig. 2 and Fig. 3), with the corresponding wave scour. Also in the last century, Santos Harbor wharves free-board (150 cm) lost around 35 cm.

The analysis of the wave climate change, using the calibrated ERA-40 and Wave Watch III data-base for the 1980-2002 period shows an increasing trend (linear and mobile average) in the Hs and Tp values

(Fig. 5 and Fig 6). It is known that the satellite facilities data after 1979 are more accurate for those assessments.

According to the linear trend, which is similar with the 5 year mobile average, it was possible to forecast an Hs increasing since 1980 (1.87 m in deep water and 1.14 in shallow water) till 2080 from 0.25 (WaveWatch III deep water) to 0.45 cm (ERA 40 calibrated shallow water). It is well known that the wave energy per horizontal area and the long shore sand transport in the surf zone of waves is proportional to the square of wave height, meaning an increasing around of 100% per century. Also according to the classical Hudson's Formula, the rubble mound weight of ripraps, breakwaters and jetties are proportional to Hs³, meaning an increasing armour weight for the new design scenario or an increasing in the damage rate and maintenance costs of those existing structures.

The consequences for navigation purposes, considering depths and channel widths, are very complex and are summarized in Fig. 7. For instance, according to the width criteria of PIANC guidelines it will be necessary to enlarge Santos Harbor Access Channel of two design vessel beam due to the increasing in waves parameters.

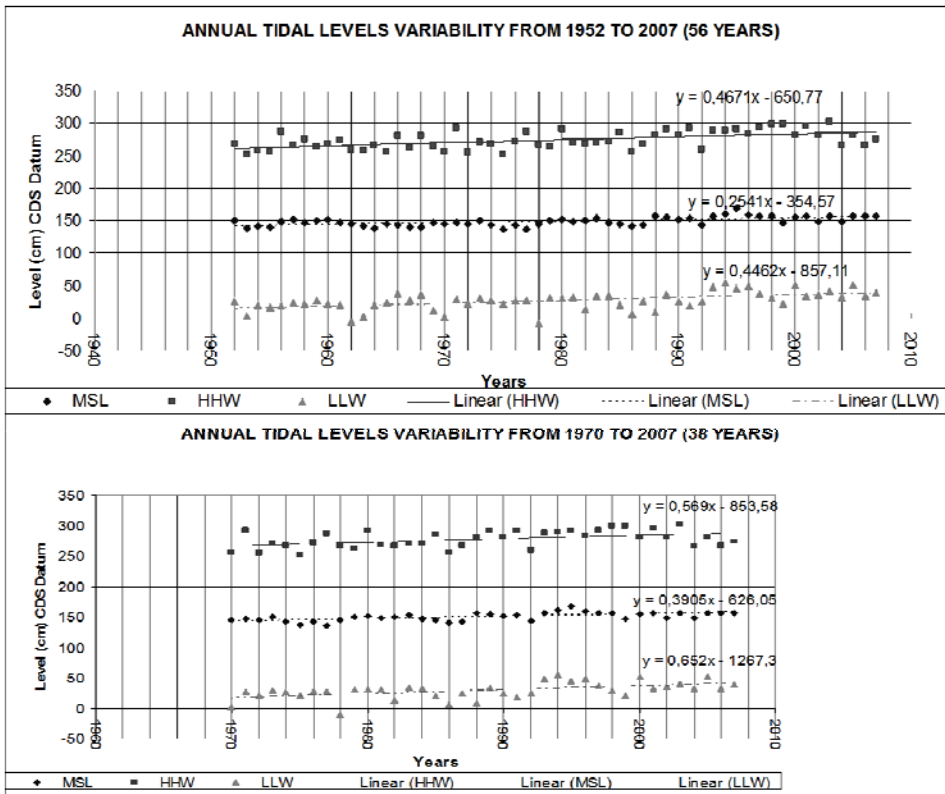


Figure 4. Santos Harbor tidal trends (1952-2007)

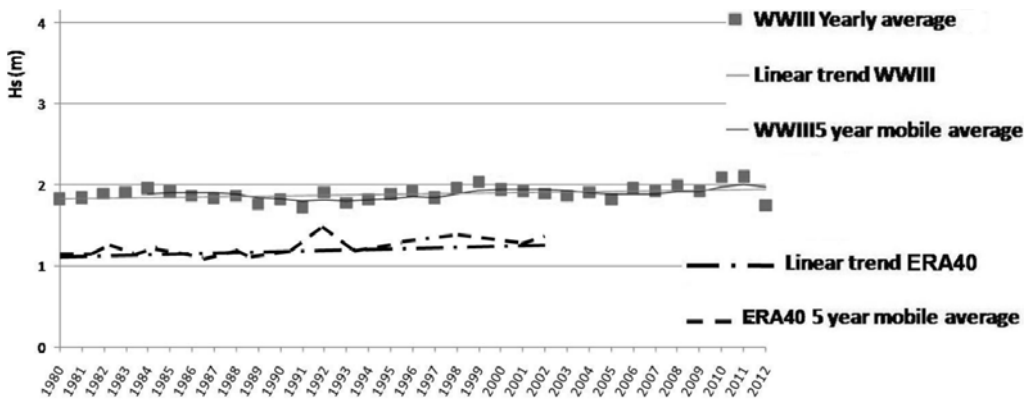


Figure 5. SHA significant wave height trend according to ERA-40 and WaveWatch III hindcast (1980-2012)

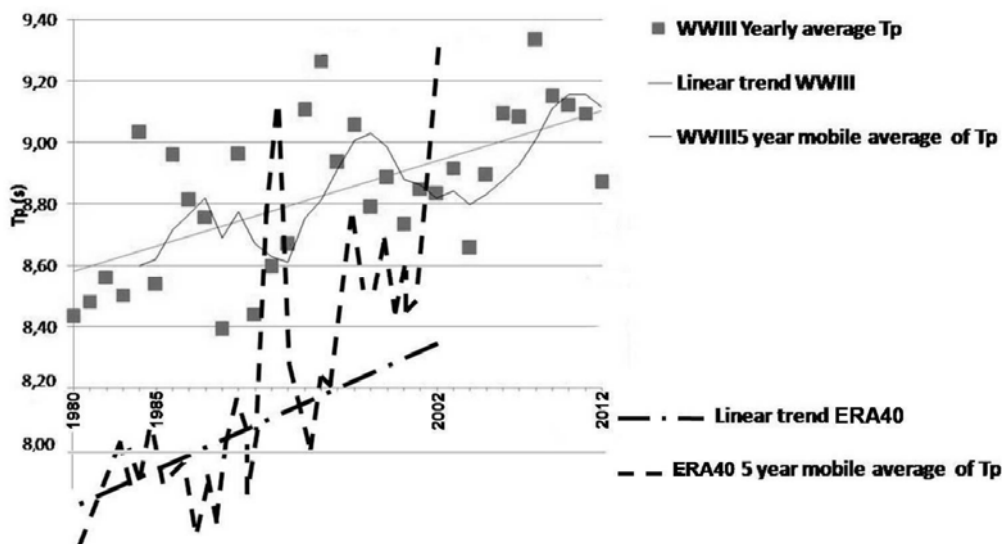


Figure 6. SHA spectral peak wave period trend according to ERA-40 and WaveWatch III hindcast (1980-2012)

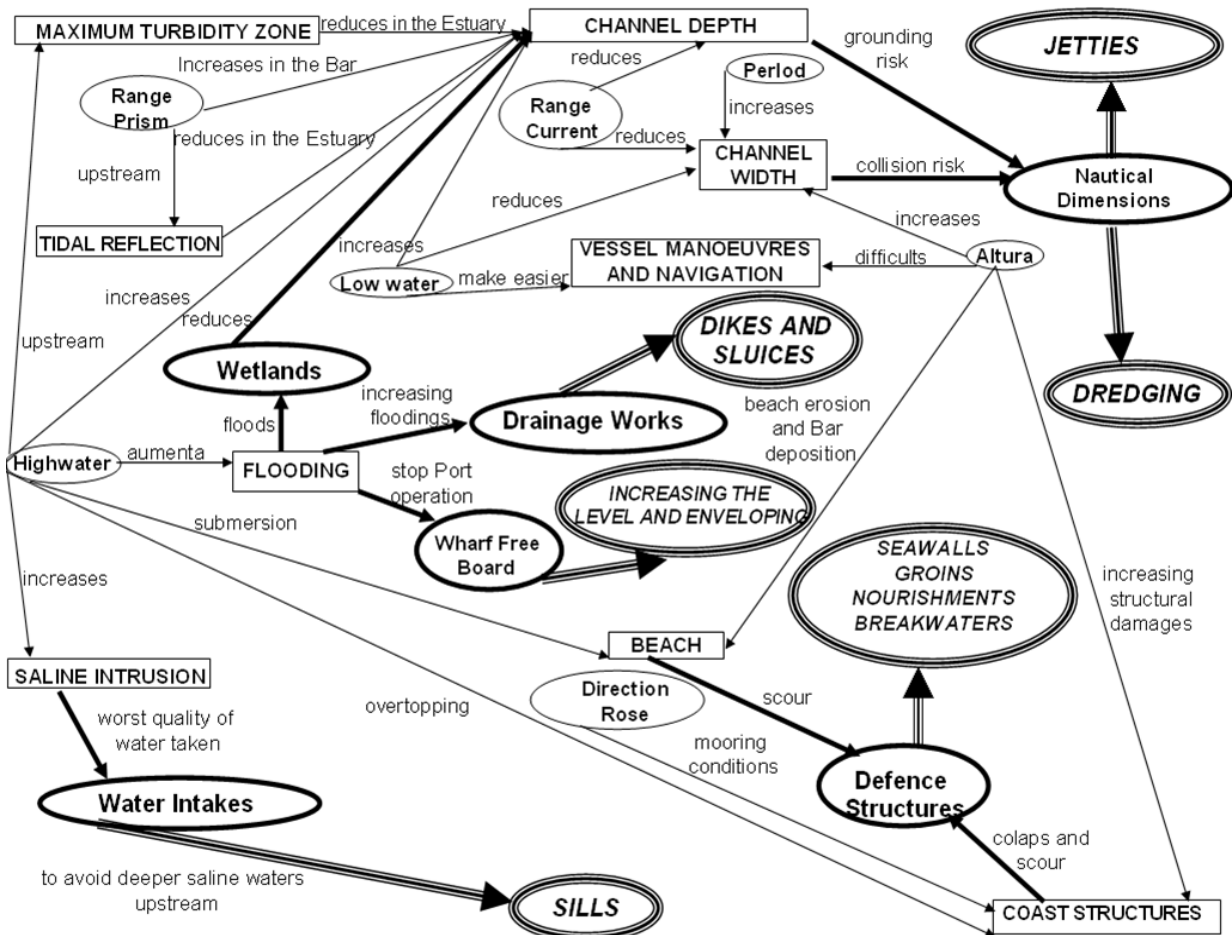


Figure 7 Frame of hydrodynamics for impacts on coastal and estuarine port areas and mitigatory measures and structures

Table 1. 19 years mobile average rates cm/century. Source: Alfredini et al. (2013)

H_{m0} (m) and $L:L_{pp}$	% per year	Additional Width (xB)
$H_{m0} < 1.0$ and $L < L_{pp}$	74.16	0
$1.0 < H_{m0} \leq 3.0$ and $L \sim L_{pp}$	24.62*	1.0
$H_{m0} > 3.0$ and $L > L_{pp}$	1.22**	2.2

Occurrences: * From March to October. ** From April to September.

Table 2 classifies Santos wave climate according to PIANC (1997) criteria for Outer Channels nautical projects (L: wave length; L_{pp} : vessel length between perpendiculars; B: vessel beam).

Table 2. SHA additional access Channel width according to long term wave climate (1980-2012)

Tidal Levels	1970-2007	1989-2007
Highest High Water	50.0	63.2
Mean Sea Level	27.6	57.9
Lowest Low Water	47.4	94.7

The SHA Pilot's Association (Alfredini et al. 2013) has made calculations with a Panamax Container Ship (Displacement: 70,055 DWT 5000 TEUs; L_{pp} : 275 m, B: 32.18 m, T: 13.00) for the second class of Table 2. At 6.5 knots, recommended vessel velocity at the Access Channel, the increase of squat and mean draught, in confined shallow waters like those (depth lesser than 1.2 times the vessel draught), is 0.60 m. The draught's

increase, due to a minimum heel of 1° , must also be included, corresponding to 0.37 m and the pitch of 0.5 m due to a 1 m wave height. Considering an under keel clearance of 0.30 m with the sand/mud soft bottom, the overall depth necessary for a safe navigation (ODSN) at the tidal level of 0 (CD) is:

$$ODSN(0) = 13.00 + 0.60 + 0.37 + 0.5 + 0.3 = 14.77m \quad [1]$$

Considering a 2 m of wave height and an heel of 2° , the ODSN, for a tidal level of 0, results to be equal at 15.65 m. Hence, such a vessel would have time limiting operation due to restrictive depth conditions at tidal level 0 (CD) in the current channel – 15.00 m (CD) dredged depth, mainly in the months from March to October, and in some cases from April to September only would be possible to cross the SHA Outer Channel using high tides.

According to Alfredini et al. (2013), two engineering solutions are possible, necessitating an understanding of the coastal engineering issues (waves and sediment transport) and an awareness of the maritime climate change.

The first one is the dredging maintenance procedure. Using historical data, from 1963, when the Outer Channel SHA dredging was initiated, to 2010, 60 million m^3 were dredged to maintain an average bed level -13.00 m (CD), at an estimated cost of US\$ 0.5 billion (present cost).

SHA Outer Access Channel, in the maritime bar, has 11,560 m (Area 1) and the Inner Access Channel

(Area 2), in the estuary region, has more 13,040 m (see Fig. 2). This Access Channel has been deepened from February 2010 to January 2011. Fig. 8, Fig. 9 and Fig. 10 show the volumes of capital and maintenance dredging in the maritime and estuarine areas. The

period 2010/2011 was characterized by strong storm surges in the winter months and by heavy rains in the summer months, hence corresponding to high longshore and fluvial sediment transport.

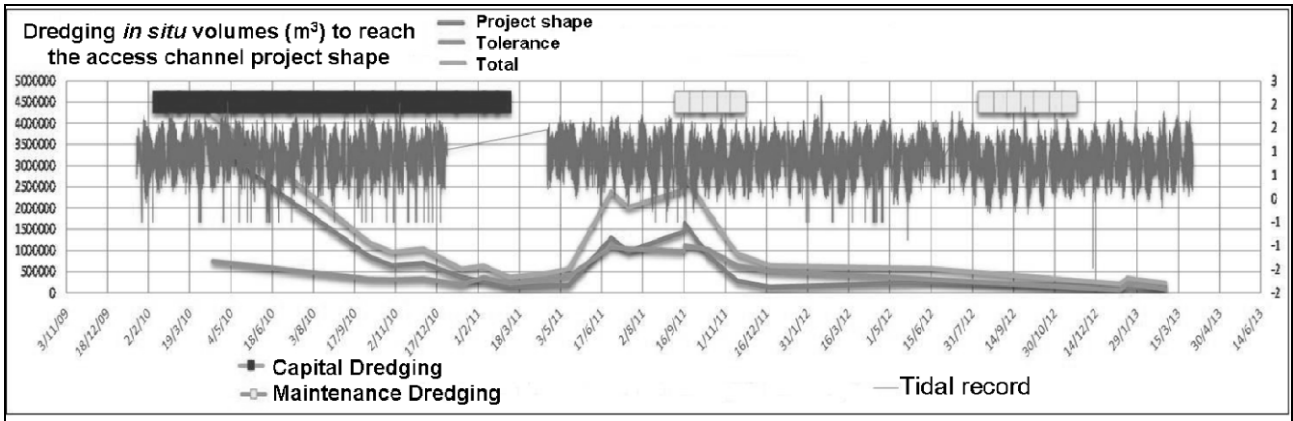


Figure 8. Capital and maintenance dredging volume (“in situ” m³) in the SHA Outer Access Channel and tidal record (2010-2013)

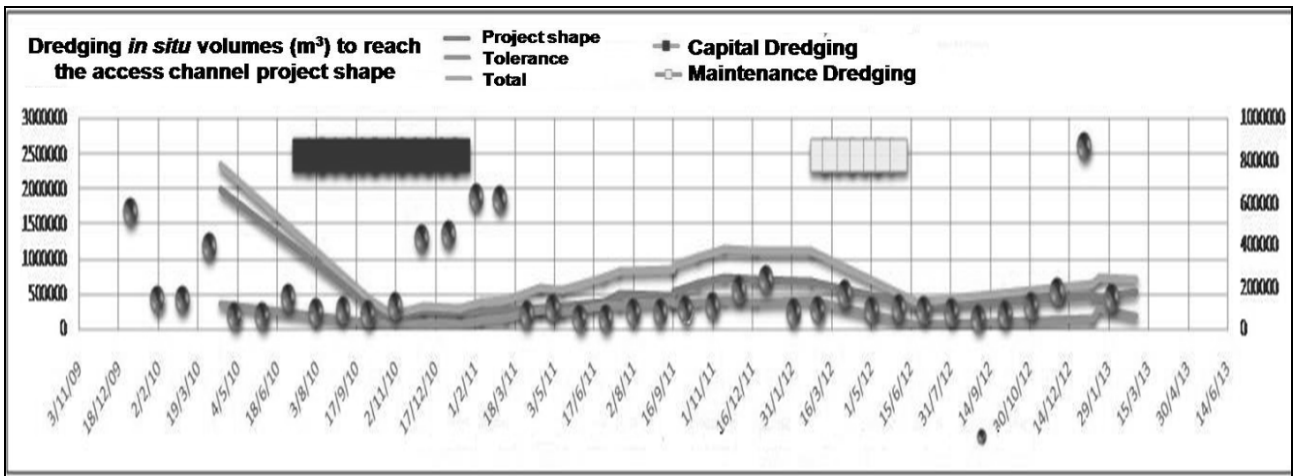


Figure 9. Capital and maintenance dredging volume (“in situ” m³) in the SHA Inner Access Channel (Area 2) and rain in the watershed contributing to the estuarine harbor area (2010-2013)

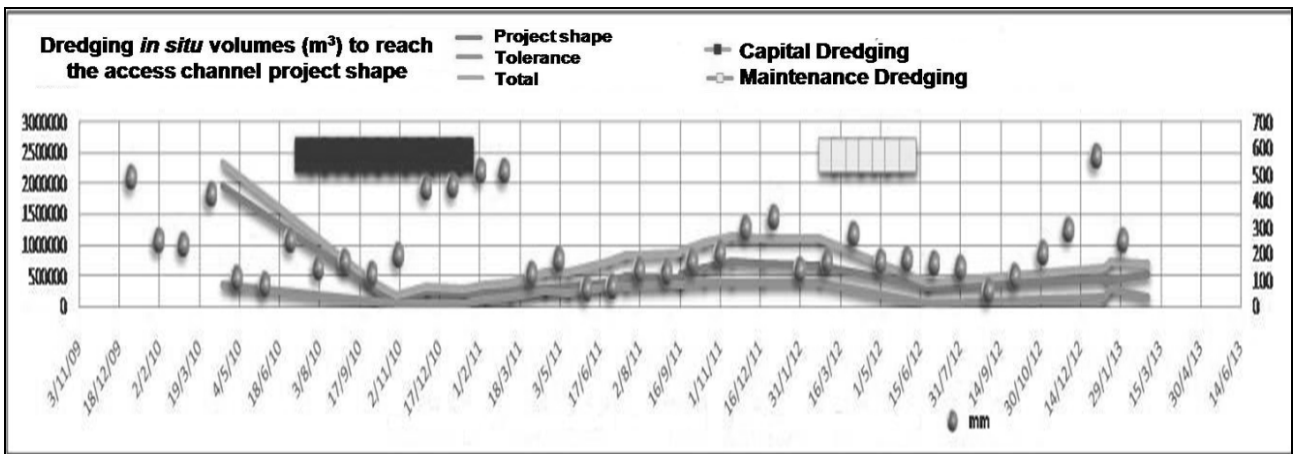


Figure 10. Capital and maintenance dredging volume (“in situ” m³) in the SHA Inner Access Channel (Area 2) and fluvial sediment transport from the watershed contributing to the estuarine harbor area (2010-2013)

4 CONCLUSIONS

About SHA can be summarized that:

- The increasing of the sea level rise is included between 50 to 100 cm/century in the next decades in agreement with the IPCC scenario (Pezzoli et al. 2013a).
- The increasing of the sea level rise generates a flooding of around 50% of the Santos Estuary mangroves and around 100m of the beaches as well demonstrate by the simulation of the physical model.
- The climate change impacts on the increasing of the H_s for a 0.45 m in the next 100 years as well as in the peak period of the wave.

This analysis confirmed how the system is to be considered as a complex one, where the effects on the channel, jetties and harbor structures are generated by sea level rise, the wave climate and the flooding jointly with the sediment transport.

The consequences for navigation purposes, considering depths and channel widths are very complex and are summarized in Fig.7, elaborated considering the obtained results and the related assumptions.

As said in the Introduction, the paper summarizes ten years of research about the impact of maritime climate changes in the São Paulo State Coastline, mainly in the Santos area, where there is the major amount of hydrodynamics data. It was possible to reach the goal of quantifying the magnitude order of tides and wave changes and to correlate them with the impact on maritime structures and the proposed mitigatory measures and structures.

Based on the quantitative assessment made it is possible to present the following strategic plan (Table 3) focusing on the navigation and coastal defenses for São Paulo State Coastline (Pezzoli et al. 2013a).

Table 3. Strategic plan focusing on the navigation and coastal defenses

1. Protection	<ul style="list-style-type: none"> • Wetlands restoration • Shoreline enhancement and land preservation • Jetties, seawalls, dikes construction/ upgrades against higher design waves and to 1 m of relative sea level rise
2. Resistance and Resiliency	<ul style="list-style-type: none"> • Life cycle upgrades: 1 m higher elevation of quays • Increasing the external access channel width • Increasing maintenance dredging and capital dredging to enlarge external channels and for milder bank slopes
3. System Management	<ul style="list-style-type: none"> • Focus investments on lower-risk assets and shift operations away from higher risk assets
4. Impact Management	<ul style="list-style-type: none"> • "Green Port" to manage emissions and other impacts
5. Information and Coordination	<ul style="list-style-type: none"> • Develop information to support consistent risk assessment, best practice responses, and necessary partnerships between ports and their host regions

Considering the awareness about the importance of climate changes impacts in a coastal area prone to extreme flood and erosion events, the structural solution (i.e. two jetties as shows in Fig.11),

maintenance dredging (flexible solution), or non-intervention in the waterway are important because:

- 1 There is an overall sea level rising trend.
- 2 LLW has the highest rate of linear tidal rising.
- 3 There is an overall tidal range reduction.
- 4 The tidal prism will change and the tidal currents velocity should increase if the HHW levels will drown large fluvial areas, compensating the velocity reduction due to the tidal range decreasing.
- 5 Considering the issues above, the bar depth should increase.
- 6 The overall rise of the sea will produce more coastal erosion and littoral drift in opposition to the outcome of issue 5.
- 7 It is possible to observe a general significant height and average period wave increasing for annual averaged figures. Hence, should be a trend to increase littoral drift, reducing bar depth.

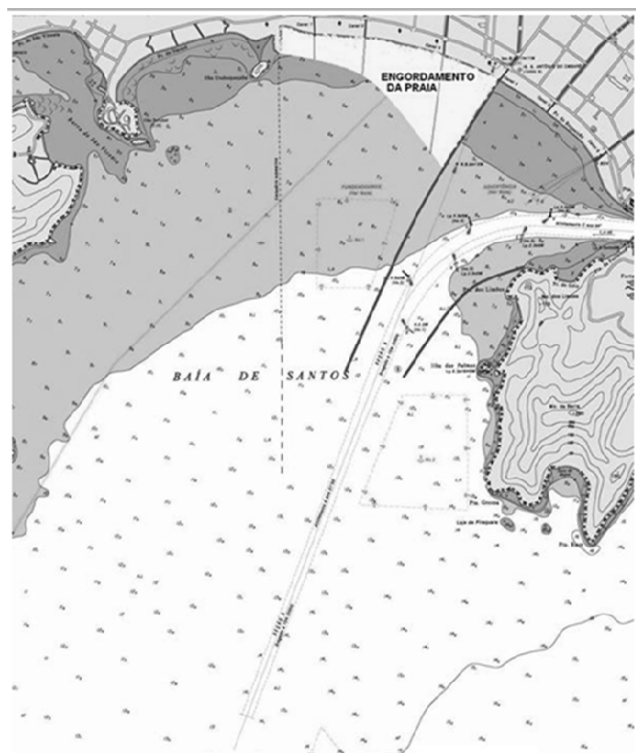


Figure 11. Example of a possible structural solution for the protection of the harbor entrance

In other, merging the results of the climatological analysis with the result of the physical model, it is possible to made other assumption about the management policies of the SHA. Indeed, there are some areas of mud, which may be fluid and sufficient to consider the nautical bottom concept (PIANC 1997), in practice for mud density lower than 1250 kg/m³. In these cases it is possible to reduce the under keel clearance.

Awareness with climate changes impacts importance for the intervention's plan must be considered to obtain a final balanced solution among structures, dredging and non-structural measures for nautical master plan.

It is important to recognize that great natural events are not avoidable, but great disasters are, as the ancient Greek Aristotle (384 - 322 B.C.) said: "It is probable that the improbable will happen".

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