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PREDICTIONS OF THE IMPACTS OF THE SEA-LEVEL RISE IN ARGENTINA

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ABSTRACT

Global sea level is rising and it is expected to continue rising as the atmosphere is warming, inducing glacier melting. Based on this, a minimum of 0.4 m of sea level rise (SLR) is expected for the year 2100. While coastal erosion is the most evident consequence of SLR, its impacts on estuarine areas are more difficult to discern. In some areas, climate is warming and rains are increasing, and are thought to continue doing so in Buenos Aires, while they are decreasing in Patagonia. Therefore, estuarine and freshwater/salt marshes areas would have different responses along the Argentine coast. Even more significant will be the effects in urban areas where planning and management strategies have systematically overlooked these risks. In low-lying areas such as the Samborombón Bay, the SLR will cause a surface retreat of the salt-fresh water interface affecting cities like General Lavalle. Flash floods today can affect San Clemente del Tuyú city, but the performance of the discharge pipelines depends on the meteorological effects on the tides. Flash floods have also affected coastal cities of the semidesertic Patagonia: Puerto Madryn and Comodoro Rivadavia have suffered unprecedented floods during recent years. Two models are applied to coast evolution in response to SLR: Bruun's model predicts shore erosion and deposition below the wave base level (closure depth). However, in low-lying areas where there is enough sediment availability, the onshore migration of bedforms (beaches, cheniers) can occur. Changes in estuarine areas are particularly difficult to predict. Tidal prisms can increase significantly in microtidal coasts due to SLR, but in macrotidal coasts these increments were not significant. Another effect of the SLR occurs at the hydrogeological interphase between fresh and salt groundwater. The simulation of these interactions should be carefully estimated considering the groundwater discharge and the climate change effects on the precipitation.

INTRODUCTION

If the Present is the key to the Past, it is more logical that the Present is a necessary key to the Future. However, it is not as simple: The Earth System behaves as a single, self-regulating system comprised of physical, chemical, biological and human components... Human activities are significantly influencing Earth's environment in many ways in addition to greenhouse gas emissions and climate change… Global change cannot be understood in terms of a simple cause-effect paradigm… Earth System dynamics are characterised by critical thresholds and abrupt changes… In terms of some key environmental parameters, the Earth System has moved well outside the range of the natural variability exhibited over the last half million years at least. (Pronk, 2002).

Based mainly on altimeter data from satellites, it is forecasted that global sea level would rise 0.4 to 0.8 m by the year 2100 (Oppenheimer *et al.*, 2019; Fig. 1). However, these methods do not discriminate increments due to thermosteric changes (Thompson and Tabata, 1987). In South America, sea-level rise (SLR) also increases temporarily in areas subject to El Niño Southern Oscillation (ENSO) floods (Isla, 2018).

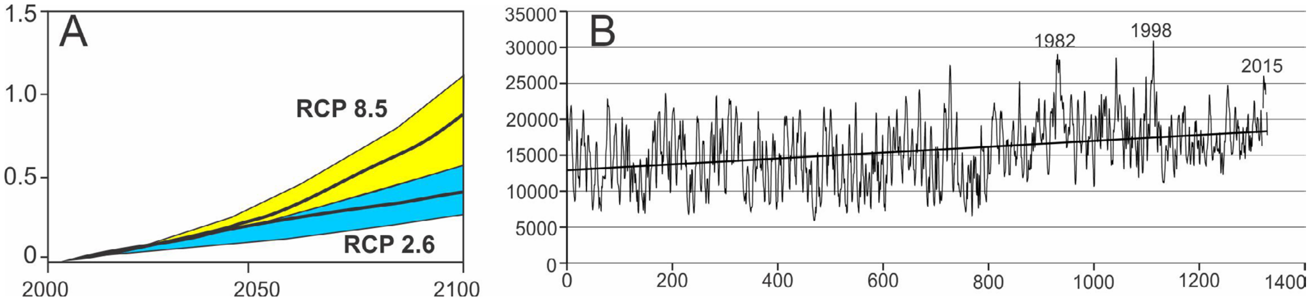

Figure 1. a) Future projections of the sea level according to the International Panel on Climate Change (Oppenheimer *et al.*, 2019). Representative concentration pathways (RCP) are the different scenarios estimated by the IPCC. **b)** ENSO-triggered floods of the Paraná River of 1982, 1998, and 2015 recorded at the Timbúes Station, Santa Fe province (m3/s vs. months; Isla, 2018).

This review considers the effects of the SLR in Argentina, specifying the impacts in different regions with particular environmental and/or anthropogenic conditions. This analysis comprises results from several processes such as coastal retreat, tidal prism and minimum area relationships, coastal wetlands evolution, groundwater saline intrusion, water supply to coastal cities, and their pluvial and sewage discharges.

ARGENTINE COASTAL VARIATION

From north to south, the coast of Argentina extends from temperate to cold climates, with temperature and precipitation diminishing southward (Isla *et al.*, 2010), and a prevalence of westerly winds (Fig. 2A).

Rains have increased in the last 100 years in Buenos Aires, Mar del Plata and Tres Arroyos (Cortizo and Isla, 2007; Barros *et al.*, 2014; Kruse *et al.*, 2014; Fig. 2B) while are diminishing in Patagonia,

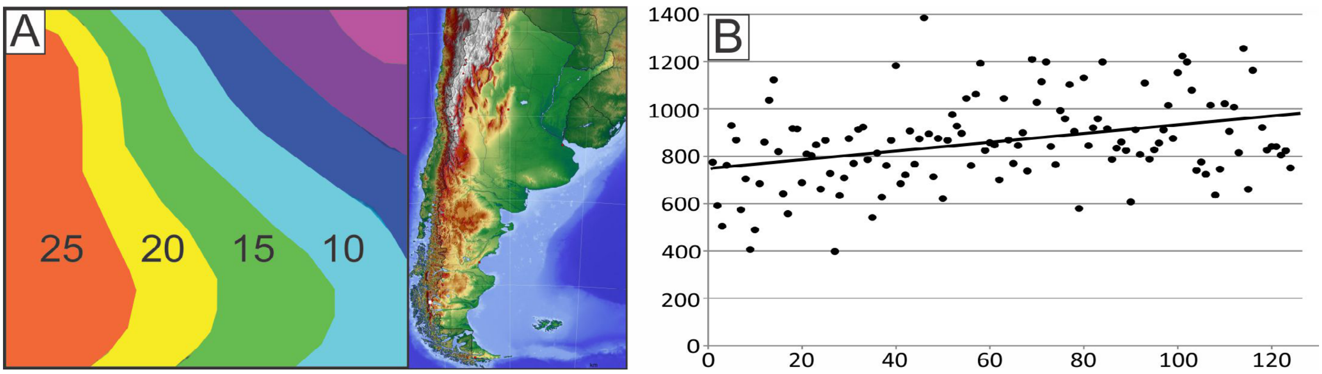

Figure 2. a) Wind velocity frequencies (km/h) along the Southern Hemisphere (modified after Isla *et al.*, 2021). **b)** Annual precipitation (mm vs. years) in Mar del Plata (Camet airport) from 1901 to 2024.

although the intervals of measurements are much shorter (Isla and Isla, 2024).

The Argentine coast comprises microtidal areas at the north and macrotidal to the south (Isla and Bujalesky, 1995; Fig. 3). Tidal ranges increase in embayments (Bahia Blanca, Bahia Grande), gulfs (San Matías, San José, Nuevo, San Jorge) and the Magallanes Strait.

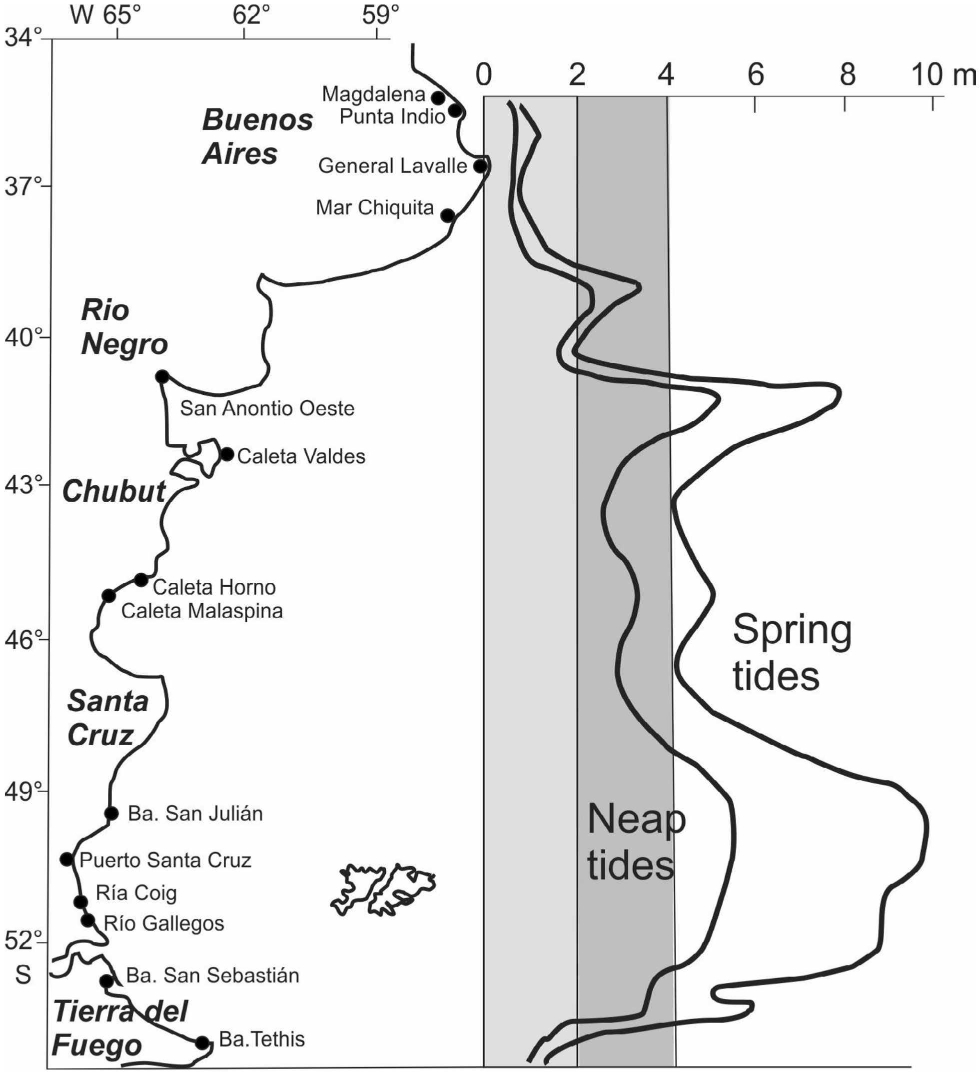

Figure 3. Tidal ranges along the Argentine coast (modified after Isla and Bujalesky, 1995). Estuaries where minimum flow areas were estimated are indicated with dots; the Mar Chiquita coastal lagoon is the only outlet located in the microtidal coast.

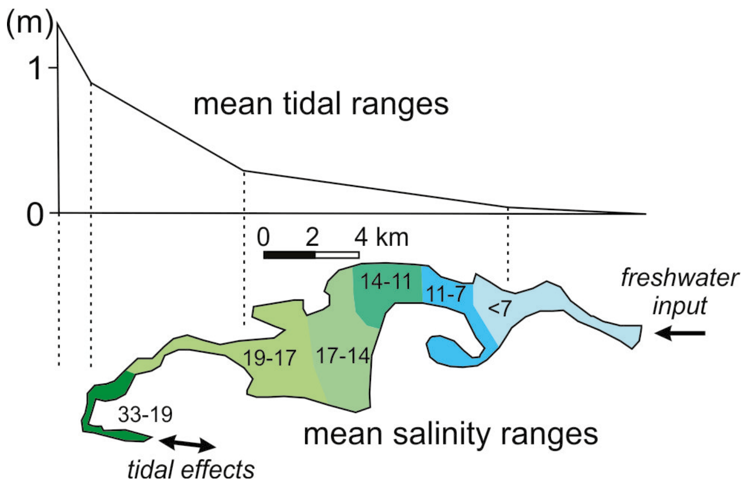

Figure 4. Mean tidal ranges along the Mar Chiquita coastal lagoon diminish to the headlands (modified after Isla and Gaido, 2001). The mean salinity values (UPS) during normal conditions also diminish to the headlands.

The tidal excursion can change to the headlands of estuaries. The tidal range can increase (amplification) or decrease (dampening). Topography variations along the estuarine profile can cause reflection effects, and the sinusoidal wave can be significantly deformed to the headlands (Fig. 5). Amplifications are common along the Patagonian gulfs and bays as at the Bahia Blanca embayment, and the San Matías and San Jorge gulfs (Isla *et al.*, 2002, 2023). Dampening effects have been recorded along the Mar Chiquita coastal lagoon (Isla and Gaido, 2001). Reflection effects were measured at the Quequén Grande estuary (Perillo *et al.*, 2005).

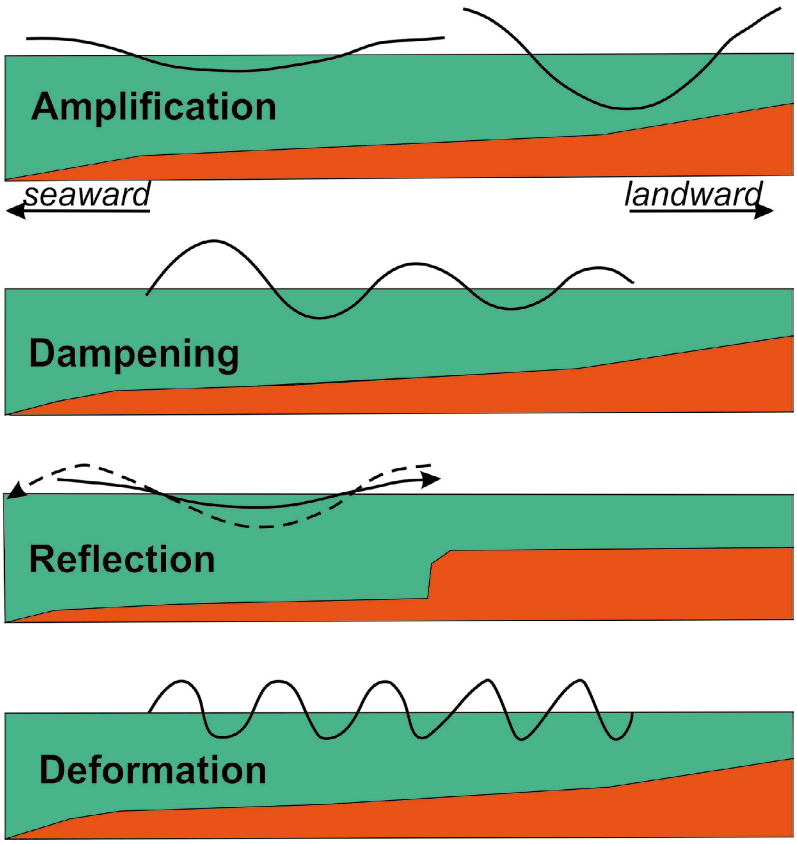

Figure 5. Mechanisms altering the propagation of tidal waves along different types of river discharges and morphologies (modified after Khojasteh *et al.*, 2021).

Regarding the recurrence of storms from the south and southeast (sudestadas), an inventory of the stronger storms (Storm erosion potential index) based on tidal data from Mar del Plata Station has been reported for the end of the 20th century (Fiore *et al.*, 2009). However, there is no report about this recurrence during the 21st century or about an increase in their trends.

METHODS

Tidal parameters were collected from the main harbours of the Argentine coast (https://www.hidro.gov.ar/oceanografia/Tmareas/Form_Tmareas.asp). Minimum flow areas were estimated from nautical charts of the best accuracy of the National Hydrographic Survey of Argentina. Based on maximum tidal ranges recorded at certain locations of Mar Chiquita coastal lagoon interpolations were estimated along it applying GIS procedures. Coastal retreats, in m/yr, are average estimates of the coastal erosion. They were estimated comparing aerial photographs, Korona KH4satellite photographs, and satellite images. Details of these procedures and accuracy were already reported (Isla *et al.*, 2018).

RESULTS

Coastal retreat and beach erosion

Two kinds of erosion processes can be distinguished in the Argentina coasts. The retreat of cliffs or scarps of dunes is of special concern for the country and province authorities that are losing their heritage territories. On the other hand, the unbalances of beaches are of main concern to the touristic counties of Buenos Aires province that usually give concessions for renting shadow (tents or beach umbrellas).

Regarding coastal evolution, the simple Bruun's model is worldwide accepted, where the SLR means both shoreline retreat and deposition below the wave-action level (Bruun, 1962, 1988).

Shoreline retreat (R) is therefore:

$$\text{eq. (1) } R = S\,[L/(b+h)]$$

Where S is the rise in mean sea level, b is the elevation of the berm, h is the depth of closure, and L is the width of the active beach profile (Bruun, 1962). This rule has been repeatedly accepted by many authors (Wallace *et al.*, 2010; Rosati *et al.*, 2013; Atkinson *et al.*, 2018).

However, when the coastal slope is very gentle with certain sediment availability, an onshore migration of the shoreline could apply (Fig. 6; Roy *et al.*, 1995; Davidson-Arnott, 2005). For pocket beaches, or artificial beaches between groins, a shoreline retreat is expected but the subtidal deposition depends on the position of the salients (groynes lengths) that condition the entrance of the compartment. These conditions have been evident in crenulated paraglacial coasts where the concavity of the bay controls longshore transport (Carter *et al.*, 1987).

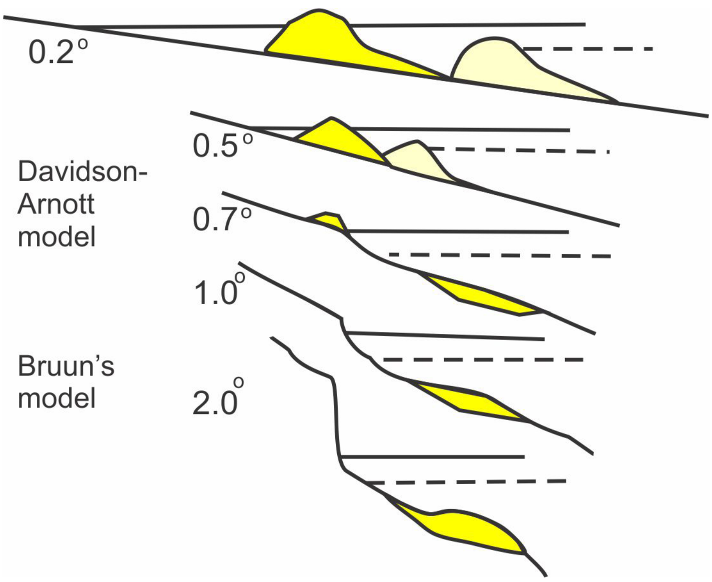

Figure 6. Shoreline response to sea level rise in relation to the coastal slope (modified after Roy *et al.*, 1995). The dashed line represents the previous sea level and solid line after the SLR.

Coastal retreats in the Argentine coast were estimated comparing ancient photographs with modern satellite images (Isla and Cortizo, 2023). As the fixed points were lighthouses, located in places rather resistant to erosion, these rates are considered conservative (Fig. 7). Coastal retreat has been estimated during several intervals with more details in Buenos Aires province (Isla *et al.*, 2018; Isla and Cortizo, 2023). These intervals were selected to detect increments of dune-cliff retreats, the performance of coastal defences, and the effects of recent SLR.

The evolution models for sandy beaches do not apply as simply to gravel (gravel and sand) beaches. Several particular processes occur at these beaches: armouring, rollover, overwashing, overtopping, and overstepping (Forbes *et al.*, 1991; Isla, 1992; Orford *et al.*, 1995a, b). Different sea-level evolutions were proposed according to SLR rates, sediment-supply rates, and gravel-barrier types (swash-aligned or drift-aligned; Forbes *et al.*, 1995). Although tall cliffs dominate the coast of Patagonia and Tierra del Fuego, some areas are protected by the armouring effect of gravel-dominated bedforms at their feet conditioning coastal retreat (Isla and Lamarchina, 2023).

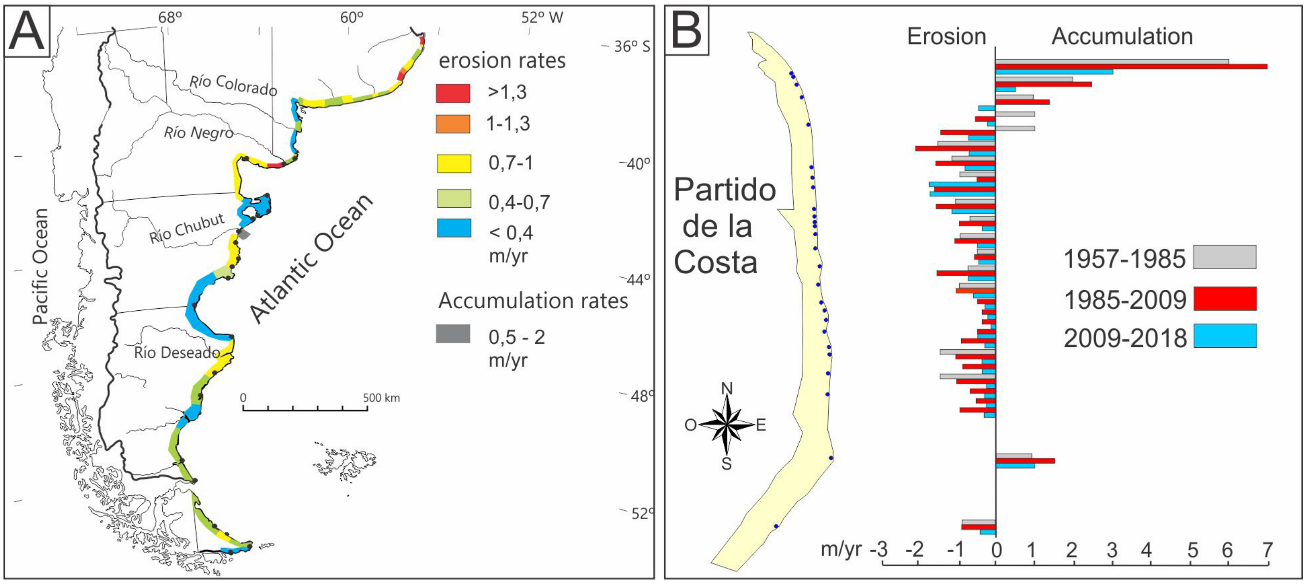

Figure 7. a) Coastal retreat (m/yr) at the Argentine coast (modified from Isla and Cortizo, 2023). **b)** Dune retreat (m/yr) at Partido de la Costa during several intervals: 1957-1985 (before anthropogenic SLR), 1985-2009 (after anthropogenic SLR), and 2009-2019 (increase in storms recurrence; modified after Isla and Cortizo, 2023).

Tidal prism – Minimum flow area relationships

O'Brien (1969) proposed a simple empirical relationship between the tidal prism (P) and the minimum flow Area (Ac) for tidal inlets. These relations were estimated for some estuaries and tidal inlets of the Argentine coast (Isla and Bujalesky, 1995). SLR implies an increase in P and therefore increments in the depths and widths of the inlets. These variations can be significant in microtidal coasts, compared to macrotidal coasts (Fig. 8). SLR also implies variations in tidal prisms, tidal asymmetries, increments in flooding depths, and the inundation excursions during storms (Passeri *et al.*, 2015).

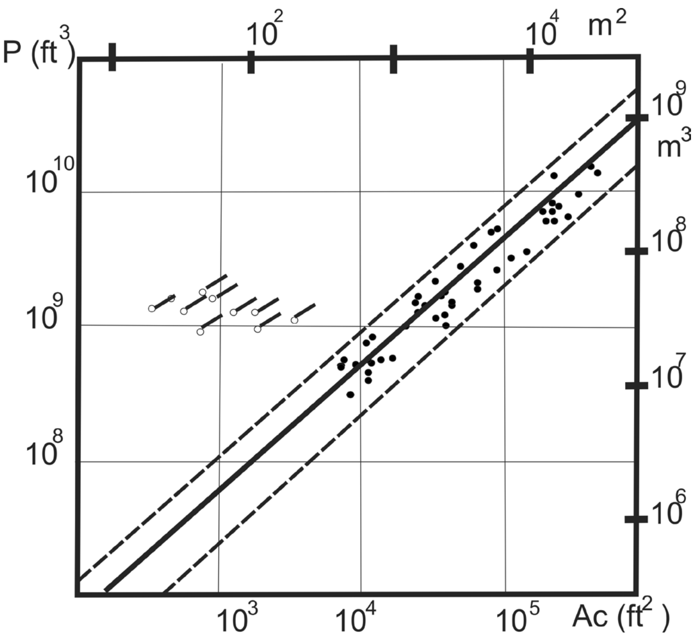

Figure 8. O`Brien (1969) relationships (tidal prisms vs. minimum flow areas) applied to different tidal inlets of Argentina: Mar Chiquita, San Antonio Oeste, Caleta Valdés, Caleta Malaspina, Caleta Horno, Bahia San Julián, Puerto Santa Cruz, Ría Coig, Río Gallegos, Bahía San Sebastián, and Bahía Tethis (see locations in Figure 3). White circles with dashes are tidal wedges estimated in Mar Chiquita that would increase due to the SLR (modified after Isla and Bujalesky, 1995).

SLR can cause significant changes in the estuarine and tidal dynamics (Khojasteh *et al.*, 2021). Where the depth of the tidal range is very large, SLR will not cause any significant effect (Fig. 9a). In other cases, there is an upstream tidal attenuation. Frictional effects dominate in choked lagoons (*e.g.*, Mar Chiquita coastal lagoon) and therefore the tidal prism deforms into a wedge towards the headlands (Fig. 9b). In the case that the SLR would increase the minimum flow area, the tidal prism may increase (Fig. 9c). If the bathymetry and shape of the estuary remain unchanged, the SLR would signify a reduction in the energy slope during the ebb cycle (Fig. 9d). In large areas of low-lying floodplains (*e.g.*, Samborombón Bay), the SLR would imply an increase in the area of intertidal environments as tidal flats and marshes (Fig. 9e).

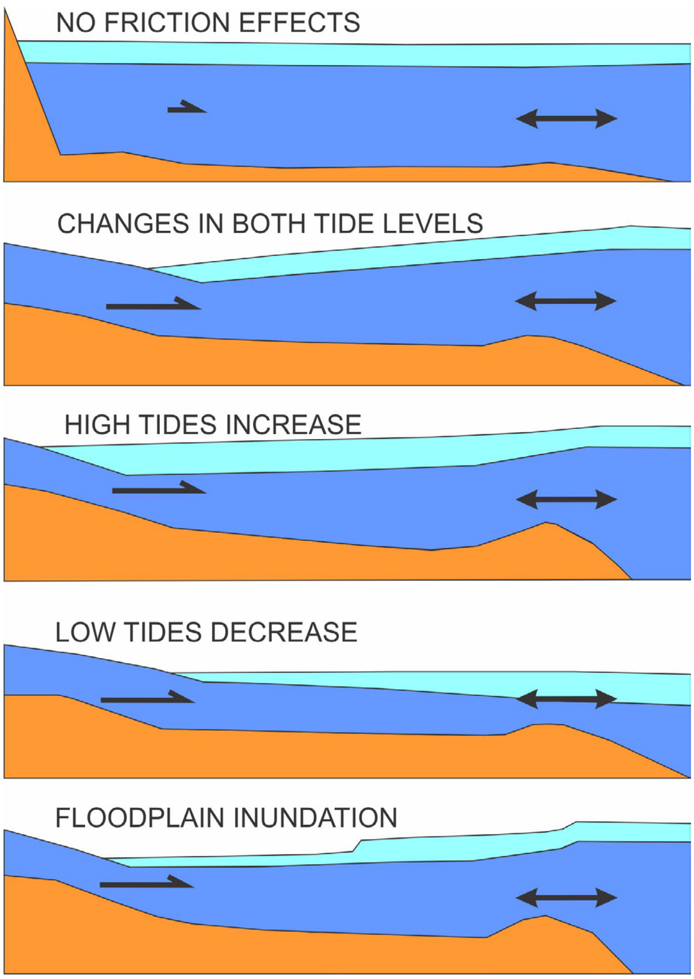

Figure 9. Variations of the estuarine processes due to SLR (modified after Khojasteh *et al.*, 2021).

At the coast of Magdalena and Punta Indio counties (outer Río de la Plata), the increase in the estuary level would affect the freshwater marsh communities, composed of Juncus acutus (juncal), Scirpus americanus (totora), Typha sp. (totora), Zizaniopsis bonariensis (espadaña), Vigna luteola (poroto de la playa), and trees of Erytrhina Crista Galli (ceibo) (Cellone *et al.*, 2016; Lasta *et al.*, 2019). Many authors believe that SLR would cause erosion of these vegetated areas (*e.g.*, Fletcher, 1992). Others trusted that the increase in temperature and in CO_2 atmospheric concentration would induce a higher marsh production that could compensate the SLR (Fitzgerald and Hughes, 2019). The sedimentation rates of the Paraná river delta (Marcomini *et al.*, 2018; Quesada, 2019; Gallo, 2023) would surely fulfill the SLR requirements for the freshwater marsh progradation and accretion at the headlands of the Río de la Plata estuary. At the Magdalena coast, the zonation of Juncus, freshwater grass, and riverine woods (Fig. 10) can migrate onshore if there is enough sediment (fine sand) in proportion to the

SLR rates. Simlar effects are expected with some herbaceous plants from the north of the Eastern Buenos Aires Barrier, whose distribution is related to landform types, freshwater availability, and sea proximity (Marcomini *et al.*, 2017).

Figure 10. Zonation of Juncus, riverine grass, and woods (Salix humboldtiana) at Balneario Magdalena.

SLR and saltwater intrusions

Recently, it was claimed that the contribution of wind waves to the coastal SLR has been underestimated (Melet *et al.*, 2019, 2020). This proposal has been questioned based on the scarce information about wave setup statistics and their long-term trends (Aucan *et al.*, 2018). To estimate these trends, it is necessary to analyse the foreshore slopes, avoiding those that have changed due to man-made sand unbalances.

SLR also impacts coastal aquifers (Carretero *et al.*, 2013). Along the Eastern Barrier of Buenos Aires, saltwater intrusion advances westwards, affecting the water table below the dunes in Pinamar, Villa Gesell, and Mar Chiquita. This salinization increases temporarily at crowded touristic cities (Pinamar, Villa Gesell). Along the Southern Barrier, instead, lateral salt intrusion is not significantly affected, as the salt content is related to the marine formations composing the coastal cliffs (Isla *et al.*, 2024; Fig. 11).

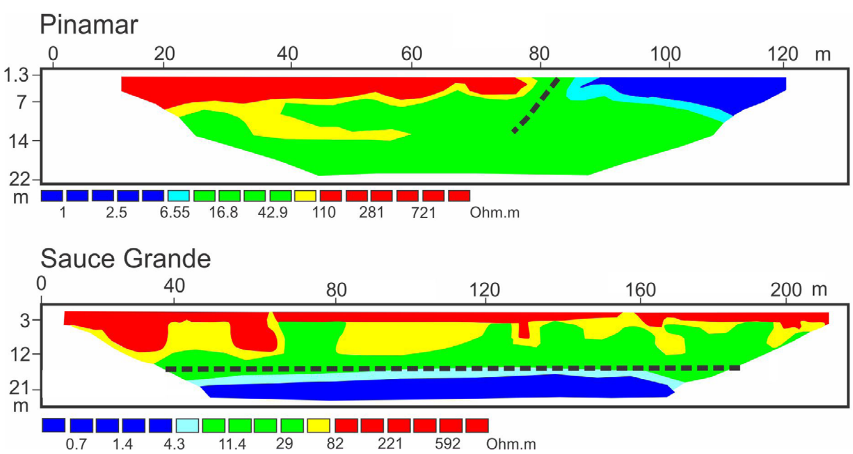

Figure 11. Sketch diagrams compared regarding the groundwater resistivity (ohm.m) across the Eastern and Southern barriers of Buenos Aires (modified after Rodrígues Capítulo, 2015; Albouy *et al.*, 2020; Isla *et al.*, 2024). At the Eastern Barrier the interface is an oblique dash line; at the Southern Barrier the interface is horizontal.

Water supply to cities

SLR means a translation of the surface interface of fresh and salt water. In Patagonia, the freshwater supply is scarce, and many cities have had to apply to pipelines from distant rivers or lakes (San Antonio Oeste, Puerto Madryn, Comodoro Rivadavia, Caleta Olivia). Macrotidal regimes condition the landward extent of this interphase along estuaries. In these cases, the decrease in water supply for some rivers (Isla and Isla, 2024) would be critical for the fresh water availability to these cities. The forecasted minimum increment of 0.4 m in mean sea level for the year 2100 (Oppenheimer *et al.*, 2019) should be simulated for some of these coastal cities. The water supply for these cities of the macrotidal coast is more dependent on the future rain and fluvial decreases than on the SLR.

Quite different would be the availability of fresh water along the low-lying coast of Buenos Aires (*i.e.*, the Samborombón Bay). During the peak of the crisis induced by the 2022-2023 drought, General Lavalle city had to be supplied by water delivered from the closer counties: La Costa and General Madariaga. The drainage that supplies freshwater to the city Channel 2 was very low in February 2023; therefore, the most plausible alternative selected was to construct a Reverse Osmosis plant with a capacity of 30 m3/h.

Although an increase in precipitation is recorded and expected for the Southeast of South America (Magrin *et al.*, 2014; Barros *et al.*, 2014), it is very difficult to apply for long-term trends. Cycles, trends, and jumps were recorded in the recent past (Minetti and Vargas, 1997). At the same time, South America is particularly subject to anomalous years; for this region, El Niño means more rain in Argentina while La Niña imply drier conditions (Magrin *et al.*, 2014).

Pluvial and sewage discharges

SLR will signify floods in low-lying cities. For example, pluvial pipelines constructed to drain urban areas at San Clemente del Tuyú (Partido de la Costa, Buenos Aires province) are beginning to receive seawater when meteorological tides induce the reversal of their purpose (Isla and Garzo, 2023). Combined sewer outfalls for coastal cities should therefore be planned considering the SLR (Passeri *et al.*, 2015; Hummel *et al.*, 2018) but also increments in flash floods recurrence.

Flash floods

Climate change also implies an increase in the risk of flash floods (Hirabayashi *et al.*, 2013). Global models predict that 21% of the flood risk can be assigned to climate change, and 76.8% to population increase (Rogers *et al.*, 2025). These kinds of floods have affected several cities in the last years and led to a specific PAGES project. For example, the flash floods of 2024 in Valencia, Spain, were attributed to climate change. Unprecedented floods were recently reported in Patagonia. In Puerto Madryn city, average rainfall is about 215 mm/yr. However, between April 21 and April 24, 1998, 255 mm were recorded in 4 days. On January 21, 2016, 24 mm precipitated in half an hour, and later 33 mm in 1 hour (Bilmes *et al.*, 2016). Average rainfall sums about 244 mm/yr in Comodoro Rivadavia city. On March 29, 2017, 399 mm precipitated and another 232 mm on March 31 (Paredes, 2019). On March 7, 2025, 300 mm precipitated in the Bahia Blanca area in 4 hours (Barraza, 2025).

DISCUSSION

Most of the predictions for SLR are based on the issues analysed in the IPCC reports, in terms of confidence levels, likelihoods, and uncertainties (Abram *et al.*, 2019). Considering these assumptions, some predictions can be subject to worldwide (SLR) or regional changes (precipitation in South America). This was considered as extreme and abrupt changes on the IPCC report about the ocean and cryosphere (Collins *et al.*, 2019). For example, in 2004, the first hurricane was recorded in the South Atlantic Ocean (Pezza and Simmonds, 2005).

Although the SLR forecasted by the IPCC was based on worldwide-estimated altimeter projections, there have been many doubts about regional accelerations (Church and White, 2006; Houston and Dean, 2011; Cronin, 2012; Gehrels and Woodworth, 2013; Boon and Mitchell, 2015; Ezer *et al.*, 2016). Global variability in SLR has been continuously changing during recent times. No significant variations were recorded before 1930, but during the 1930-1960 interval, the SLR rates were about 2.5 mm/yr. Significant variability was recorded for the 1960-1980 interval but increasing to 3 mm/yr since 1993 (Church and White, 2006). However, considering sea-level records from the

Northern Hemisphere, it has been proposed that the SLR started between 1905 and 1945, although data from the Southern Hemisphere has been largely disregarded (Gehrels and Woodworth, 2013).

The predictions listed above were based on SLR rates forecasted by IPCC (Oppenheimer *et al.*, 2019). However, episodic jumps in sea level can occur and have occurred. A crucial issue in coastal areas is the impact of storm surges that are very difficult to predict in temperate areas (Bernier *et al.*, 2024). On the other hand, some Antarctic glaciers are receding at anomalous rates (Graham *et al.*, 2022). The effect of the rebound induced by the collapse of the Western Antarctic Ice Sheet is another issue difficult to forecast (Pan *et al.*, 2021).

Regional variations in the SLR rates can be explained by significant changes in the groundwater and oil pumping rates (Boon and Mitchell, 2015; Bagheri-Gavkosh *et al.*, 2021). Although the tidal record of the harbour of Comodoro Rivadavia is too short (Brandani *et al.*, 1985), its particular higher rate of sea level rise could be assigned to the historic oil pumping at that particular area. Subsidence is not expected for the Argentine coast, not even in areas that were glaciated. Only at the two largest deltas (Paraná and Colorado) can subsidence be expected, but there are no precision reports. The islands that were eroded at the Colorado River delta were assigned to changes in the distributary channels (Spalletti and Isla, 2003). Water pumping in northern Partido de la Costa (outer Río de la Plata) led to saltwater intrusion (Carretero *et al.*, 2013).

The effects of the SLR on the tidal current components of the continental shelf of Patagonia were simulated for future increments of 1, 2, and 10 m (Luz Clara *et al.*, 2015). However, some of these scenarios are unlikely to occur during the 21st century.

As it has been reported, SLR is not the only process related to climate variations. Rains are assumed to increase along the Buenos Aires coastline. At the same time, based on the meteorological station records, rainfalls are assumed to diminish in Patagonia, affecting river discharges (Isla and Isla 2024).

Global simulations estimated that the wetland areas can increase up to 60% if there were enough accommodation space and sediment supplies remain at present levels (Schuerch *et al.*, 2018). However, based on climate-based and socioeconomic-based scenarios, 33 of the 47 major deltas would experience reductions in their sediment supply by the end of the 21st century (Dunn *et al.*, 2019).

In the last years, strong ENSO floods have been particularly recurrent and stronger than in previous years. Stronger ENSOs were recorded during 1982-1983, 1997-1998, 2015-2016, and 2023-2024. The main effect derived from this scenario is the flooding of low-lying coastal areas, as the wetlands of the Paraná delta, and headlands and southern floodplain of the Río de la Plata (Isla, 2018).

Using tidal records from Buenos Aires, Montevideo and Mar del Plata it is concluded that stream-flow can explain half of the SLR of Buenos Aires record and a quarter of the tidal record from Montevideo (Piecuch, 2023). These SLR rates are faster-than-global and particularly affect the mouth of the Paraná and Uruguay rivers, but it is very difficult to discern the interannual components of these records. Integrated assessment models were formulated for climate-socioeconomic response interactions (Moss *et al.*, 2010).

CONCLUSIONS

Considering the IPCC predictions on global SLR, and the particular conditions of the Argentine coast, some plausible conclusions are formulated:

1. The Buenos Aires microtidal coast is more subject to impacts derived from the predicted SLR. In this context, tidal prism increase can cause significant variations in the morphology of tidal inlets. In addition, the local availability of sand observed at Samborombón Bay, will condition the onshore migration of bedforms and the formation of cheniers and sand ridges by recurrent storms.
2. Along the outer Río de la Plata, the retreat of the overbanks (low-altitude cliffs) will condition the preservation of freshwater plant communities.
3. In the Northern coast of Argentina, beach erosion will be subject to increments due to a higher energy and recurrence of southeastern storms. However, along some intervals, present erosion is significantly subject to anthropogenic activities.
4. Future coastal erosion in Patagonia would be conditioned by the armouring effect of gravel-dominated bedforms.
5. SLR will affect coastal cities, not only in their freshwater supply, but also in their drainage and sewage alternatives.

6. The impact of flash floods on coastal areas is another issue that could not be analysed from statistical records.

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