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Sea-level trends along freshwater and seawater mixing in the Uruguayan Rio de la Plata estuary and Atlantic Ocean coast

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Abstract Sea level is rising worldwide with local differences due to global and regional drivers. This article analyses yearly freshwater and sea level trends and fluctuations during the mixing of fresh- and sea-water along the Uruguayan coast of the Rio de la Plata River estuary and the Atlantic coast from 1961 to 2014. The global and regional drivers as well as local co-variables are described, classified in nine discrete classes and inter-correlated. Despite the observed increasing trends, local sea level rises (SLR) are not well correlated with global SLR except at the estuarine-ocean boundary (Punta del Este station). Freshwater inflow, which variability often coincides with Oceanic El Niño-La Niña (ONI-ENSO) events, is the first descriptor of sea level fluctuations and outliers all along the coast, particularly at Punta del Este. Local SLR roughly follows the overall global trend with periods of acceleration and stabilization often coinciding with ENSO events.

Keywords Global sea level rise; ENSO; Global and local drivers; Estuaries

1 Introduction

Sea level rise (SLR) is changing the dynamics at play along coasts. The dynamics at play includes (UCS, 2013):

- Amplified wind-storm surge. With rising seas, storm surge occurs on top of an elevated water level (UCS, 2013).
- More intensive shoreline erosion, degradation and coastal destabilization. SLR increases the potential for erosion by allowing waves to penetrate further inland, even during calm weather (Bruun, 1962; Shepard et al., 1962; Zhang et al., 2004; Syvitski et al., 2005).
- Permanent inundation of low-lying coastal lands (Cooper et al., 2008).

Because of tidal and wind-driven changes, sea level is constantly fluctuating. Therefore, it is important to calculate the mean sea level (MSL), which is the average sea level at a given location over several years (Douglas, 2001). According to Chao et al., (2002) sea level change occurs on all time-scales, and with a continuous range of spatial scales, from local (e.g., wind storm surge), to regional (e.g., El Niño Southern Oscillation (ENSO)), and global (eustatic). On decadal to multi centennial time scales sea level fluctuations are mainly driven by climate change in response to natural forcing factors (e.g. solar radiation variations, volcanic eruptions) and to internal variability of the climate system (related for example to atmosphere–ocean perturbations such as El Nino-Southern Oscillation – ENSO, North Atlantic Oscillation – NAO, Pacific Decadal Oscillation – PDO) (Meyssignac and Cazenave, 2012).

As SLR accelerates, it will become increasingly necessary and useful to distinguish coastal "flooding" from "inundation" (Flick et al., 2012). The Rio de la Plata (RdlP) river estuary (Argentina-Uruguay) is the most exposed region of Latin America to coastal inundation due to SLR and storm surges, mainly due to Southeastern winds (Volonté and Nicholls, 1995; Barros et al., 2005; Nagy et al., 2005; Magrin et al., 2007, 2014; Nagy et al., 2007; ECLAC, 2011; Losada et al., 2013; Nagy et al., 2015). Along the Uruguayan coast of the RdlP the impacts of episodic flooding related to storm surges are greater than the permanent inundation related to SLR from 1983 to 2013 (Verocai et al., 2015).

Most estuaries have a series of landscape subcomponents: i) a fresh water source, ii) a tidal-estuarine segment, and iii) a pass to the sea. The interaction of three primary natural forces causes estuaries to be unique and different (Montagna et al., 2013):

- Climate: causing variability in the freshwater runoff, which is fundamental to the functioning of estuaries.
- Continental geology and geomorphology: causing variability in elevation, drainage patterns, landscapes, and seascapes (Measurements of isostatic land uplift or downlift are not available yet and is assumed not to be relevant in coastal Uruguay).
- Tidal regime: causing differences in the degree of mixing and elevation of the mixing zone.

This study review the background and investigates sea level (SL) trend patterns and fluctuations at four stations along the freshwater and ocean mixing along the Uruguayan coasts of RdlP river estuary (Argentina-Uruguay) and the Atlantic Ocean over the last 50 to 60 years. Emphasis is put on the relationships of SL with global and regional drivers of trends, fluctuations and extremes, including a few local co-variables from 1961-2014.

2 Study Area and Background

2.1 Geographical setting

The Uruguayan coast is 670 km in length with 450 km lying within the RdlP estuary and the remaining 220 km on the Atlantic Ocean (Figure 1).

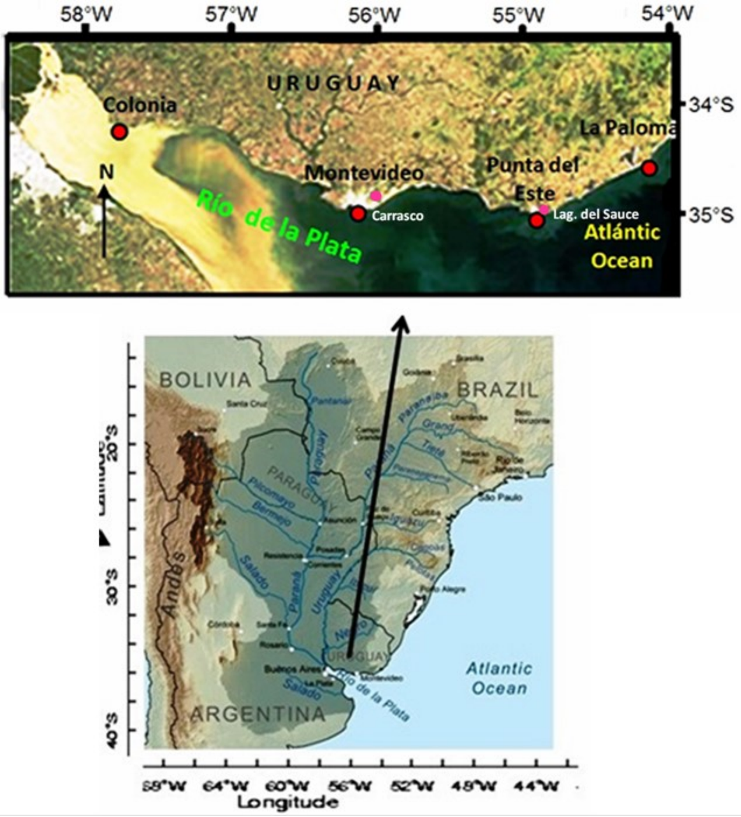


Figure 1 Rio de la Plata basin and river estuary, Southeastern South America. The four tide gauges are shown (red circles), and weather stations Carrasco and Laguna del Sauce airports (violet circles). The turbidity satellite image shows the divide of tidal fresh turbid water and estuarine marine water for a very low La Niña-linked river inflow. Modified from Nagy et al. (2014a).

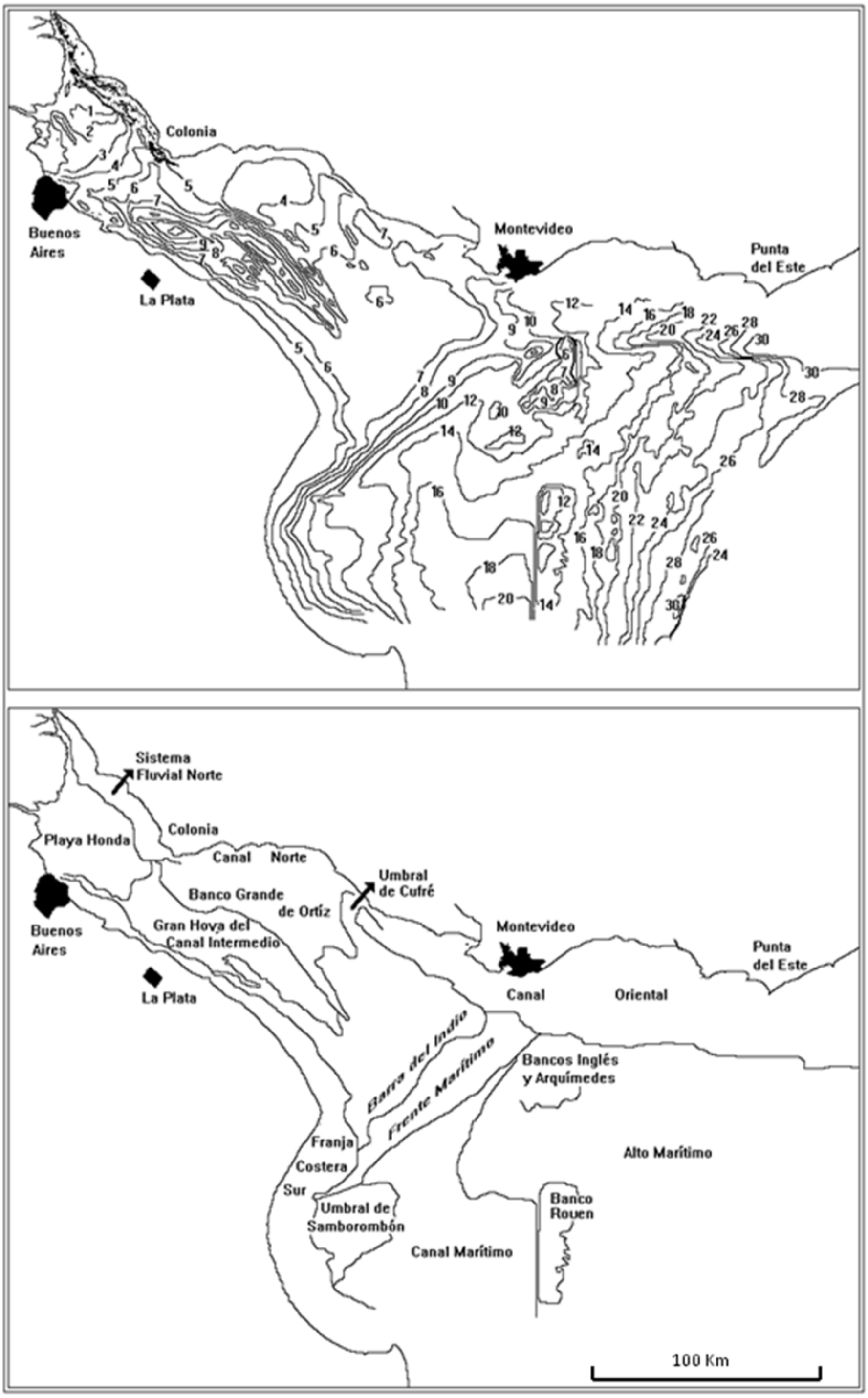


Figure 2 Río de la Plata bathymetry and morphological units. The most relevant for the hydology and water/sea level are the natural channels along the northern coast (Sistema Fluvial Norte, Canal Norte and Canal Oriental) which canalize fresh- and estuarine discharge, and. the “estuarine delta” (Barra del Indio) which roughly represent the upward limit of salt intrusion. Source: López Laborde and Nagy (1999)

The RdlP is a large (38 x 10^3 km^2; 40-30 km wide) river-influenced tidal river and primary estuary (Perillo, 1995a,b), defined by López Laborde and Nagy (1999) as “a funnel-shaped coastal plain tidal river with a semi enclosed shelf area at the mouth and a river paleovalley at the northern coast that favors river discharge and sediment transport to the adjacent continental shelf” (Figure 2).

The system may be divided into four regions (Nagy et al., 2002): i) Tidal River (1 to 6 m depth), ii) Estuarine Front (6 to 12 m depth), iii) Marine region (12 to 20 m depth), and iv) "Canal Oriental" (Paleovalley, 7 to 25 m depth), which behaves as an effective highly stratified mass transporting channel to the coastal ocean thus influencing both salinity and water-levels along the Uruguayan coast (Nagy et al., 2003; 2008a; Lappo et al., 2005).

2.2 Hydrological and climatic background

The main system's forcings are the big tributary discharges (namely Parana river and Uruguay river), the weak tidal currents (amplitude < 0.5 m) and front that propagates from the sea, and the action of winds (Balay, 1961; Guerrero et al., 1997; Simionato et al., 2007; Nagy et al., 2008a; Meccia et al., 2009).

The tide wave comes from the Atlantic Ocean, being deformed within the estuary due to the shape, banks, channels, depth, and Coriolis deflection towards Montevideo, where the cross-sectional area sharply decreases (Figure 3). Therefore, isoamplitudes increase upstream the transverse sections 24-20 (estuarine front). This facilitates the occurrence of "storm surges", that is to say the positive anomaly between the astronomic tide and the observed water level due to residual effects of winds, waves, sea level pressure (SLP), and freshwater inflow (Balay, 1961; Nagy et al., 1997; López Laborde and Nagy, 1999; Luz Clara, 2014; Verocai et al., 2015).

The fluctuations of freshwater inflow and axial offshore and onshore winds influence those of sea-level (Balay, 1961; Verocai et al., 2015). For this reason, the observed increase of river flow (García and Vargas, 1998; Nagy et al., 2002; 2014b) and Southeastern (SE) and East-Southeastern (ESE) winds over the last few decades (Escobar et al., 2004), which are the main causes of storm surges in the RdlP (Balay, 1961; D'Onofrio et al., 2008; Verocai et al., 2015), is changing the balance of the physical forcings on the system.

Historically, as a consequence of the permanent South American anticyclone (High Pressure Belt) over southeastern South America (SESA), the predominant wind direction has been from Northern quadrants (N to NE) (Balay, 1961; Nagy et al., 1997). An increase of S, SE and ESE wind directions was reported over the RdlP region since the 1960s (Escobar et al., 2004; Simionato et al., 2005; Nagy et al., 2008a, b; Meccia et al., 2009; Ortega et al., 2013; Pescio, 2015) and SE wind became the predominant one in Montevideo since 1998 (Nagy et al., 2014 b; Verocai et al., 2015). A relationship between stronger E to SE wind waves at the estuarine front was reported by Panario et al., (2008), whereas an increase of ESE winds was found during moderate to strong El Niño years (Gutierrez et al., 2016).

3 Materials and Methods

3.1 Global sea level and Uruguayan tide gauge stations

Global sea level from 1961 to 2014 was taken from EPA (EPA, 2014) and CSIRO (CSIRO, 2016). Yearly averages from four tide gauge stations (Figure 1) were analysed over the last 50-60 years: Colonia (*Station* 1), Montevideo (*Station* 2, for which a time-series from 1902 to 2014 is presented), Punta del Este (*Station* 3) and La Paloma (*Station* 4) which are part of the global network of tide stations "Permanent Service for Mean Sea Level" (PSMSL), National Oceanography Centre (NOC, UK) (http://www.psmsl.org/about_us/overview/). *Station* 2 Montevideo ("Punta Lobos") is an international GLOSS program station (number 300) of the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) of the World Meteorological Organisation (WMO) and the Intergovernmental Oceanographic Commission (IOC), (http://www.gloss-sealevel.org/). The four stations meet standard equipment, measurement, storage and data communication, and quality control requirements, including the correction for the effect of local sea level pressure (SLP).

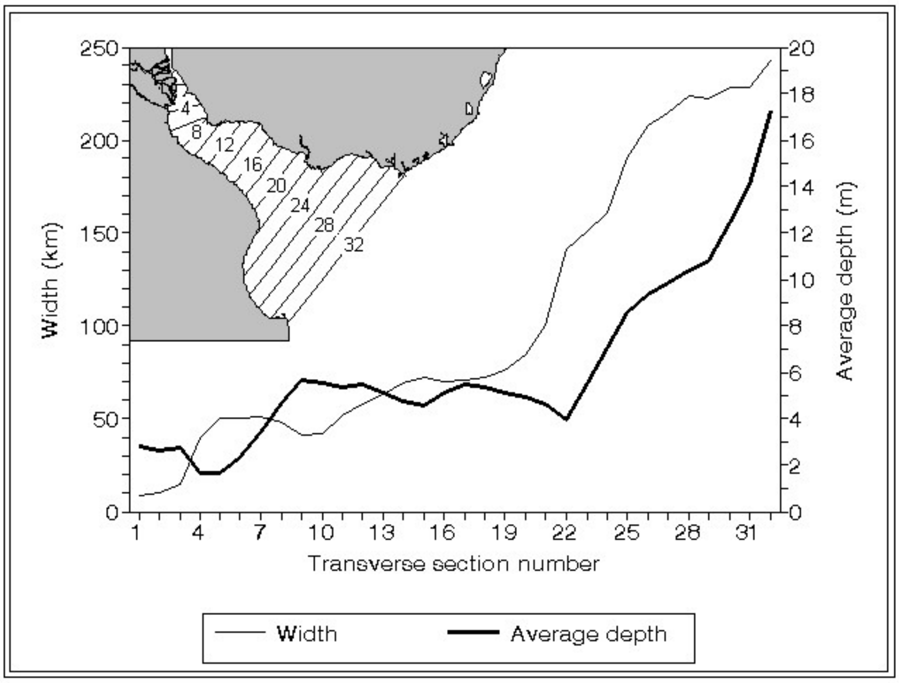


Figure 3 Southeastern width and average depth increase of Rio de la Plata river estuary. Source: López Laborde and Nagy (1999). The tidal freshwater extends from sections 1 to 18 or 22. The Atlantic coast extends from section 32 northeastward.

Station 1: Colonia from 1954 to 2014, with a few gaps (N = 51), located at the tidal river close to the mouth of the main tributary discharges. Data was available from the Navy Oceanographic, Meteorological and Hydrographic Bureau (SOHMA), and from Ministry of Public Works and Transports (MTOP).

Station 2: Montevideo, located within the estuarine front, from 1902 to 2014 (N= 113). Data was available from several institutions and locations (Harbor Authority-ANP, SOHMA and MTOP). The four sites are referred to the local zero of the hydrometric scale (0 Wharton).

Station 3: Punta del Este, located in the estuarine-marine boundary close to the mouth of the Canal Oriental to the Atlantic ocean. There are data available from SOHMA and MTOP from 1964 to 2014. The latter, with fewer gaps (N = 42) is used.

Station 4: La Paloma, located at the Atlantic coast 80 km to the East of the mouth of the RdlP, from 1955 to 2014, with gaps (N = 51) shows. Data was available from SOHMA and the Ministry of the Environment (DINAGUA). Table 1 shows relevant water heights at *station* 2.

3.2 Analyzed Variables and Methods

Time-series of aggregated yearly averages of selected global drivers (ENSO-ONI Index, sea level rise), regional drivers [(Paraná river flow (Q_P), Uruguay river flow (Q_{UY}), freshwater inflow to the RdlP system (Q_F: $Q_P + Q_{UY}$)], and local co-variables [(sea level pressure-SLP, air temperature-T_{MV} at Montevideo, water level at Colonia (WL_{CL}), sea level (SL) at Montevideo (SL_{MV}), Punta del Este (SL_{PE}) and La Paloma (SL_{LP})] are presented from 1961 to 2014.

The observed continuous values were converted into discrete nine unequal classes or "class variables" (Pasta, 2009; Hauke and Kossowski, 2011) relative distribution for each one where 1 is the observed minimum minimorum, 5 the average and 9 the observed maximum maximorum (Table 2).

Table 1 Relevant water heights at Montevideo

Water height (meters)	What and why?	Source
0.91	Mean sea level at mid 1940s. Used as reference in cadastre, civil works, hydrography, and surveying.	Presidential decree of 1949
0.96	Long-term sea level average.	Verocai et al., (2015)
≈1.02	Current sea level (2003-2014).	Bidegain et al., (2005); Verocai et al., (2015)
≈1.17	Maximum yearly mean recorded (1982)	This article
2.00	Height reached at least once a year.	Nagy et al., (2005)
2.50	Coastal gravity drainage, storm water infrastructure and sewerage systems are affected. Many beaches and bars are flooded. Beach water bacteriological quality is affected.	Verocai et al., (2015); Nagy et al., (2014b)
≈2.80	Beach erosion-accretion balance is affected with appreciable morphological impact due to flooding.	Gutiérrez et al., (2015, 2016)
≈3.00	Extreme event which occurrence is each 2-5 years.	Verocai et al., (2015)
≈3.10	Beaches are completely flooded	MTOP (1979); Gutiérrez et al., (2015)
≈3.50	Estimated impact threshold for extreme storm surges	Verocai et al., (2015)
4.30	Maximum ever recorded. Strong to catastrophic impacts in coastal landscape and built environment.	Verocai et al., (2015) Gutiérrez et al., (2015)

Table 2 Discrete class rank of analyzed variables from 1961-2014 (N= 55). Central classes 4 to 6 contain ≥ 70 percent of the observed values.

Class rank	Absolute value	ONI classes	Examples
1	Minimum minimorum	Unfilled	Observation ranked #1
2	Very low (≤ 5 % observations except the minimorum)	ONI mininum minimorum: 1972-73	Infrequent low values usually ranked #2-4
3	Low (5< Values<33)	-1 to -2ºC	Frequent low values
4	Central, below average	-0.5 to -1ºC	Typical values close to long-term average
5	Average	-0.5 to + 0.5ºC	
6	Central above average	+ 1 to +2 ºC	
7	High	+1 to +2ºC	Frequent high values
8	Very high (≥ 5% observations)	> 2° C (1972-73; 1982-83)	Unfrequent high values usually ranked #52-54
9	Maximum maximorum	1997-98	Observation classed #55

The discretization of data was done because some variables are not normally distributed, the relationship between them is not linear, and, particularly, some have strong outliers; the selection of a unequal 9-class sub-classification instead of a 5-class which is usually recommended for the number of data (N= 54) (Cochran, 1968; Pasta, 2009) was done both to reduce the effect of strong outliers and to represent all relevant intervals. Then a matrix of discrete Spearman's Rank-Order Correlation (r_S) of the nine classes was performed (Table 3) and the correlations with significances $p < 0.05$ (light gray) and $p < 0.01$ (dark gray) are shown. The strength of the correlation is described using the following guide for the absolute value of r_S: 0.20-0.39 “weak”, 0.40-0.59 “moderate”, 0.60-0.79 “strong”, 0.80-1.0 “very strong”.

For each station yearly water/sea level (WL/SL) averages were calculated (N = 8,800 hourly data per year) referred to the former customary national zero scale (Wharton hydrometric Zero reference plane, from now on 0-Wharton). The average, linear regression and Pearson correlation (r_P) were calculated for the time-series.

For ENSO years the water level anomaly (residue) was calculated for each station, that is to say the difference between the local mean level (WL/SL) and the yearly level for each year identified as moderate and strong. Then the average of these residues for the moderate, strong and all El Niño years are shown for the four studied sites.

The Oceanic Niño Index-ONI El Niño and la Niña neutral, moderate and strong events were identified (including very strong El Niño) [3 month running mean of ERSST.v4 (Huang, 2014, Liu, 2014) SST anomalies in the Niño 3.4 region (5^{o}N-5^{o}S, 120^{o}-170^{o}W)], centered 30-year base periods updated every 5 years (NOAA, 2015). ONI 3-month running mean (December to February - October to December) were aggregated on yearly basis. Therefore, following NOAA-ONI ranges, eight ENSO classes are defined which adapted for the 9-classes distribution includes classes 2 to 9. ONI class 1 is unfilled because it was not recorded any La Niña event < -2ºC or equivalent to extreme El Niño (class 9). Then, only for ONI index, the minimum minimorum becomes class 2.

Freshwater inflow data (Q_F: $Q_P + Q_{UY}$) were provided by "Instituto Nacional del Agua y el Ambiente" (INAA, Argentina) and calculated for yearly averages. Wind data are available from weather stations at Colonia, Carrasco (20 km to the east of Montevideo gauge station), the both from 1961 to 2014, Laguna del Sauce (30 km to the west of Punta del Este gauge station, Figure 1) from 2001 to 2014, and from NOAA NCEP Climate Forecast System (CFSR) Reanalysis (http://cfs.ncep.noaa.gov/cfsr/).

Twelve global, regional and local co-variables were analyzed on yearly basis as follows (Table 3):

i) Global drivers: 1- SLR Yearly, 2-ENSO ONI.
ii) Regional drivers: 3-River Paraná Flow (Q_P), 4-River Uruguay Flow (Q_{UY}), 5-Freshwater Inflow to the RdlP (Q_F).
iii) Local co-variables: 6-$Temp_{Mv}$, 7-SLP_{Mv}, 8-WL_{Col}, 9-SL_{Mv}, 10-SL_{PE}*, 11-SL_{LP}, 12-VV_{Mv}

4 Results

4.1 Oceanic Niño Index, freshwater inflow, sea level pressure, and winds

The two global drivers, SLR and ONI have shown a gradual increase. The former was likely greater than 3.2 mm per year between 1993 and 2010 (Church et al., 2013). Figure 4 shows the discretized 9-class global sea level time-series from 1961-2014.

The yearly Oceanic Niño Index (ONI) has steadily evolved from 1961 to 2014, with strong positive values (El Niño) in 1965-66, 1972-73, 1982-83, 1987-88, 1991-92, 1997-98, 2002-03, 2009-10, the strongest of which were 1997-98 (maximorum) and 1982-83. The negative values (La Niña) have been 1971-72, 1973-74, 1975-76, 1988-89, 1998-99-2000, 2007-08, 2010-11, the strongest of which were 1988-89, 1998-99-2000 (Figure 5). There was no clear minimum minimorum.

Yearly freshwater inflow (Q_F) to the RdlP has steadily increased from early 1970s up to mid 1990s with negative and positive fluctuations during La Niña and El Niño years respectively. Over the last decade (2004-2013) six years in ten were below the central class (5), four of which classified as low discharge (3). Figure 6 shows the polynomial evolution of Q_F .

Sea level pressure (SLP) has fluctuated from 1979 to 2014 around a slightly positive trend (+ 0.4 to 0.7 hPa), particularly at Colonia (Table 4).

Northern wind (N) has slightly decreased at Montevideo and, more markedly, at Colonia, where a decrease in NE-ENE winds and an increase in S-SE quadrants were observed. At Laguna del Sauce NE-ENE-E and S winds were predominant during 2001-2014 whereas East-southeast wind (ESE) became the predominant one in Montevideo during 2001-2014 (Figure 7).

Table 3 Yearly global (SLR, ENSO), regional (Q), and local ($Temp_{Mv}$, SLP_{Mv}, VV_{Mv}, WL_{Col}, SL at MV, PE and LP) discrete ranking (expressed as nine class intervals) of climatic variables from 1961-2014. Class intervals: 1: Minimorum (highlighted in light gray); 5: Average; 9: Maximorum (highlighted in dark gray), i.e., ENSO-ONI 0: Very strong La Niña, 5: Neutral and 9: Very strong El Niño year (1960-61 to 2013-14).*SL Punta del Este $_{PE}$ (source MTOP). Number of years N: 54.

Year	ENSO	SLR	River Flow (Q_F)			Temp	SLP	VV	WL	SL		
	ONI	Global	Q_P	Q_{UY}	Total	Mv	Mv	Mv	Col	MV	PE*	LP
1961	5	2	5	6	5	7	1	6	5	6		3
1962	5	2	2	2	2	2	9	6	4	4		3
1963	5	2	3	5	4	7	5	6	8	5		2
1964	7	1	2	2	2	3	5	7	3	2	2	1
1965	4	2	5	5	5	5	5	6	6	6	3	3
1966	8	1	7	7	6	4	7	7	5	5	3	3
1967	5	2	3	4	4	6	6	7	5	6	2	3
1968	4	2	1	2	1	6	8	8	5	4	1	3
1969	7	2	2	4	3	8	5	8	3	3	4	3
1970	6	2	2	3	2	7	5	9	2	5	4	3
1971	3	2	3	5	4	5	5	7	1	5	4	5
1972	4	2	4	5	4	6	2	6	3	5	5	6
1973	9	2	4	7	5	6	2	6	4	6	5	7
1974	2	1	5	3	5	4	6	6	2	5	4	6
1975	4	3	6	7	6	6	5	5	-	5		6
1976	2	3	5	4	4	2	5	5	4	5	5	-
1977	6	3	5	5	5	5	2	5	4	6	4	-
1978	6	3	3	3	3	2	5	6	-	5	5	-
1979	5	3	5	5	5	2	7	6	4	6	4	5
1980	6	3	5	4	5	6	4	6	-	6	5	5
1981	5	3	4	2	4	5	6	4	2	8	3	5
1982	5	4	6	6	6	6	5	5	5	7	5	5
1983	8	4	9	8	9	3	5	5	8	6	7	6
1984	4	4	5	6	6	1	4	6	4	7	7	6
1985	3	4	6	5	6	5	2	6	5	6	6	5
1986	5	4	5	6	5	5	2	6	6	5	5	5
1987	7	4	5	6	5	3	2	6	5	6	5	5
1988	8	4	4	3	4	1	5	6	3	2	5	5
1989	2	4	5	4	5	6	5	5	3	2	5	5
1990	5	5	6	7	7	5	5	5	4	5	6	5
1991	5	5	5	3	4	5	3	5	4	5	6	5
1992	8	5	7	6	7	3	2	6	5	5	7	5
1993	6	5	5	5	6	5	2	6	6	7	9	6
1994	5	5	5	5	5	6	2	4	4	4	7	5
1995	7	5	5	3	5	6	3	3	4	6	8	5
1996	4	5	5	4	4	2	5	3	5	5		4
1997	5	5	6	6	6	3	2	3	8	7		3
1998	9	6	8	9	8	7	6	2	9	9		7
1999	3	5	5	3	4	3	7	3	5	5	7	5
2000	2	6	4	5	4	2	4	3	5	5	7	6
2001	4	7	4	6	5	5	4	3	4	7	4	4
2002	5	7	5	7	5	9	2	4	8	7		7
2003	7	7	5	5	5	5	5	4	7	5		7
2004	5	8	4	2	3	6	7	4	5	5		6
2005	6	8	4	5	4	6	6	3	8	7	7	6
2006	4	8	3	2	3	6	6	3	7	5		9
2007	3	8	5	5	5	2	5	3	4	6		8
2008	4	8	3	3	3	6	6	2	5	5	6	5
2009	8	7	3	6	4	2	5	2	3	6	7	7
2010	3	8	5	6	6	6	6	2	5	6	8	5
2011	4	7	5	5	5	4	6	2	6	2	6	7
2012	4	8	5	1	5	8	4	1	6	5	8	7
2013	4	8	3	4	3	5	5	2	7	1	8	7
2014	6	9	5	5	5	8	5	2	7	6	7	7

Table 4 Current climate and sea level scenarios for the Uruguayan coast. Modified from Bidegain et al., (2011); Nagy et al., (2015); Verocai et al. (2015); and Gutiérrez et al. (2015) ↑: Increasing trend ↓: decreasing trend, Δ:interannual variability

Variable/period	Observed long-term trend and current (1979-2014) scenarios
Methods	Instrumental *in situ* meteorological, hydrological and oceanographic observations; NCEP reanalysis (1979-2014).
Air temperature (ºC)	+0.8 to 1.0, up to 0.5°C of which since 1961, 0.1. to 0.2 since 1979.
Sea-level pressure (hPa)	Long-term: ↓ 3 Current: ↑ variability (Δ) and ↑0.5 since 2001 (reverted the decreasing trend before 2001) reaching 1015-16, > eastward
Predominant Winds	> ESE-SSE (since 1998) and ≤ SW. E and N frequency increases during El Niño, and SW-WSW and > E–SE–SSE–N and < SW ("Pamperos") during El Niño, and > SW-WSW during La Niña events. Colonia: ESE, NE, S. Since 2001: ↑S and ↓NE Montevideo: ESE (spring-summer) and NNE (fall-winter). Since 2001: ↑ESE Laguna del Sauce (since 2001): NE,ENE, E,S, La Paloma: E
Freshwater inflow to the Rio de la Plata Q_F: (Q_P +Q_U) (Δ%)	↑ Δ and ≥ 30% ↑ Floods and ↓ Hydroclimatic homogeneity of the basin by ca. 2002 ≥ 20% since 2002 because the trend reverted by 2003: -9 (2000-08) due to Q_P: + 1 and Q_U: −35. ↑ Δ 2009-2014
Water/sea level (cm)	Past and current: Global SLR trend plus/minus regional Q_F and/or local wind effects. Future: Likely change in seasonal regime and storm surges.
Colonia	Since 1954: + ≥10cm,+1.68 mm/year
Montevideo	Since 1902: + ≥11-12 cm, +0.09-1.2 mm/year. Acceleration from 1971-2002 and stabilization from 2003-2012
Punta del Este	Since 1964. ≥18 cm,/yr, +4.7 mm/year with recent acceleration since the 1990s.
La Paloma	Since 1955. ≥20 cm, +3.4 mm/year.

Table 5 Differences (cm) between average WL/SL and the observed heights during El Niño (moderate, strong and all) for each of the four stations.

El Niño Event	**Colonia**	**Montevideo**	**Punta del Este**	**La Paloma**
Moderate	1,03 cm	0,54 cm	-2,00 cm	-0,60 cm
Strong	1,60 cm	5,02 cm	1,70 cm	-0,17 cm
All	1,29 cm	2,53 cm	0,10 cm	-0,38 cm

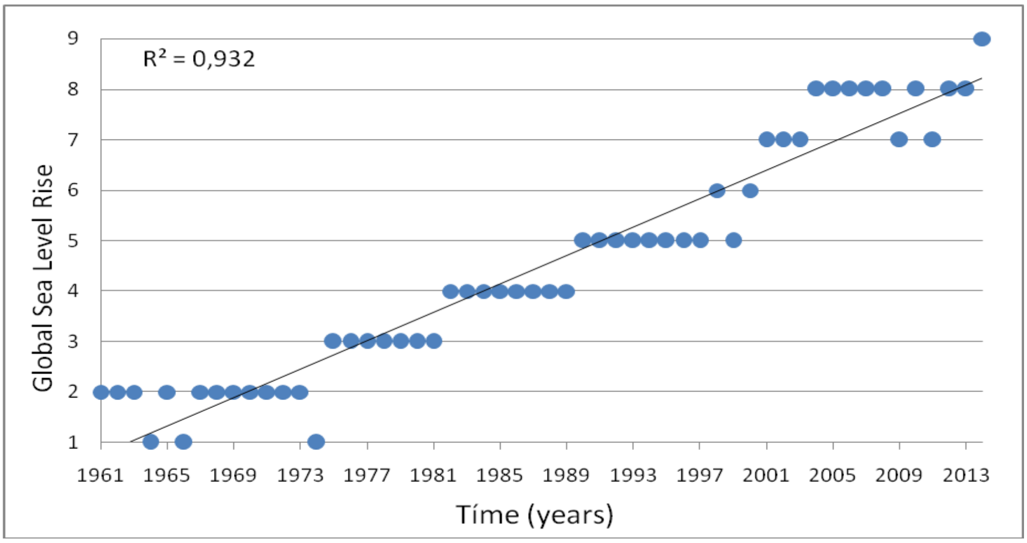


Figure 4 Discretized (9 classes) Global mean sea level from 1961 to 2014.

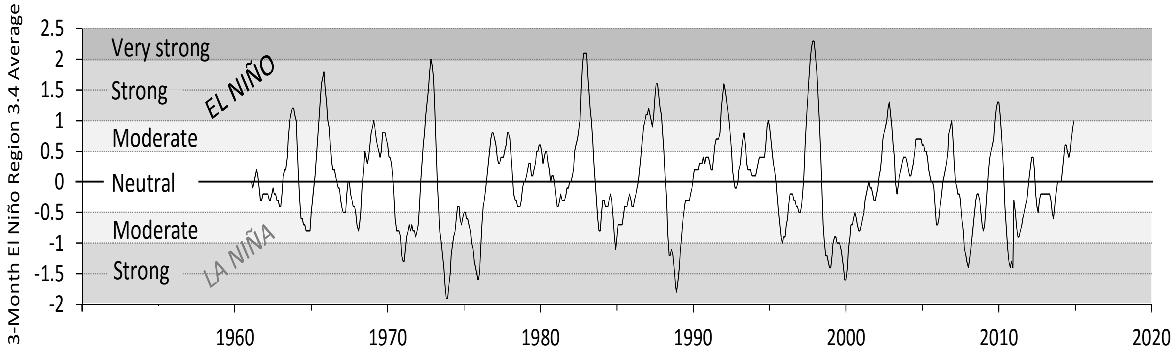


Figure 5 Oceanic Niño Index from January 1961 to December 2014. Source: NOAA (2015)

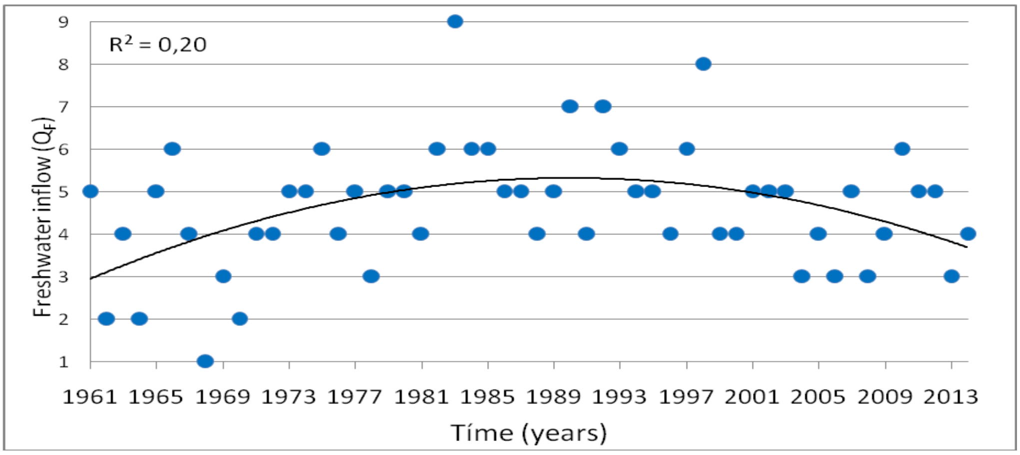


Figure 6 Freshwater Inflow to the Rio de la Plata shown in discrete classes (1-9) from 1961-2014.

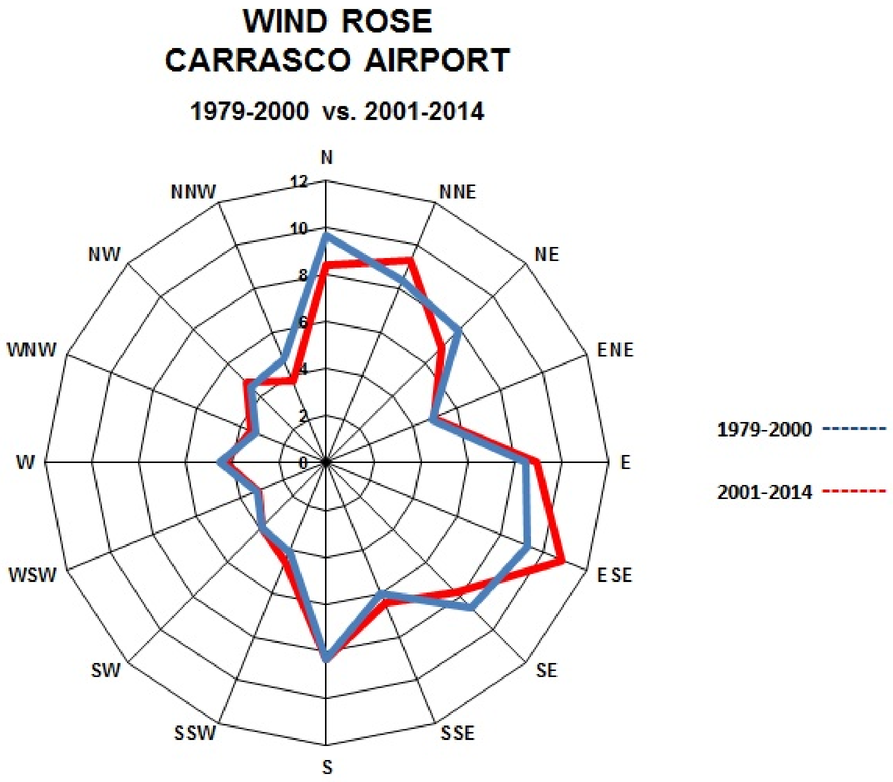


Figure 7 Wind rose (1979-2000 and 2001-2014) at Carrasco airport station (20 km to the east of Punta Lobos tide gauge).

4.2 Freshwater and Sea Level

Time-series of water (WL) and sea level (SL) are shown for the four studied tide gauge stations at Colonia, Montevideo, Punta del Este and La Paloma (Figure 8, from top to bottom respectively). Despite the different length and some discontinuities (particularly in Punta del Este) of these series, all of them showed similar increasing trend, fluctuations and extremes over the last 50 to 60 years.

4.2.1 Colonia (WL_{Cl})

Tidal freshwater level time-series (1954-2014) showed a mean water level of 77 cm, short-term fluctuations and trends with an increase in both mean and variability since the 1980s. The minimum recorded was 66 cm in 1981, reaching high values associated with El Niño years in 1998 (91 cm), 2002 and 2005. The water level has increased by 1.68 cm/year, accelerating over the last few decades (Figure 8). From 25 El Niño years, 6 events have been strong and 7 moderate. During these 25 years 16 have shown mean WL above the average and 9 below it.

4.2.2 Montevideo (SL_{Mv})

This station showed a gradual SLR of 11 cm from 1902 to 2014, with a long-term MSL of 96 cm and a positive weak significant trend with time (R^2 = 0,225; $p< 0.0001$; rate 0.9 mm/year). During 1961-2014 both MSL and acceleration rate strongly fluctuated, with a marked acceleration from 1971 to 1998, a stabilization period from 1999 to 2010 (long-term SLR: 10-11 cm), and a decrease to + 10 cm SLR by 2013. From 1961 to 2014 the number of years when SL was above the long-term SL_{MV} average of 96 cm was 17, whereas only 10 years were below this average. The number of El Niño events was 8. The average of the anomalies (observed SL_{MV}-Average SL_{MV}) for strong and moderate El Niño years were +5 cm and +0.5 cm respectively (Table 5).

4.2.3 Punta del Este (SL_{PE})

The correlation between available yearly means SL_{PE} and time (1964-2014, 42 years) was positive and strong (R^2 = 0,54, $p< 0.0001$; rate 4,7 mm/year). The SLR in Punta del Este was the highest along the Uruguayan coast, and above the global SLR rate (3.2 mm/year). During the observed period five strong and moderate El Niño events and five La Niña events coincided with recorded sea level. During El Niño events yearly SL was ≥ 92 cm (long-term SL average) and the trend-line, whereas during La Niña only two yearly SL were beneath the average, and other two were above it (2008 and 2011), but beneath the trend-line. The average anomalies (observed SL_{PE} - average SL_{PE}) for strong and moderate El Niño events were -2 cm beneath 92 cm and 1.7 cm above it respectively (Table 4). The extremes occurred in 1995 (maximorum) and 1968 (minimorum).

4.2.4 La Paloma (SL_{LP})

The average SL was 89 cm and showed two relatively accelerated increases from 1955 to 1983 and from 2000 to 2014. During the observed period (1955-2014) 15 years showed yearly SL_{LP} higher and 9 lower than the average of 89 cm, whereas 5 El Niño events coincided with data from LP. The average anomalies for strong and moderate El Niño's were -0.60 and -0.17 cm beneath the average (Table 4). The extremes occurred in 2006 (maximorum) and 1964 (minimorum). The trendline was above the average (90 cm) since 1993 and accelerated since 2002. During La Niña years, particularly the strong ones, SL was often beneath the average at most stations, i.e., 1955, 1971 and 1989, as well as 2009 when both la Niña (2008-2009) and El Niño (2009-2010) events occurred.

4.3 Spearman correlation matrix

Table 6 shows the discrete correlation matrix (R_S) of the twelve ranked variables from 1961 to 2014 presented in Table 3. Only moderate ($rs \geq 0.4$) and significant ($p< 0.05$ and $p < 0.01$) correlations were taken into account. The best correlated variable with others were Q_F, and SL_{PE} with 3 significant correlations >0.4 (N: 3), GSLR, Q_P, WV_{MV} and Q_{UY} (N: 2), whereas ENSO-ONI, SL_{MV}, SLP_{MV}, WL_{CL}, T_{Mv} and SL_{LP} had no significant weak to strong correlations (R_S) (N:0).

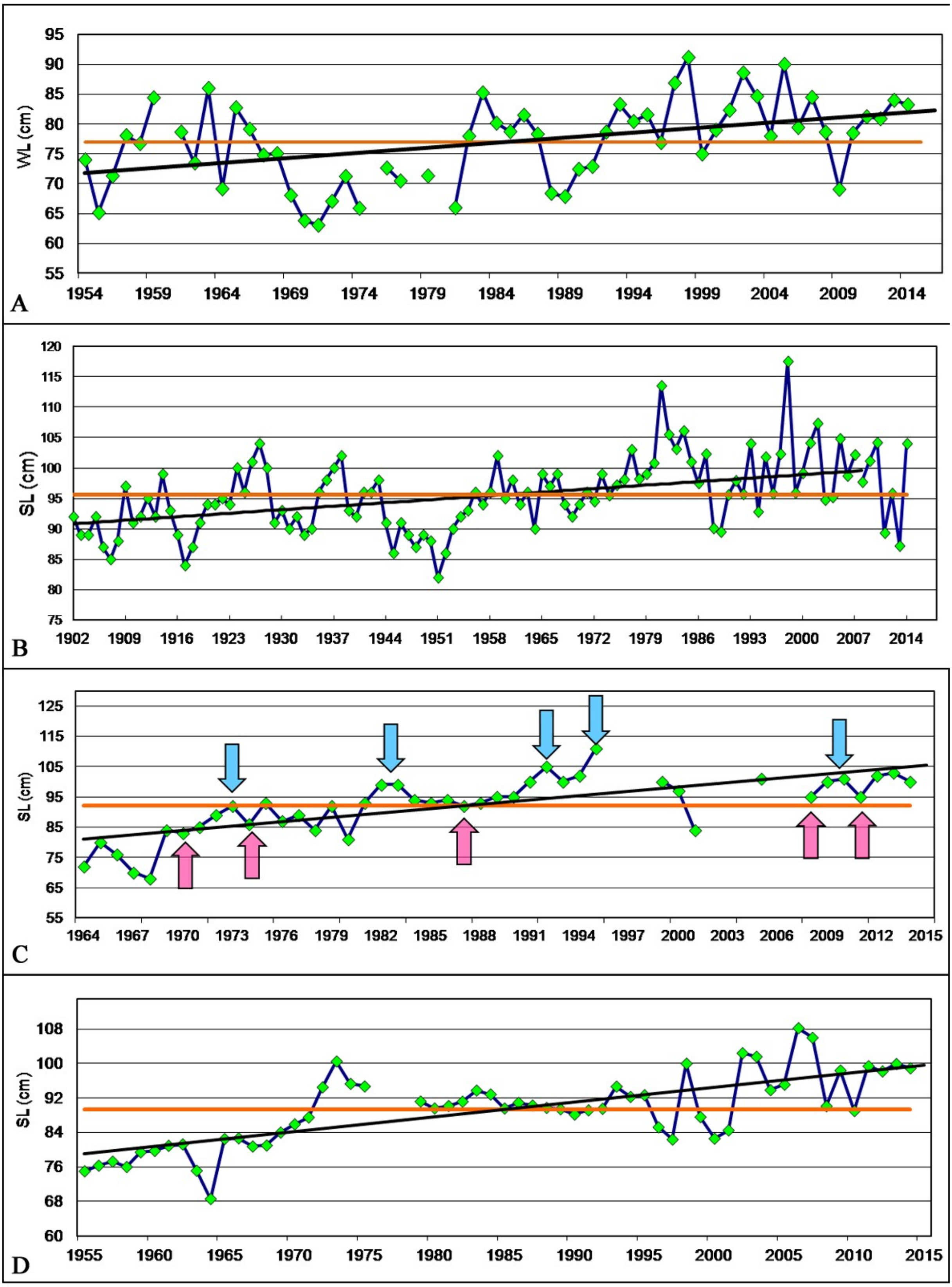


Figure 8 Water/sea level (cm) yearly average at the four stations of the Uruguayan coast. From top to bottom: A, Colonia, B, Montevideo, C, Punta del Este and D, La Paloma, (time-series do not start in the same year). For Punta del Este the moderate and strong El Niño and La Niña events are shown with wide light blue and violet color respectively.

Table 6 Spearman rank r-matrix of climatic and oceanographic variables: 1 ONI; 2 SLR Global; 3 River Flow-Q_P; 4 River Flow-Q_{UY}; 5 River Flow-$_{QF}$; 6; Temp $_{Mv}$; 7 SLP_{Mv}; 8WL_{Col}; 9 SL_{Mv}; 10 SL_{PE}; 11 SL_{LP}; 12 WV_{Mv}. The number of yearly averages (N), and the median and mean of the correlations (r_S md and x) are shown for each variable. The r_S significance (according to the number of data of each correlated pair) are colored in gray tones as follows: p<0.01;p<0.05. Not significant and/or r_s< 0.4 (NS).

Variable Yearly average	Data	ONI	G_{SLR}	Q_P	Q_{UY}	Q_F	T_{MV}	SLP_{MV}	WV_{Mv}	WL_{CL}	SL_{MV}	SL_{PE}	SL_{LP}
	N	54	54	54	54	54	54	54	54	51	54	42	51
Variable Number		1	2	3	4	5	6	7	8	9	10	11	12
1	ONI	1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
2	GSLR	NS	1	NS	NS	NS	NS	NS	-0.88	NS	NS	0.74	NS
3	Q_P	NS	NS	1	0.56	0.93	NS	NS	NS	NS	NS	NS	NS
4	Q_{UY}	NS	NS	0.56	1	0.70	NS	NS	NS	NS	NS	NS	NS
5	Q_F	NS	NS	0.93	0.70	1	NS	NS	NS	NS	NS	0.43	NS
6	T_{MV}	NS	NS	NS	NS	NS	1	NS	NS	NS	NS	NS	NS
7	SLP_{MV}	NS	NS	NS	NS	NS	NS	1.00	NS	NS	NS	NS	NS
8	WV_{Mv}	NS	-0.88	NS	NS	NS	NS	NS	1	NS	NS	-0.64	NS
9	WL_{CL}	NS	NS	NS	NS	NS	NS	NS	NS	1	NS	NS	NS
10	SL_{MV}	NS	NS	NS	NS	NS	NS	NS	NS	NS	1	NS	NS
11	SL_{PE}	NS	0.74	NS	NS	0.43	NS	NS	-0.64	NS	NS	1	NS
12	SL_{LP}	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	1
N significant		0	2	2	2	3	0	2	2	1	0	3	0

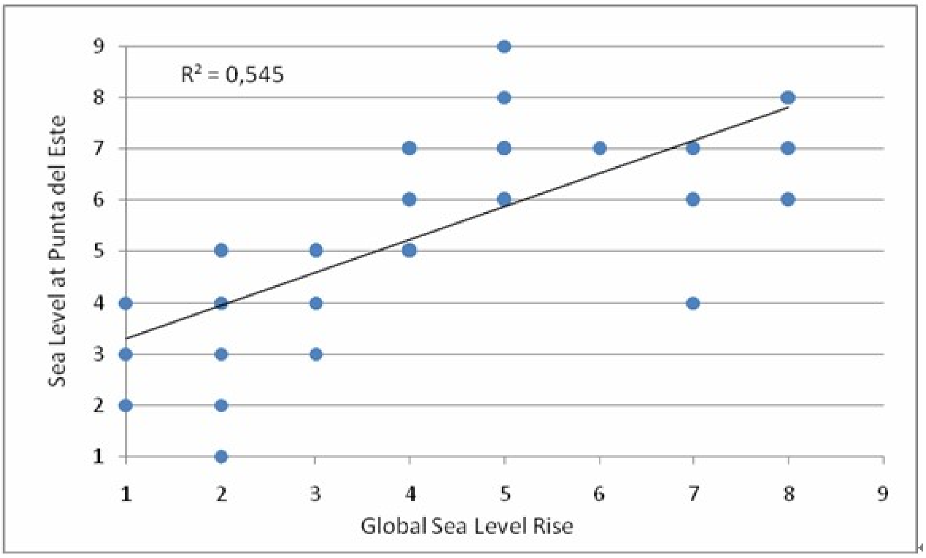
Punta del Este was the only station with significant correlations (Table 6) with both global drivers (GSLR Vs SL_{PE}, r_s: 0.74 and Q_F Vs SL_{PE}, r_s: 0.43). The scatter plot between the discrete series GSLR and SLR_{PE} shows twelve years (i.e. 28%) located at more than one discrete class from the trendline (residual years) (Figure 9). In addition, the scatter plot between freshwater inflow (Q_F) and the residual GSLR-SL_{PE} years is strongly correlated (r_p: 0.76; p< 0.002). The discrete time series WV_{MV} showed a very strong correlation with SL_{PE} (r_s: -0.88). However, the correlation between the wind discrete series with the twelve residues of the scatter plot GSLR - SL_{PE} was weak.

5 Discussion

Slow onset processes like SLR will result in a range of impacts that will, to a great extent, place a disproportionately large burden on poor and vulnerable groups in developing as well as developed countries (Roberts and Andrei, 2015).

A surprising finding is that the Oceanic Niño Index (ONI) is not well and significantly correlated with any other variable, despite the observed relationships with outliers (residues) of freshwater inflow, wind regime and sea level reported in recent papers (Nagy et al., 2008 a,b; 2014b; Verocai et al., 2015; Gutiérrez et al., 2016), and with values above/beneath the trendlines and outliers in the four stations.

The observed yearly sea level fluctuations along the Uruguayan coast are mostly attributable to regional and local climate patterns, e.g., freshwater inflow. Although in meso-and macro-tidal estuaries, river flow has little influence on tidal dynamics away from the upper reaches (Environment Agency, 2010), in micro-tidal environments like the RdlP, river flow has strong influence sea-ward in the lower estuary and plume beyond the geographical limits of the system, e.g. at La Paloma (Nagy et al., 2014a). There are several other periodic climate variabilities to be accounted for the regional hydro-climatologic and oceanographic fluctuations e.g., the North Atlantic Oscillation-NAO, the Atlantic Multidecadal Oscillation-AMO, and the Pacific Decadal Oscillation-PDO (Ortega et al., 2013; Nagy et al., 2014b; Gutiérrez et al., 2015) which have not been discussed here.



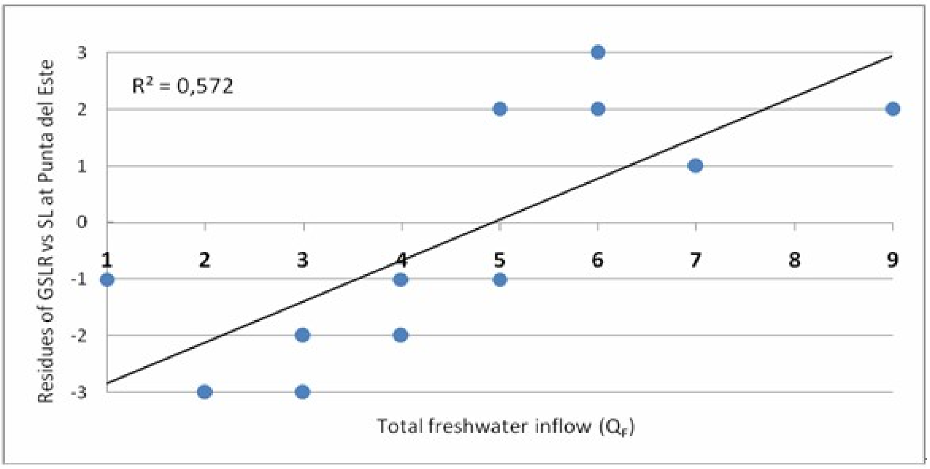


Figure 9 Scatter plots of Global Sea Level Rise (GSLR) Vs Sea Level at Punta del Este (top), and Total freshwater inflow (Q_F) Vs twelve outliers (residues) of GSLR Vs SL_{PE}.

The most relevant finding was the strong SLR at Punta del Este, which accelerated from 1964 to 1995, matching quite well global SLR trend and regional freshwater inflow increase from about 1971 to mid 1990s. At La Paloma, SLR acceleration since 2002 follows quite well global trends. The strong correlation of global sea level rise with sea level at Punta del Este (+0.74) suggest this station is key to monitoring SLR and understanding the complex multi causal sea level fluctuations. The moderate relationship between La Niña events and negative SL residues (anomalies) over the last decade at this station is likely explained by the primary control of global sea level rise. The negative very strong correlation with wind velocity at Montevideo (-0.88) seems to be related to opposed trends at global and regional scales. The question then arises if this could be somewhat associated with the displacement of the South Atlantic High Pressure reported by several authors (Liu et al., 2007; Reichler, 2009; Bidegain et al., 2014, 2015).

The very strong correlation of observed wind speed at Montevideo and sea level at Punta del Este (-0.88) seems to be the consequence of coevolution rather than causality. The moderate (+0.43) relationship of total inflow (Q_F) with sea level at Punta del Este shows some degree of influence of hydroclimatic trends and fluctuations on sea level along the Uruguayan coast, particularly for strong events and residues.

6 Summary and Conclusions

Freshwater inflow was the main driver of sea level fluctuations for the Uruguayan coast as a whole, whereas

Global sea level rise was the main driver of sea level rise at Punta del Este.

Freshwater inflow explains most of outliers (residues) of the relationship Global sea level rise - Sea level at Punta del Este, whereas the very strong correlation found between the latter with wind speed at Montevideo seems to be mostly a covariation.

Oceanic Niño Index was not correlated with sea level trends. Conversely, it was qualitatively associated, mainly for strong events, with fluctuations, particularly with outliers (residues) of freshwater inflow and, in a less degree, of sea level.

Punta del Este station showed greater sea level rise (4.7 mm/year) than the other sites along the Uruguayan coast, above world's rate (3.2 mm/year). It was the most and best correlated with global and regional drivers. This station seems to be the one which shows the best the multi causal factors which determine trends, fluctuations and extremes.

Author's contributions

JEV designed methods and analyzed sea level. GJN designed methods and analyzed oceanographic and climatic data. MB analyzed meteorological and climatic data. All authors read and approved the final manuscript.

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References

Balay M.A., 1961, El Río de la Plata entre la atmósfera y el mar. 153p., Publicación H-621, Servicio de Hidrografía Naval (SHN), Secretaria de Marina Argentina, Buenos Aires.

Barros V., Menéndez A., and Nagy G.J. (Eds.), 2005, El Cambio Climático en el Río de la Plata, Centro de Investigaciones del Mar y la Atmósfera (CIMA). Universidad de Buenos Aires (UBA), Buenos Aires, 200 pp.

Bidegain M., Stella J.L., Betolli M.L., and Quintana J., 2015, [Regional climates] Southern South America [in "State of the Climate in 2014"]. Bulletin American Meteorological Society. 96, S182–S184. doi:10.1175/2015BAMSStateoftheClimate.1
http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1

Bidegain M., Stella J.L., and Penalba O.C., 2014, [Regional climates] Southern South America [in "State of the Climate in 2013"]. Bulletin American Meteorological Society 95, S172–S173. doi:10.1175/2014BAMSStateoftheClimate.1
http://dx.doi.org/10.1175/2014BAMSStateoftheClimate.1

Bidegain M, de los Santos B, Skusunosky S, and Kitoh S., 2011, Escenarios Climáticos futuros con el modelo japonés MRICGCM2.3. Anais do 7° Simpósio de Meteorología e Geofísica da APMG y XIV Congreso Latinoamericano e Ibérico de Meteorologia, Portugal.

Bidegain M., Caffera R.M., Blixen F., Pshennikov V.A., Lagomarsino J.J., Forbes E.A., and Nagy G.J., 2005, Tendencias climáticas, hidrológicas, y oceanográficas en el Río de la Plata y Costa Uruguaya, in: Barros, V., Menéndez, Á., Nagy, G. (Eds.), El Cambio Climático En El Río de La Plata. Centro de Investigaciones del Mar y la Atmósfera - CIMA/CONICET, Buenos Aires, Argentina, pp. 137–143.

Bruun P., 1962, 'Sea-level rise as a cause of shore erosion', Journal Waterways and Harbours Division, vol. 88(1-3), pp. 117-130.

Church J.A., Clark P.U., Cazenave A., Gregory J.M., Jevrejeva S., Levermann A., Merrifield M.A., Mlne G., Nerem R.S., Dunn P.P., Payne A.J., Pfeffer W.T., Stammer D., and Unnikrishnana A.S., 2013 'Sea level change', in Climate Change 2013: Sea Level Change, Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin, D., Plattner, G-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (Eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Chao B.F, Farr T., La Brecque J. Bindschadler R., Douglas B., Rignot E., Shum C.K., and Wahr J., 2002, Understanding sea level changes. Geoscience and Remote Sensing Symposium, 2002.IGARSS '02. 2002 IEEE International.1):125 - 127. Print ISBN:0-7803-7536-X; DOI:10.1109/IGARSS.2002.1024962
http://dx.doi.org/10.1109/IGARSS.2002.1024962

Cochran W. G.., 1968, "The effectiveness of adjustment by subclassification in removing bias in observational studies", *Biometrics,* 24:295-313.
http://dx.doi.org/10.2307/2528036

Cooper M.J.P., Beevers M.D., and Oppenheimer M., 2008, The potential impacts of sea level rise on the coastal region of New Jersey, USA. Climatic Change 90:475–492.
http://dx.doi.org/10.1007/s10584-008-9422-0

CSIRO,2016, Sea Level – Understanding the Past. Historical sea level changes. Last few hundred years.
http://www.cmar.csiro.au/sealevel/sl_hist_few_hundred.html

D'Onofrio E.E., Fiore M.M.E., and Pousa J.L., 2008, Changes in the Regime of Storm Surges at Buenos Aires, Argentina. Journal of Coastal Research,

24(1A):260-265. DOI: 10.2112/05-0588.1
http://dx.doi.org/10.2112/05-0588.1

D'Onofrio E.E., Fiore M.M.E., and Romero S.I., 1999, Return periods of extreme water levels estimated for some vulnerable areas of Buenos Aires. Continental Shelf Research, 19(13):1681-1693. DOI: 10.1016/S0278-4343(98)00115-0.
http://dx.doi.org/10.1016/S0278-4343(98)00115-0

Douglas B., 2001, "Sea level changes in the era of the recording tide gauges," 37-64, in Sea Level Rise: History and Consequences, Douglas, B., Kearney, M., and Leatherman, S. (eds). Academic Press, San Diego, 2001
http://dx.doi.org/10.1016/s0074-6142(01)80006-1

ECLAC, 2011, Effects of climate change on the coast of Latin America and the Caribbean: dynamics, trends and climate variability. LC/W.447. Economic Commission for Latin America and the Caribbean (ECLAC), United Nations, Santiago de Chile, Chile. http://www.cepal.org/publicaciones/xml/2/45542/W.447.pdf

Environment Agency, 2010, Vulnerability to Sea Level Rise in Estuaries - Stage 1: A Review. Report SC080016/R1.Environment Agency, Rio House, Waterside Drive, Aztec West, Almondsbury, Bristol, BS32 4UD. ISBN: 978-1-84911-183-6. www.environment-agency.gov.uk

EPA (2014) Trends in global average absolute sea level, 1880–2013.
http://www.epa.gov/climatechange/science/indicators/oceans/sea-level.html.

Escobar G., Vargas W., and Bischoff S., 2004, Wind tides in the Rio de la Plata estuary: meteorological conditions. International Journal of Climatology, 24(9):1159–1169. DOI: 10.1002/ joc.1026.

Flick R.E., Chadwick D.B., Briscoe J., and Harper K.C., 2012, Flooding" versus "inundation". Eos, 93(38):365-366. American Geophysical Union. DOI: 10.1029/ 2012EO380009.

García N.O., and Vargas W., 1998, The temporal climatic variability in the Rio de la Plata Basin displayed by the river discharges.Climatic Change, 38(3),359-379. DOI: 10.1023/A: 1005386530866

Guerrero R.A., Acha E.M., Framiñán M.B., Lasta C.A., 1997, Physical oceanography of the Rıo de la Plata estuary, Argentina. Continental Shelf Research. 17, 727–742, 1997.
http://dx.doi.org/10.1016/S0278-4343(96)00061-1

Gutiérrez O., Panario D., Nagy G.J., Piñeiro G., and Montes C., 2015, Long-term morphological evolution of urban pocket beaches in Montevideo (Uruguay): impacts of coastal interventions and links to climate forcing. Journal of Integrated Coastal Zone Management, 15(4): 467-484. DOI: 10.5894/rgci553.
http://dx.doi.org/10.5894/rgci553

Gutiérrez O., Panario D., Nagy G.J., Bidegain M., and Montes C., 2016, "Climate teleconnections and indicators of coastal systems response". Ocean & Coastal Management (OCMA), 122: 64-76. March 2016. D.O.I. 10.1016/j.ocecoaman.2016.01.009.

Hauke J., and Kossowski T., 2011, Comparison of values of Pearson's and Spearman's correlation coefficients on the same sets of data. Quaestiones Geographicae, 30:2:87-93. ISSN (Print) 0137-477X, DOI: 10.2478/v10117-011-0021-1, June 2011
http://dx.doi.org/10.2478/v10117-011-0021-1

Huang B., Banzon V.F., Freeman E., Lawrimore J., Liu W., Peterson T.C., Smith T.M., Thorne P.W., Woodruff S.D., and Zhang H.-M.., 2014, Extended Reconstructed Sea Surface Temperature version 4 (ERSST.v4): Part I. Upgrades and intercomparisons. Journal of Climate, 98, 911-930. http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-14-00006.1

IPCC, 2013, Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker T.J, Qin D., Plattner G.K., Tignor M., Allen S.K., Boschung J., Nauels A., Xia Y., Bex V., and Midgley P.M., (Eds.), 29 pp. Cambridge University Press, Cambridge, UK and New York, NY, USA. http://www.climatechange2013.org/.../WG1AR5_SPM_FI

Lappo S.S., Morozov E.G., Severov D.N., Sokov A.V., Klyuvitkin A.A., and Nagy G., 2005, Frontal mixing of river and sea wa-ters in Rio de La Plata. Doklady Earth Sciences C/C of Doklady- Akademii Nauk (ISSN: 1028-334X), 401(2):226-228.

Liu W., Huang B., Thorne P.W., Banzon V.F., Zhang H.M., Freeman E., Lawrimore J., Peterson T M., Smith T.C., and Woodruff S.D., 2014, Extended Reconstructed Sea Surface Temperature version 4 (ERSST.v4): Part II. Parametric and structural uncertainty estimations. Journal of Climate, 28, 931-951.
http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-14-00007.1

Liu J.,Vecchi G., and Reichler, T., 2007, "Expansion of the Hadley cell under global warming", Geophys. Res. Lett., 34, doi:10.1029/2006GL028443.
http://dx.doi.org/10.1029/2006GL028443

López Laborde J., and Nagy G.J., 1999, Hydrography and sediment transport characteristics in the Rio de la Plata. In: Perillo Piccolo and Pino-Quivira (eds.) Estuaries of the South America: their geomorphology and dynamics. Springer-Verlag, Berlin. 1999
http://dx.doi.org/10.1007/978-3-642-60131-6_7

Losada I.J., Reguero B.G., Méndez F.J., Castanedo S., Abascal A.J., and Mínguez R., 2013, Long-term changes in sea-level components in Latin America and the Caribbean. Global and Planetary Change, *104*(0), 34-50. Doi: 10.1007/s10236-005-0008-3.
http://dx.doi.org/10.1007/s10236-005-0008-3

Luz Clara M., Simionato C.G. D'Onofrio E., Fiore M., and Moreira D., 2014, Variability of tidal constants in the Río de la Plata estuary associated to the natural cycles of the runoff Estuarine, Coastal and Shelf Science 148 (2014): 85-96. www.elsevier.com/locate/ecss
http://dx.doi.org/10.1016/j.ecss.2014.07.002

Magrin G., Marengo J., Boulanger J.P., Buckeridge M., Castellanos E., Poveda G., Nobre C., Scarano F., and Vicuña S., 2014, Chapter 27 "Central and South

America". In V.R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, & L.L. White (Eds.). Climate Change 2014: Impacts, Adaptation and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change IPCC, 2014. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1499-1566.ISBN 978-1-107-68386-0. http://ipcc-wg2.gov/AR5/report/citations/.

Magrin G., García C.G., Choque D.C., Giménez J.C., Moreno A.R., Nagy G.J., Nobre C., and Villamizar A., 2007, Latin America. Climate Change 2007: impacts, adaptation and vulnerability. In: Parry, M.L.; Canziani, O.F.; Palutikof, J.P.; van der Lin-den, P.J.; Hanson, C.E. (eds.), Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 581–615, Cambridge University Press, Cambridge. ISBN: 978-0521 88010-7. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch13.html

Meccia V.L., Simionato C.G., Fiore M.E., D'Onofrio E.E., and Dragani W.C., 2009, Sea surface height variability in the Rio de la Plata estuary from synoptic to inter-annual scales: results of numerical simulations. Estuarine, Coastal Shelf Sci. 85: 327–343.
http://dx.doi.org/10.1016/j.ecss.2009.08.024

Meyssignac B., and Cazenave A., 2012, Review Sea level: A review of present-day and recent-past changes and variability Journal of Geodynamics 58 (2012) 96–109. doi:10.1016/j.jog.2012.03.005
http://dx.doi.org/10.1016/j.jog.2012.03.005

Montagna P., 2013, Conceptual Model of Estuary Ecosystems, 2: 5-21, in Montagna PA, Palmer TA, Besseres Pollack J (Eds) Hydrological Changes and Estuarine Dynamics. ISBN 978-1-4614-5832-6. http://www.springer.com/978-1-4614-5832-6

Nagy G.J., Gómez-Erache M., and Kay R., 2015, A risk-based and participatory approach to assessing climate vulnerability and improving governance in coastal Uruguay. In: B. Glavovic, R. Kay, M. Kelly, A. Travers (Eds.), Climate change and the coast. Building resilient communities. CRC Press / Taylor & Francis, London. ISBN: 978-0-415-46487-1
http://dx.doi.org/10.1201/b18053-23

Nagy G.J., Seijo L., Verocai J.E., and Bidegain M., 2014a, Stakeholders' climate perception and adaptation in coastal Uru-guay.International Journal of Climate Change Strategies and Management, 6(1):63-84. DOI: 10.1108/IJCCSM-03-2013-0035.
http://dx.doi.org/10.1108/IJCCSM-03-2013-0035

Nagy G.J., Muñoz N., Verocai J.E., Bidegain M., and Seijo L., 2014b, Adjusting to current climate threats and building alternative future scenarios for the Rio de la Plata coast and estuarine front, Uruguay. Journal of Integrated Coastal Zone Management, 14(4):1-15. DOI: 10.5894/rgci472.
http://dx.doi.org/10.5894/rgci472

Nagy G.J., Severov D.N., Pshennikov V.A., De los Santos M., Lagomarsino J.J., Sans K., and Morozov E.G., 2008a, Rio de la Plata estuarine system: Relationship between river flow and frontal variability. Advances in Space Research, 41(11):1876-1881. DOI: 0.1016/j.asr.2007.11.027.

Nagy G.J., Bidegain M., Caffera R.M., Norbis, W., Ponce A., Pshennikov V., and Severov D.N., 2008b, *Fishing strategies for managing climate variability and change in the Estuarine Front of the Rio de la Plata (2008),* 20:353-370. In: Leary, N., J. Adejuwon, V. Barros, I. Burton, J. Kulkarni and R. Lasco (eds), Climate Change and Adaptation, Earthscan, London, UK. ISBN: 978-1844074709

Nagy G.J., Gomez-Erache M., and Fernandez V., 2007, El aumento del nivel del mar en la costa uruguaya del Río de la Plata: Tendencias, vulnerabilidades y medidas para la adaptación. Medio Ambiente y Urbanizacion (ISSN: 0328-0306), 67(1):77-93, Buenos Aires, Argentina. http://www.ingentaconnect.com/content/iieal/meda/2007/00000067/ 00000001/art00006
http://dx.doi.org/10.1007/978-94-017-2464-7_10

Nagy G.J., Ponce A., Pshennikov V., Silva R., Forbes E.A., and Kokot R., 2005, Desarrollo de la capacidad de evaluación de la vulnerabilidad costera al Cambio Climático: Zona Oeste de Montevideo como caso de estudio. In: B. Barros, A. Menéndez, G.J. Nagy, (eds.), El Cambio climático en el Río de la Plata, 17:173–180, AIACC, CIMA/CONICET, Buenos Aires, Argentina. http://www.cima.fcen.uba.ar/~lcr/libros/ Cambio_Climatico-Texto.pdf

Nagy G.J., Pshennikov V., and Robatto P., 2003, Monthly variability of salinity at Montevideo, Rio de la Plata´s frontal zone, in response to ENSO fluctuations and to the River Uruguay Flow (1998-2000). Contribution Nº 1 in The Rio de la Plata: Research to Manage the Environment, Fish Resources and the Fishery in the saline front. In: Vizziano D, Puig P, Mesones C, Nagy GJ (Eds). EcoPlata, Programme, Montevideo, Uruguay. ISBN 9974-7646-1-0

Nagy G.J., Gómez-Erache M., López C.H., and Perdomo A.C., 2002, Distribution patterns of nutrients and symptoms of eutrophication in the Rio de la Plata river estuary system. Hydrobiología, 475/476:125-139. DOI: 10.1007/978-94-017-2464-7_10.

Nagy G.J., 2000, Uruguay estuarine systems: The frontal zone of the Río de la Plata system, Uruguay/Argentina. In: Smith, S.V, Dupra, V., Marshall-Crossland, J.I.,and Crossland, C.J. (eds.), Estuarine systems of the South American region: carbon, nitro-gen and phosphorus fluxes, pp.40-43, LOICZ Reports & Studies No. 15, LOICZ-UNEP, Texel, The Netherlands. ISSN: 1383-4304.
http://www.loicz.org/imperia/md/content/loicz/print/rsreports/15report.pdf

Nagy G.J., Martínez C.M., Caffera R.M., Pedrosa G., Forbes E.A., Perdomo A.C., and López Laborde J., 1997, Marco hidrológico y climático del Río de la Plata (The Hydrological and Climatic Setting of the Rio de la Plata). In: P.G. Wells & G. R. Daborn (eds.), The Río de la Plata: An Environmental Over-view. An EcoPlata Project Background Report. pp.17-70, Dalhousie University, Halifax, Nova Scotia, Canada. ISBN: 0770328520. http://www.ecoplata.org/wp-content/

NOAA, 2015, Oceanic Niño Index. http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ ensoyears.shtml

Ortega L., Celentano E., Finkl C.and Defeo O., 2013, Effects of climate variability on the morphodynamics of Uruguayan sandy beaches. Journal of Coastal Research, 29(4):747–755. DOI:10.2112/JCOASTRES-D-13-00003.1
http://dx.doi.org/10.2112/JCOASTRES-D-13-00003.1

Panario D., Gutiérrez O., and Piñeiro G., 2008, Propuesta técnica para la conservación recuperación de la playa del Buceo y playas certificadas de Montevideo. Informe final. Montevideo, Uruguay. doi:10.13140/RG.2.1.2508.8725.

Pasta D.J., 2009, Learning When to Be Discrete: Continuous vs. Categorical Predictors, Paper 248–2009, Washington D.C, SAS Global Forum, Statistics and Data Analysis. https://scholar.google.com/citations?user=0gwKxRgAAAAJ&hl=es&oi=sra

Perillo G.M.E., 1995a, Geomorphology and sedimentology of estuaries: an introduction. In: Perillo GME (ed) Geomorphology and sedimentology of estuaries, Elsevier Science BV Amsterdam, pp 1–16. http://dx.doi.org/10.1016/S0070-4571(05)80021-4

Perillo G.M.E., 1995b, Definition and geomorphologic classifications of estuaries. In: Perillo GME (eds) Geomorphology and sedimentology of estuaries, Elsevier Science BV Amsterdam, pp 17–47 http://dx.doi.org/10.1016/S0070-4571(05)80022-6

Pescio A., Martín P.B., and Dragani W., 2015, Wind speed trends over the southwestern Atlantic Ocean, between 33° and 50°S. International Journal of Climatology, First published: 27 April 2015. DOI: 10.1002/joc.4348 http://dx.doi.org/10.1002/joc.4348

Reichler T., 2009, Changes in the Atmospheric Circulation as Indicator of Climate Change. In Letcher T.M., (ed.), Climate Change: Observed impacts on Planet Earth, The Netherlands, 2009, pp. 145-164. ISBN: 978-0-444-53301-2 , Elsevier BV, http://www.elsevier.com/locate/permissionusematerial http://dx.doi.org/10.1016/B978-0-444-53301-2.00007-5

Roberts, E., and Andrei S., 2015, The rising tide: migration as a response to loss and damage from sea level rise in vulnerable communities. Int. J. Global Warming, Vol. 8, No. 2:258-273. DOI:10.1504/IJGW.2015.071965 http://dx.doi.org/10.1504/IJGW.2015.071965

Simionato C.G., Meccia V.L., Guerrero R.A., Dragani W.C., and Nuñez M.N., 2007, Rio de la Plata estuary response to wind variability in synoptic to intraseasonal scales: 2. Currents' vertical structure and its implications for the salt wedge structure. Journal of Geophysic Research. 112, C07005. doi:10.1029/2006JC003815 http://dx.doi.org/10.1029/2006JC003815

Simionato C.G., Vera C.S., and Siegismund F., 2005, Surface wind variability on seasonal and interannual scales over Río de la Plata area. Journal of Coastal Research, 21(4):770–783. DOI: 10.2112/008-NIS.1. http://dx.doi.org/10.2112/008-NIS.1

Syvitski J.P.M., Harvey N., Wolanski E., Burnett W.C., Perillo G.M.E., and Gornitz, V., 2005, Dynamics of the coastal zone. In: *Coastal Change and the Anthropocene: The Land-Ocean Interactions in the Coastal Zone Project of the International Geosphere-Biosphere Programme*. C.J. Crossland, H.H. Kremer, H.J. Lindeboom, J.I.M. Crossland, and M.D.A. Le Tissier, Eds., Global Change - The IGBP Series. Springer, 39-94. http://www.waterencyclopedia.com/Re-St/Sea-Level.html#ixzz3geZIl8vJ

UCS, 2013, Rapidly Rising Seas: What the science tells us. Causes of Sea Level Rise.Union of Concerned Scientists (2013), 7 pp. http://www.ucsusa.org/sealevelrisescience

Verocai J.E., Bidegain M, Gómez-Erache M, and Nagy G.J., 2015**,** Addressing climate extremes in Coastal Management": The case of the Uruguayan coast of the Rio de la Plata System from 1983-2013. International Journal of Integrated Coastal Zone Management (IJCZM)15(1):91-107. http://www.aprh.pt/rgci/pdf/rgci-555_Verocai.pdf.DOI: 10.5894/rgci555. http://dx.doi.org/10.5894/rgci555

Villamizar A., Gutiérrez M.E., Nagy G.J., Caffera R.M., Leal Filho W., 2016, *Climate adaptation in coastal areas of South America: Current trends and Case Studies from Venezuela and Uruguay*. Journal of Climate and Development. D.O.I. 10.1080/17565529.2016.1146120.

Volonte C.R., and Nicholls R.J., 1995, Uruguay and sea level rise: potential impacts and responses. Journal of Coastal Research (ISSN: 0749-0208), SI14:262–284. http://www.jstor.org/stable/25735712

Yang, Z., Wang T., Voisin N., and Copping A.E., 2014, Estuarine response to river flow and sea-level rise under future climate change and human development, Estuarine, Coastal and Shelf Science, 156:1:1-12 http://dx.doi.org/10.1016/j.ecss.2014.08.015

Zhang K., Douglas B.C., and Letherman S.P., 2004, Global warming and coastal erosion. Climatic Change 64:41–58. http://dx.doi.org/10.1023/B:CLIM.0000024690.32682.48