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El Niño driven extreme sea levels in an Eastern Pacific tropical river delta: landward amplification and shift from oceanic to fluvial forcing

Jean-Philippe Belliard¹, Luis Dominguez-Granda², John A. Ramos-Veliz², Andrea M. Rosado-Moncayo², Jorge Nath³, Gerard Govers⁴, Olivier Gourgue¹,⁵, and Stijn Temmerman¹

¹University of Antwerp, Ecosystem Management research group, Antwerp, Belgium.
²Escuela Superior Politécnica del Litoral (ESPOL), Centro del Agua y Desarrollo Sostenible, Faculdad de Ciencias Naturales y Matemáticas, Guayaquil, Ecuador.
³Instituto Oceanográfico de la Armada (INOCAR), Guayaquil, Ecuador.
⁴KU Leuven, Department of Earth and Environmental Sciences, Leuven, Belgium.
⁵Department of Earth and Environment, Boston University, Boston, MA, United States.

Corresponding author: Jean-Philippe Belliard (jean-philippe.belliard@uantwerpen.be)

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Abstract

As greenhouse warming is predicted to intensify the El Niño–Southern Oscillation (ENSO), it is key to understand relationships between the magnitudes and spatial distribution of ENSO events and associated extreme sea levels (ESLs). Current understanding is lacking for river deltas, where human societies and ecosystems are particularly vulnerable to coastal hazards. Using long-term tide gauge records, we report on ESLs during historical ENSO events of different magnitudes, spatial distribution and temporal evolution in the Guayas delta–Gulf of Guayaquil (Ecuador), the largest estuarine system on the Pacific coast of South America and a relevant hotspot for coastal hazards. Here, we found a landward amplification of sea level anomalies during Eastern Pacific El Niño events, with monthly mean values peaking from +43 cm at the open coast to +75 cm in the inner delta, producing among the highest ENSO driven ESLs ever documented. This landward amplification is shown to coincide with a sea-to-land gradient from a predominantly oceanic (thermosteric) to meteorological (fluvial) El Niño contribution to these ESLs, demonstrating the strong coupling between these two forcings of El Niño. Our findings highlight the strong exposure of coastal societies and ecosystems to ENSO driven ESLs and the pressing need for adaptation measures in face of continued global warming.
1 Introduction

Extreme sea levels (ESLs) constitute one of the major impacts of climate change on coastal societies and ecosystems (IPCC, 2019). They are caused by a combination of factors including tides, storm surges, wind waves and swells, and interannual variability in sea levels. With greenhouse warming, ESLs will intensify in frequency and magnitude, leading to increasing hazards in low-lying coastal areas (Rasmussen et al., 2018; Vitousek et al., 2017; Vousdoukas et al., 2018) where human population, assets and valuable ecosystems are concentrated. For instance, coastal flooding in 2100 is estimated to affect up to nearly 5% of the global population and 10% of the global GDP if no adaptation measures are taken (Hinkel et al., 2014).

Interannual ESLs are usually driven by modes of natural climate variability. The largest of all is the El Niño–Southern Oscillation (ENSO) with worldwide influence but strongest impacts in the tropical Pacific where it originates. During the warm phase of ENSO, known as El Niño, sea levels increase in the eastern Pacific by up to 40 cm (Colas et al., 2008) and, at the same time, decrease by similar magnitude in the western Pacific (Becker et al., 2012). This characteristic Pacific-wide zonal sea level seesaw reverses during the cold phase of ENSO, known as La Niña, although with less pronounced ESLs (Widlansky et al., 2015).

These ESLs are caused by coupled ocean-atmosphere dynamical processes which are central to ENSO. In the eastern Pacific, during El Niño, weakened equatorial trade winds associated with eastward-propagating downwelling Kelvin waves trigger a reduced upwelling of cold waters, a deepening of the thermocline and a consequent warming of the subsurface waters. These effects, which can reach as far as the coastal waters of Ecuador and northern Peru during a strong El Niño (Timmermann et al., 2018), cause sea levels to increase via thermal expansion (i.e. thermosteric contribution; Nerem et al., 1999). Additionally, this accumulation of warm waters promotes the development of atmospheric convection, leading to intense precipitation and streamflow, which further affect sea levels off coastal watersheds along the eastern Pacific coast (i.e. meteorological contribution; see J. Bendix et al., 2003; Takahashi, 2004). Conversely, in the western Pacific, these processes cause the thermocline to shoal, leading to cooler waters, reduced precipitation, and lower sea levels (Becker et al., 2012; Hamlington et al., 2016; Merrifield et al., 2012). Despite the global impacts of these phenomena, making faithful and converging model
projections on how ENSO may change under future greenhouse warming remains challenging (Stevenson, 2012), in part due to uncertainties on the future projected equatorial zonal sea surface temperatures (Collins et al., 2010; Watanabe et al., 2012). Nevertheless, recent climate model projections show a tendency for an increase in the frequency and magnitude of extreme El Niño/La Niña with greenhouse warming during the 21st century (Cai et al., 2014, 2015, 2018; Wang et al., 2019), and this may increase the frequency and magnitude of related ESLs (Widlansky et al., 2015).

While studies have quantified ENSO driven ESLs at regional (Barnard et al., 2017; Barrie & Conway, 2002; Blanco et al., 2002; Echevin et al., 2018; Goodman et al., 2018; Merrifield et al., 2012; Ryan & Noble, 2002), Pacific-wide scale (Barnard et al., 2015; Becker et al., 2012; Hamlington et al., 2016), and even global scale (Muis et al., 2018), no knowledge exists on how ENSO driven ESLs are manifested across coastal river deltas, despite their high socio-economic and ecological vulnerabilities to ESLs (Temmerman et al., 2013). Here we analyse multi-decadal tide gauge (TG) records and report on ESLs during historical El Niño events (between 1984 and 2017) in the Guayas delta–Gulf of Guayaquil, Ecuador, which is the largest estuarine system on the Pacific coast of South America, in the region where El Niño impacts are maximal (Reguero et al., 2015). We show that during strong El Niño events, sea level anomalies (SLA) nearly double from the open coast to the inner delta, producing some of the highest ENSO driven ESLs ever documented. This landward amplification of SLA correlates with a sea-to-land gradient from a predominantly thermosteric to a predominantly meteorological contribution to ESL. We finally demonstrate implications of these spatial patterns of ENSO driven ESLs for the flooding exposure of coastal societies and mangrove ecosystems within the Guayas delta–Gulf of Guayaquil.

2 Regional setting

The Guayas delta, located in the southern coastal province of Ecuador (Figure 1), represents a typical example of many tropical coastal areas where valuable wetland ecosystems and intensive socio-economic development are highly vulnerable to ESLs. This delta is home to ca. 3.1 million people, most of which are concentrated in the city of Guayaquil (see Figure 1), Ecuador’s largest population and economic centre. Similar to other cities across the delta,
Guayaquil suffers from floods especially during strong El Niño events (A. Bendix & Bendix, 2006). As a result, Guayaquil ranks fourth among the world’s most vulnerable coastal cities to flood risks, where sea level rise is expected to result in 2050 in an annual average economic loss of about US$ 3 million (Hallegatte et al., 2013). Furthermore, ENSO driven ESLs are expected to impact shrimp aquaculture activities in the region, which provides an annual economic profit of ca. US$ 3.1 million (ICEX, 2019), and the tidal flooding of mangrove forests in the delta, which may strongly affect ecosystem functioning and valuable services such as crab catching, currently representing an economic value of more than US$ 15 million (USAID, 2012).

The Guayas delta is dissected by the Guayas river, which forms at the confluence of the Daule and Babahoyo rivers, runs through the city of Guayaquil, and flows into the Jambelí channel, southeast of Puná Island, that ultimately connects to the Gulf of Guayaquil (see Figure 1). Together, the Guayas delta and Gulf of Guayaquil forms the largest estuarine system on the Pacific coast of South America. Along its course, the Guayas river intersects large areas of mangroves and tidal flats (ca. 4000 km²), of which many have been converted for aquaculture since the 1960s (Hamilton, 2020; see Figure 1). The Guayas delta is a tide-dominated delta. Tides are semi-diurnal and the mean tidal range increases from 1 m at the entrance of the gulf to 3-5 m in the Guayas river (4 m at Guayaquil harbour), before decreasing further upstream, up to 90 and 120 km in the Babahoyo and Daule rivers, respectively. Discharge in the Guayas river varies strongly over the seasons, ranging from 200 m³ s⁻¹ during the dry season (June to November) to 1600 m³ s⁻¹ during the rainy season (December to May) for a year of average precipitation (about 900 mm yr⁻¹; Cifuentes et al., 1996).
3 Data collection and processing

3.1 Tide gauge data quality control

We analysed TG records spanning from 1984 to 2017 at four stations distributed along the sea-to-land gradient across the Guayas delta–Gulf of Guayaquil (Supplementary Information Figure S1; see locations in Figure 1): at the open coast (La Libertad), at the outer delta (Puerto Bolívar), mid delta (Puná) and inner delta (Guayaquil).

Hourly TG records at the outer delta, mid delta and inner delta were provided by INOCAR (the Ecuadorian Oceanographic National Institute) and underwent a series of quality control steps.
controls. A stability test was performed to flag periods characterized by no oscillatory changes in tidal water levels using a time interval corresponding to six data points and a tolerance value of 5 cm. A spike detection test was then performed to flag potential outliers following the method of Williams et al. (2019), i.e. based on the deviation from a polynomial fit applied to the data. Specifically, the deviation from the polynomial was measured using a running median absolute deviation (MAD), with a threshold value of 6 MAD. A final test was performed to flag potential timing errors, by looking at large fluctuations of the residuals, defined as the observed minus predicted tidal water levels. The predicted tides were obtained by performing yearly tidal self-predictions (see hereinafter for further info on the tidal harmonic analysis/prediction method). Whenever a large residual value was detected, the observed series was then shifted to its lagged position showing highest cross-correlation with the predicted series. We did not apply this pre-processing for the hourly TG records at the open coast station as they were obtained and already science-ready quality controlled by UHSLC (University of Hawaii–Sea Level Center; Caldwell et al., 2015).

3.2 Tide gauge data comparison with satellite altimetry

Quality controlled TG records were also compared to satellite altimetry data to assess whether patterns of interannual sea level variability observed on the TG records, and supposedly related to ENSO, were correlated with similar broader scale patterns detected in the altimeter data series. For the purpose of this comparison, both data sources underwent additional processing, following the approach by Prandi & Valladeau, (2016), in order to project them into a common frame and obtain a comparable sea surface height quantity. With regard to the satellite altimetry data, time series of delayed-time (reprocessed) along-track sea surface height anomalies were extracted from satellite tracks within a radius of 250 km from the considered TG station, and were then averaged on a regular 1° by 1° grid. For the TG data, high frequency tidal signals were corrected using the Dermeliac low-pass filter and high frequency atmospheric effects were corrected by withdrawing the Mog2d Dynamical Atmospheric Correction (DAC). The TG data were then averaged over one altimeter cycle and finally referenced against the pre-processed satellite altimetry. Correlation analysis between the pairs of collocated altimetry and TG data showed correlation scores in agreement with the literature (Vinogradov & Ponte, 2011; Supplementary Figure S2-S5).
3.3 Detection of ENSO events

El Niño/La Niña events were identified during the period of the TG records using the combination of two climate indices: Oceanic Niño Index (ONI) and Niño1+2 index, both based on measurements of sea surface temperature anomalies (SSTA).

First, the ONI index, which is a standard indicator used by NOAA for monitoring El Niño and La Niña in the tropical Pacific, was used to identify ENSO events. ONI is defined as a three-month running mean of SSTA calculated from the NOAA extended reconstructed sea surface temperature (ERSST) v.5 dataset in the Niño3.4 region (5°N-5°S, 170°-120°W), with respect to centred 30-year base periods, updated every 5 years. Based on the ONI index, an El Niño (or La Niña) event is present when at least 5 consecutive months show SSTA above (or below) a threshold of +0.5°C (or -0.5°C). The onset and termination of every event was further constrained by using the Niño1+2 index. The Niño1+2 index is defined as monthly SSTA calculated from the NOAA optimum interpolation sea surface temperature (OISST) v.2 dataset in the Niño1+2 region (0°-10°S, 90°-80°W; i.e. eastern equatorial Pacific), being more representative of the timing of SSTA and their absolute values in a region nearby the study area, despite its larger variance.

Nine El Niño and La Niña events were as such identified during the considered period (Figure S6). Yet, not all El Niño/La Niña events were evident in the TG records and the stations did not always provide continuous data. For instance, gaps in TG records for the open coast and mid delta stations as well as for the river gauge stations (see section 3.5) did not allow to analyse the 2015-2016 El Niño event. Therefore, we focused our sea level anomalies (SLA) analysis on four El Niño events for which we had sufficient data coverage: 1986-1987, 1991-1992, 1997-1998 and 2009-2010. These events cover different El Niño types, characterized by either a pronounced warming of the eastern Pacific (EP- or “canonical” El Niño; Yeh et al., 2009), central Pacific (CP- or “Modoki” El Niño; Ashok et al., 2007; Yeh et al., 2009) or a mix of the two (mixed-El Niño; Johnson, 2013), thus capturing ENSO variability in terms of spatial extent, magnitude and temporal evolution. For the sake of comparison, we also analysed SLAs for two La Niña events: 1999-2000 and 2011-2012.
3.4 Computation of sea level anomalies

The quality-controlled hourly TG records were harmonically analysed to reconstruct the predicted sea levels caused by astronomical tides, which were then subtracted from the observed sea levels to determine the residuals, i.e. SLAs (Figure S7).

A tidal harmonic analysis was performed on the quality-controlled hourly TG records to estimate tidal harmonic constituents and their constants (amplitudes and Greenwich phase lags) via a least-square fit method coupled with nodal corrections. Primary diurnal and semi-diurnal, non-linear shallow water constituents (overtides and compound tides) and long-period tidal constituents were estimated; long-period solar annual (SA) and semi-annual (Ssa) constituents were also included to capture the meteorological forcing found at these frequencies, i.e. here caused by seasonal variations in precipitation that affect sea levels. The observed tides were first detrended to remove the long-term SLR component. Then time spans corresponding to neutral periods (outside El Niño/La Niña years) with minimal data gaps were selected and harmonically analysed to resolve tidal constituents and their constants over the length of the input data series. These constants were subsequently used to perform hindcast reconstructions of astronomical tides. To minimise quality loss of the reconstructions, as the year to be reconstructed moves away from the input data series, reconstructions were run for up to three years ahead in time, encompassing the nearest El Niño/La Niña. Then the tidal analysis was reiterated with the next ENSO neutral time span to refresh the harmonic constants used for the next reconstruction of astronomical tides. We performed the tidal analysis using the “UTide” (Codiga, 2011) Matlab package, an unified tidal analysis and prediction framework specifically designed for multi-year and irregularly spaced/discontinuous records.

For every TG station, we tested the performance of the tidal harmonic analysis on time periods for which tidal constituents and constants were previously published, used here as validated series. We also evaluated the quality of the reconstructed astronomical tides by comparing the root-mean-square-differences between the observed and self-reconstructed astronomical tides (see Supplementary Information Table S1). For every tidal cycle at every TG station, we identified the water level at high tide of the reconstructed (HWL_{pre}) and observed (HWL_{obs}) series. Specifically, HWL_{obs} was defined as the maximum water level within ± 2 hours of the time of HWL_{pre}, to handle noise and distortion present in the observed tides. Then, each
local HWL\textsubscript{pre} and HWL\textsubscript{obs} were paired, allowing to calculate the corresponding sea level anomaly (i.e. SLA), yielding:

\[
\text{SLA} = \text{HWL}_{\text{obs}} - \text{HWL}_{\text{pre}}
\]

Therefore, SLA here refers to anomalies at high tide, which best represent the flooding conditions experienced by coastal societies and wetland ecosystems. These SLAs were then classified as occurring either during El Niño, La Niña or neutral periods (Figure S7), based on the climate indices described above. These SLAs, as initially computed, correspond to single temporal point measurements which could be influenced by processes contributing to sea levels on short time scales, in particular storm driven processes. Yet, contribution of storm surges to sea levels is minimal in the study area (Losada et al., 2013), which can be explained by the geographical location of the Guayas delta–Gulf of Guayaquil, as being situated at the western coast of South America near the equator and at the southern limit of the intertropical convergence zone, making it practically free from coastal storms and tropical cyclones. As such, wave processes associated with storms including wave setup are very rare and the relatively shallow and sheltered areas characterizing the study area also contribute to a low exposure to waves.

SLAs were ultimately monthly averaged when compared and tested for relationships against proxies of oceanic forcing of El Niño events (i.e. SSTAs) and meteorological forcing (i.e. river discharge anomalies – QA), consistent with previous studies reporting on El Niño driven SLAs.

3.5 Computation of river discharge anomalies

We computed river discharge anomalies (QA) of the Guayas river for the selected El Niño events, based on upstream daily discharge measurements at several river gauge stations along the Babahoyo and Daule tributaries (see locations in Figure 1), obtained from INAHMI (the Ecuadorian Meteorological and Hydrological National Institute).

We first calculated the monthly mean river discharges for the Babahoyo and Daule tributaries over their measurement periods (1964-2015 and 1982-2015, respectively). Then, for a single El Niño/La Niña event, we computed the river discharge anomaly (i.e. QA) as the difference between monthly mean river discharge during the event and the mean of all monthly
mean river discharges within the two nearest neutral periods before and after the considered event. The computation of QA was then reiterated for every month and all considered El Niño/La Niña events. Ultimately, QA for the Guayas river was calculated by summing up QAs of the Babahoyo and Daule tributaries.

3.6 Computation of tidal inundation of mangrove soils

To estimate changes in flooding exposure of mangrove ecosystems during El Niño or La Niña conditions, we first measured tidal inundation of mangrove soils during neutral conditions using Rugged TROLL 100 pressure sensors (In-Situ Inc.). These pressure sensors were deployed in 2019-2020 in several sites as part of a complementary research project (see locations in Figure 1). These sites encompass both young mangrove forests dominated by the black mangrove (*Avicennia germinans*), and older mangrove forests dominated by the red mangrove (*Rhizophora somoensis*), which are the two main types of mangrove forests found in the Guayas delta.

Absolute pressure recorded by the pressure sensors in the field was corrected for atmospheric pressure, recorded by a Rugged BaroTROLL deployed in a nearby location, and then converted to metres of water depth above the mangrove sediment surface. Then, times of predicted low water levels at the nearby mid and inner delta TG stations were used to truncate the derived water levels per tidal cycle, for which inundation depth, time and frequency statistics were calculated subsequently during neutral conditions. These statistics were then recalculated by accounting for the SLAs per El Niño and La Niña event, as measured in the nearest TG station.

3.7 Statistical analysis

Statistical differences in SLAs between the four TG stations were assessed using one-way ANOVA or the equivalent Kruskal Wallis non-parametric test when assumptions of data normality and variance homogeneity were not met, followed by multiple pairwise comparisons. Regression models were validated by ensuring that the different assumptions underlying multiple linear regression were satisfied. Normality of the residuals was thus assessed using the Anderson–Darling normality test; heteroscedasticity was evaluated visually by plotting the residuals versus regression fits; and autocorrelation structures were assessed by plotting the residuals versus observation orders. Multicollinearity between the independent variables were
assessed by looking at the standard error values of the regression coefficients. Presence of an interaction effect between the independent variables was assessed in two ways: statistically by running multiple regression analyses with and without the interaction term included and evaluating the significance of each regression coefficients, and graphically by looking at the slope of regression lines for different values of the secondary (least significant) independent variable. All statistical methods were carried out with a 95% confidence interval.

4 Results

4.1 Spatial patterns of extreme sea levels across the delta

The EP-El Niño of 1986-1987 and 1997-1998 showed a significant landward amplification of SLAs across the delta (Figure 2a and 2c). Smallest SLAs were systematically measured at the outer delta, with relatively low values (< +7 cm) averaged over the 13-month and 18-month duration of the 1986-1987 and 1997-1998 EP-El Niño, respectively. Monthly mean SLA maxima reached +27 cm and +20 cm, respectively, while maximum SLAs of all single high tides (i.e. 95th percentile) attained +32 cm during these two events. By comparison, largest SLAs measured at the inner delta corresponded with average (± 1 s.d.) values of +24±20 cm and +37±22 cm calculated over the duration of the 1986-1987 and 1997-1998 EP-El Niño, respectively. Monthly mean SLA maxima during these two events were +58 cm and +75 cm, and maximum values of all single high tide SLAs even reached +70 cm and +88 cm, respectively. In contrast, both the mixed El Niño of 1991-1992 and the CP-El Niño of 2009-2010 did not exhibit a significant landward amplification of SLAs across the delta and were characterized by smaller SLAs (Figure 2b and 2d). SLAs also showed contrasting patterns for different La Niña events (Figure 2e and 2f). For example, during the strong 1999-2000 La Niña, SLAs displayed some variations across the delta with average SLA ranging from -23±11 cm at the outer delta to -5±40 cm at the inner delta. SLAs during the moderate 2011-2012 La Niña were more uniform, with average values only varying from -5 to -7 cm between the stations, except for the mid delta station where SLA averaged -15±19 cm.
Figure 2. Box plots of SLAs computed from the TG records at the four stations during the (a) EP-El Niño 1986-1987, (b) Mixed-El Niño 1991-1992, (c) EP-El Niño 1997-1998, (d) CP-El Niño 2009-2010, (e) La Niña 1999-2000 and (f) La Niña 2011-2012. For every event, stations that share the same letter/colour are statistically not significantly different from each other (after running a Kruskal Wallis test followed by multiple pairwise comparisons using Dunn's procedure with Bonferroni correction). The average SSTA over every El Niño/La Niña event duration based on the Niño1+2 index is also displayed.
4.2 Relationships with oceanic and meteorological El Niño forcings

During the EP-El Niño events, periods of highest SLAs occurred simultaneously at all stations, and coincided with periods of high SSTAs and QAs. In particular, during the strong EP-El Niño of 1986-1987, we observe that SLAs rose to their highest values during the initial period of the event, with the strongest response for the inner delta station (Figure 3). A similar pattern was found during the extreme EP-El Niño of 1997-1998 (Figure S9). After this initial peak, SLAs quickly decreased except at the inner station where they decreased much more gradually until June 87. SLAs also showed a secondary lower peak in October 87 at all stations, coinciding with high SSTAs. This concomitance of periods of high SLAs, SSTAs and QAs was not systematically observed for other El Niño types. During the mixed-El Niño of 1991-1992, not all stations showed SLA peaks during periods of maximum QAs and SSTAs, and none during the CP-El Niño of 2009-2010 (Figures S8 and S10).
Figure 3. Temporal evolution of (a) monthly averaged QAs for the Guayas river, (b) monthly SSTAs derived from the Niño1+2 index and (c) monthly averaged SLAs with corresponding ±1 s.d. envelopes at the four stations during the EP-El Niño 1986-1987.

Our analysis shows a sea-to-land gradient from predominantly oceanic El Niño forcing on SLAs at the open coast to meteorological forcing at the inner delta (Figure 4). We find that SSTAs, as a proxy of oceanic (i.e. thermosteric) forcing, were indeed the most statistically significant predictor to explain SLAs at the open coast and outer delta stations (both at p < 0.0001; see Figure 4a and 4b), while QAs, as a proxy of meteorological forcing, were much less significant (p = 0.03 and p = 0.08, respectively). At the outer delta, this relationship is however
less evident as the effect of SSTAs on SLAs was almost absent for SSTAs less than ~+3.5°C. Conversely, QAs emerged as the most significant predictor at the mid and inner delta stations (both at p = 0.005; see Figure 4c and 4d), with SSTAs being in both cases non-significant. Additionally, the regression models were of highest quality at the most seaward (open coast) and landward (inner delta) stations. These results suggest that the observed landward amplification of SLAs across the delta relates to a sea-to-land gradient from a predominantly thermosteric contribution to SLAs in the most seaward (open coast) station to a predominantly meteorological contribution to SLAs in the most landward (inner delta) station. Note that SLAs were only explained by the net effects of SSTAs and QAs, evidenced by the negligible change of slopes of the different regression lines displayed on every scatter plot, thus excluding a potential interaction effect between the independent variables, although testing for this effect gives a statistical significance just above the threshold level at the outer delta. The latter suggests that the effect of SSTAs to SLAs conditioned to the values of QAs may not be completely ruled out at the outer delta.

![Figure 4](image-url)

**Figure 4.** Multiple linear regression of SLAs as the dependent variable, against SSTAs and QAs as the two independent variables, integrating the four analysed El Niño events. For every station,
the most statistically significant predicting variable is displayed in the x-axis and the second as a sequential single-hue colormap, either blue for QA or red for SSTA. Several regression lines are displayed for different fixed values of the second independent variable to visualize the possible presence of an interaction effect between the two independent variables. Significance of every regression model and coefficient of determination $R^2$ are also displayed.

5 Discussion and conclusions

5.1 Comparison with ENSO driven extreme sea levels in the eastern Pacific

Monthly mean SLA maxima reported here (~+75 cm in the inner delta during the 1997-1998 EP-El Niño) are among the highest ENSO driven ESLs ever documented in the literature. Elsewhere on the Pacific coast of the Americas, the 1997-1998 EP-El Niño generated monthly mean SLA maxima ranging from +10-20 cm off northern Chile (Blanco et al., 2002) to +30-40 cm off Peru (Carr et al., 2002; Colas et al., 2008), +20-25 cm off California (Hayward, 2000; Ryan & Noble, 2002) and ~+10 cm off Oregon (Huyer et al., 2002).

In the eastern equatorial Pacific, the increase in sea levels in the open ocean during El Niño is primarily caused by thermosteric changes associated with the eastward-propagating downwelling equatorial Kelvin waves which trigger the warming of subsurface waters (Wyrtki, 1984). For example, the passage of the Kelvin waves in the nearby Galapagos Islands during the extreme 1982-1983 EP-El Niño coincided with large positive SSTAs and consequent SLAs exceeding +35 cm (Wyrtki, 1985). The arrival of the Kelvin waves at the coast of South America causes disruption of coastal upwelling, and even a switch to downwelling when combined with strong wind stress curl anomalies and associated Ekman pumping, as observed during the 1997-1998 EP-El Niño off southern Peru (Halpern, 2002) or the recent 2017 coastal El Niño off southern Ecuador (Echevin et al., 2018). The resulting deepening of the nearshore thermocline, positive SSTAs and associated increased sea levels generated monthly mean SLAs of ~+40 cm along the northern Peruvian coast during the December peak of the 1997-1998 EP-El Niño (Colas et al., 2008). SLAs reported here at the open coast station are of a similar magnitude than those reported in these earlier studies (+42 cm averaged in December 1997; see Figure S9).

This oceanic El Niño forcing interacts with atmospheric processes that become increasingly dominant across the coastal region. The accumulation of warm waters and strong gradients in SSTAs observed off the coasts of Ecuador and Peru during El Niño events moisten and heat the air, favouring meso-scale atmospheric convection and precipitation that are further
pushed towards the coastal plains by the anomalously westerlies. Additionally, the local land-
sea-breeze phenomenon, driven by diurnal differential heating between the land and the sea, and
which is coupled with convection due to thermal upslope winds over the nearby western Andean
slopes, also trigger convection and enhanced precipitation (J. Bendix, 2000; Goldberg et al.,
1987; Horel & Cornejo-Garrido, 1986). Specifically, the coastline configuration of the Gulf of
Guayaquil promotes convergent and divergent patterns of the nocturnal land breeze and the
diurnal sea breeze, respectively. This results in deep convection with maximum rainfall
concentrated in the Gulf during the night and on the surrounding coastal plains and western
Andean slopes during the day (J. Bendix et al., 2003). Moreover, cirrus cloud remainders coming
from the Amazon and that spill over the Andes contribute to intensify deep convection and
rainfall originated by the land-sea-breeze phenomenon (J. Bendix, 2000).

These various mechanisms make the coastal region of Ecuador and northern Peru central
to El Niño impacts, with anomalously high rainfall, being particularly marked in the coastal arid
region of northern Peru (Sechua desert; J. Bendix et al., 2003). During the 1997-1998 EP-El
Niño, precipitation anomalies attained ~+200% in Guayaquil (J. Bendix et al., 2003), resulting in
monthly mean QAs >+1000 m$^3$s$^{-1}$ (+170%) in the Guayas river throughout the rainy season and
beyond (see Figure S9). These high river discharges triggered SLAs in the inner delta which
were almost twice as high as the open coast values. This meteorological forcing dampens
downstream in the delta and has limited effect on sea levels at the outer delta. Yet, oceanic
forcing is also relatively dampened at the outer delta but increases towards the open coast. The
outer delta can be therefore seen as a transition zone of this sea-to-land gradient with a
predominance of oceanic (thermosteric) forcing at the seaward side and meteorological (fluvial)
forcing at the landward side.

Although SLAs across the Guayas delta–Gulf of Guayaquil have shown to be controlled
by this sea-to-land gradient from a predominantly thermosteric to a predominantly fluvial
contribution, relationships found here between SLAs and proxies of these El Niño forcings were
only strong at the downstream and upstream regions, and appeared weaker in the midstream
region. As sea levels in estuarine systems are driven by complex processes, the forcing factors
investigated here may not fully explain variations of the observed SLAs. Additional factors like,
interactions with local bathymetry, elevation of nearby intertidal mangroves and local
streamflows, can all influence water surface dynamics and hence should all be considered to better predict these El Niño driven ESLs at individual stations.

The coupling of El Niño forcings and its coincidence with a landward amplification of SLAs across the delta does not systematically occur for non EP-El Niño events. For instance, the 1994-1995, 2002-2003 and 2006-2007 CP-El Niño events showed rainfall clearly below average in coastal Ecuador (A. Bendix & Bendix, 2006; McPhaden, 2004; Trenberth, 1997). Despite having the highest ONI index value on record, the 2015-2016 mixed-El Niño event only showed near normal precipitation in Ecuador and northern Peru (L’Heureux et al., 2017), a similar pattern found in higher latitude regions such as in northern California, with precipitation even below average conditions in southern California (Barnard et al., 2017; Jong et al., 2018; Zhang et al., 2018). This diversity of El Niño responses is partly explained by differences in the zonal displacement of the Pacific tropical SSTAs, in the Walker circulation and in extratropical teleconnections between EP- and CP-El Niño (Timmerman et al., 2018). Other contributing factors including internal atmospheric variability and interaction of ENSO with other modes of intraseasonal, interannual and decadal variability can also contribute to this diversity (Cai et al., 2020), making model predictions of El Niño impacts challenging.

5.2 Implications for coastal hazards and future recommendations

Despite the difficulty of climate models to realistically simulate present-day mean climate, ENSO properties and associated teleconnections, recent model projections point to the likelihood for an intensification of extreme ENSO events (Cai et al., 2014, 2015, 2018; Wang et al., 2019) and related ESLs (Widlansky et al., 2015) in response to greenhouse warming. This will pose further hazards to low-lying coastal areas where human societies and wetland ecosystems are already exposed to long-term SLR (Vitousek et al., 2017). For wetland ecosystems, such as tidal flats, mangroves and seagrass beds, these intensified SLAs will inevitably increase fluctuations in tidal inundations (Goodman et al., 2018), which are key to their functioning and their highly valued ecosystem services. Tidal inundations affect the rates of carbon uptake and storage into wetland vegetation and soils (Ouyang & Lee, 2014), the rates of sediment accretion and therefore the wetland’s capacity to keep up with long-term SLR (Fagherazzi et al., 2012), nutrient cycling and thereby water quality regulation, and habitat suitability to many organisms including commercial fishery species (Barbier et al., 2011).
To illustrate the large impact of ENSO driven SLAs on mangrove inundation in the Guayas delta, we examine tidal inundation measured in 2019 in several mangrove forests across the delta. For an extreme event with average SLAs equivalent to the 1997-1998 EP-El Niño, mean inundation depth at high tide would increase by ~100% and and inundation frequency by 30-57%, respectively (Figure 5), compared to neutral conditions, with the strongest increase for the mangrove forests of the inner delta. Such considerable changes in wetland flooding are expected to promote more accretion of tidally-supplied mineral sediments on coastal wetlands, allowing them to raise their surface elevation in response to SLR (Kirwan et al., 2016). Yet, exceptional flooding during strong El Niño may be so excessive that wetland vegetation could experience die-back events, knowing that some mangrove forests already show signs of submergence under long-term SLR, as observed in the Indo-Pacific region (Lovelock et al., 2015). Conversely, a La Niña similar to the 1999-2000 event would lead to a 12-41% reduction of inundation depth, and 2-22% reduction of inundation frequency (see Figure 5), with the strongest decrease for the mangrove forests of the mid delta. This decreased tidal flooding may lower sediment accretion on coastal wetlands, eventually hindering their capacity to keep pace with long-term SLR, and may increase soil salinities to levels that could cause wetland vegetation die-back, as observed for mangrove forests in northwestern Australia (Lovelock et al., 2017). Bio-geomorphic models that simulate changes in wetland sediment accretion and elevation in response to SLR through feedback mechanisms between tidal inundation, plant productivity and sediment accretion (see Fagherazzi et al., 2012 for a review) should be used to perform projections on how ENSO driven ESLs impact the capacity of wetland ecosystems to keep pace with long-term SLR via sediment accretion.
Figure 5. Mean inundation depths of mangrove soils at high tide for mangrove forests located in the mid and inner delta (see locations in Figure 1). Mean inundation depths in grey result from field measurements conducted in March 2019 - January 2020 using pressure sensors deployed at the respective locations. In red and blue are expected mean inundation depths given average sea level anomalies representative of the EP-El Niño 1997-1998 and La Niña 1999-2000, respectively. Percent numbers indicate corresponding inundation frequencies.

Coastal societies are on the frontline of flood hazards associated with SLR, especially in deltas where natural and/or anthropogenic subsidence can substantially add up to the local relative SLR. Half of the world’s top 20 coastal cities vulnerable to flooding are indeed prone to subsidence (Hallegatte et al., 2013), including the city of Guayaquil, which has partly expanded over former, compressible mangrove soils. Flood hazards due to long-term (decades) SLR are further exacerbated by short-term (months) ENSO driven ESLs. For example, during the extreme 1997-1998 EP-El Niño, we show that Guayaquil experienced an equivalent SLR of ~40 cm averaged over the event duration (i.e. 18 months). This magnitude is such that if a comparable El Niño would be superimposed onto the mid-century projected SLR under the RCP4.5 scenario (IPCC, 2019), resulting sea levels would attain the end-of-century RCP4.5 SLR projections (Table 1). This also shows that the monthly mean SLA maximum of +75 cm recorded during the 1997-1998 EP-El Niño at Guayaquil already surpassed the projected mean SLR by 2100 under this SLR scenario. Reguero et al., (2015) showed that the flooding resulting from such El Niño added to the mid-century SLR projections would expose 30% more of the population of Ecuador,
Peru, Panama, El Salvador, Guatemala and Costa Rica, as compared to exposure under SLR alone. Moreover, the 1997-1998 EP-El Niño added to the end-of-century RCP4.5 SLR projections would even exceed the end-of-century SLR projections under the RCP8.5 scenario (Table 1), and would result in more inhabitants exposed to coastal flooding, with the highest exposure in Ecuador (Reguero et al., 2015).

**Table 1.** Regional projections of relative sea level rise (RSLR) in meters by mid-century (i.e. 2050) and end-of-century (i.e. 2100) relative to the baseline period 1986-2005 under the SROCC RCP4.5 and RCP8.5 scenarios, and with superimposition of the 1997-1998 EP-El Niño driven ESLs (ESL Niño 97'). Median values and uncertainties ranging from 5% and 95% (in brackets) are reported. In addition to steric and barystatic sea level contributions, the SROCC regional RSLR projections include glacio-isostatic adjustments (being negligible in Guayaquil) and Earth’s gravitational, rotational and deformation effects. As no precise geodetic measurements are available in the Guayas delta, a local land subsidence rate of 2 mm/yr was used in agreement with Nicholls et al. (2021). ESL Niño 97' corresponds to the average SLA over the event duration recorded at the inner delta (Guayaquil) TG station.

<table>
<thead>
<tr>
<th>Forcing</th>
<th>Mid-century</th>
<th>End-of-century</th>
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<tbody>
<tr>
<td></td>
<td>RCP4.5</td>
<td>RCP8.5</td>
</tr>
<tr>
<td>RSLR</td>
<td>0.32 (0.23–0.40)</td>
<td>0.35 (0.26–0.44)</td>
</tr>
<tr>
<td>RSLR + ESL Niño 97'</td>
<td>0.72 (0.63–0.80)</td>
<td>0.75 (0.66–0.84)</td>
</tr>
</tbody>
</table>

Additionally, we demonstrate here that, during strong El Niño, coastal exposure can differ considerably depending on the location within a coastal setting. In the Guayas delta–Gulf of Guayaquil, human settlements at the open coast are impacted by ESLs primarily driven by oceanic forcing, while population centres more inland in the delta are impacted by ESLs primarily driven by meteorological forcing, and are likely to be more vulnerable to flood risks as evidenced by the strong landward amplification of SLAs shown in this study. Similar El Niño responses may manifest in other estuarine systems bordering the tropical coast of Latin America and connected to large terrestrial watersheds. Yet, impacts can strongly differ between El Niño events given their diversity in magnitude, spatial distribution and temporal evolution with repercussions on tropical and extratropical teleconnections. Pursuing modelling efforts should be thus carried out on improving simulations of ENSO diversity and teleconnection patterns and intensity at regional scales, to better identify low-lying coastal areas prone to ENSO induced flood risks. Assessments on future exposure of delta cities to interannual ESLs should also consider this landward amplification of SLAs by relying, where possible, on several
measurements across deltas and other estuarine systems to better constrain estimates. With the growing climate modelling evidences for a projected intensification of extreme ENSO events due to greenhouse warming (Cai et al., 2014, 2015, 2018; Wang et al., 2019), coastal exposure to ESLs may attain unprecedented risk levels. Our results call for further in-depth studies on ENSO related coastal hazards and adaptation measures in response to continued climate change.

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Data availability

ONI and Niño1+2 climate indices data sets are freely available from the NOAA (National Oceanic and Atmospheric Association) ESRL Physical Sciences Division at: https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php, and https://www.psl.noaa.gov/data/timeseries/monthly/NINO12/ respectively. Delayed-time (reprocessed) along-track sea surface height anomalies data sets from the TOPEX-Poseidon, Jason1 and Jason2 altimetry missions are freely available from the CMEMS (Copernicus Marine Environment Monitoring Service) at: https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=SEALEVEL_L_GLO_PHY_L3_REP_OBSERVATIONS_008_062. Raw tide gauge data obtained from INOCAR and river discharge data obtained from INAHMI are available upon request to the respective official institutions. Tide gauge data obtained from UHSLC (University of Hawaii–Sea Level Center; Caldwell et al., 2015) are openly available at: http://uhslc.soest.hawaii.edu/data/?rq. Data used to support the findings of this study are
available through the Zenodo data repository at the following link:

http://doi.org/10.5281/zenodo.4479934. This includes the source codes to perform the analysis on the raw tide data, the processed data that are reported and represented in figures in the manuscript and the scripts to generate these figures (Belliard et al., 2021).

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