

Systematic Review

A Systematic Review of Oceanic-Atmospheric Variations and Coastal Erosion in Continental Latin America: Historical Trends, Future Projections, and Management Challenges

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Abstract: The intricate interplay of oceanic-atmospheric variations has intensified erosive processes on sandy beaches in recent decades, with climate change expected to exacerbate these impacts in the future. Projections for the southern Atlantic and Pacific regions of continental Latin America predict increased extreme events and heightened impacts on sandy beaches, highlighting disparities in studies addressing coastal erosion and its causes. To address these risks, a systematic review is proposed to analyze historical trends and projections, aiming to inform local-level studies and management strategies for at-risk coastal communities. Reviewing 130 research papers, insights reveal the influence of climatic events like El Niño and La Niña on coastal dynamics, as well as the effects of storm intensification and extreme events such as high-intensity waves and storm surges on Latin American coasts, resulting in ecosystem, economic, and infrastructure losses. Projections indicate a rise in the population inhabiting Low Elevation Coastal Zones (LECZ) by the century's end, emphasizing the urgent need for effective management and planning. Community engagement in erosion monitoring and adaptation programs is crucial for addressing these challenges and developing robust, sustainable, long-term adaptation strategies. This study aims to enhance the understanding of coastal erosion in Latin American communities addressing future coastal risks.



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Keywords: climate teleconnections; coastal hazards; coastal community challenges; coastal erosion; projected oceanic-atmospheric variations

1. Introduction

Coastal erosion poses a growing challenge for Latin American coastal communities, driven by natural forces and exacerbated by variations in coastal dynamics, causing significant economic losses, and endangering coastal populations [1,2]. Climate change can amplify the drivers of coastal erosion, with the extent and nature of these effects varying depending on specific environmental factors. For instance, rising sea levels, altered wave patterns, and extreme events increase pressure on coastal communities and economies [3,4]. Climate change alters extreme weather phenomena, potentially leading to unprecedented extremes [5]. Additionally, sea-level rise could result in the loss of thousands of km² of coastal land globally during the 21st century, forcing millions of people to migrate [6,7]. The narrowing of beaches due to “coastal squeeze” reduces beaches’ adaptability to dynamic changes and extreme events [8]. According to Lincke et al. (2022) [9] the risk of coastal flooding is mainly driven by two factors: socioeconomic development and relative sea-level change. Socioeconomic development has increased coastal exposure due to population growth and assets in coastal areas, while sea-level change has expanded potential floodplains.

Furthermore, integrating the effects of El Niño-Southern Oscillation (ENSO) cycles into coastal management plans is crucial. ENSO induces variations in sea surface temperatures in the eastern tropical Pacific Ocean, leading to warming (El Niño) and cooling (La Niña)

phases. These events are associated with elevated sea surface temperatures in the tropical Atlantic due to reduced northeasterly trade winds [10]. El Niño events often necessitate short-term mitigation measures, coinciding with heightened cyclone activity and increased water levels, which impact low-lying coastlines and intensify erosive processes (leading to shoreline loss), such as heightened water levels, increased wave magnitude (including height, energy, and direction), and reduced sediment supply [11–13]. These changes in marine conditions can also increase wave energy and alter wave direction, exacerbating erosion, particularly on sandy beaches. Climate change amplifies El Niño impacts, especially affecting Pacific coastal regions [12,14]. Therefore, assessments in highly impacted coastal areas should account for climate change's impact on ENSO and other climatic phenomena such as Pacific Decadal Oscillation (PDO). It is also essential to evaluate climate change's role in local sea-level rise and changes in the intensity and frequency of extreme events [15,16].

Coastal hazards, combined with poor planning and socioeconomic challenges, lead to severe consequences like loss of life, loss of property, and economic losses [17]. Although flooding and coastal erosion are the primary impacts observed, with additional economic repercussions from marine infrastructure damage, studies often overlook these factors in some regions. Some studies focus solely on sea-level rise, neglecting variations in wave systems or cyclonic surges, which are significant drivers of coastal erosion and are also affected by climate change [8].

Effective coastal risk management in Latin America faces challenges due to insufficient local data and limited understanding of coastal dynamics. Addressing the root causes and socioeconomic effects of erosion requires collaboration between authorities and scientists to formulate comprehensive solutions [18].

Coastal communities, often economically constrained, depend on agriculture and fishing, which are threatened by sea-level rise and coastal hazards. Deterioration of coastal ecosystems, crucial for protection and resources, is threatened by changes in marine dynamics and coastal urban sprawl, increasing vulnerability [17,19,20]. Safeguarding these communities and conserving coastal resources relies on understanding and addressing the interplay between oceanographic–atmospheric processes and coastal erosion in Latin America.

The aim of this systematic review is to explore the historical evolution and projected trends of oceanic–atmospheric variations related to coastal erosion in sandy coastlines in continental Latin America, alongside addressing the challenges posed by coastal degradation. These variations have both direct and indirect impacts on processes leading to shoreline loss, as patterns in oceanic and atmospheric conditions influence dynamics and processes in coastal regions. For instance, sea-level rise, exacerbated by glacier melting due to global warming and ocean thermal expansion, has endangered coastal communities, necessitating their relocation to new areas. Additionally, higher sea surface temperatures provide more energy for the formation and intensification of storms, cyclones, and hurricanes, accompanied by intense precipitation, resulting in more powerful waves penetrating further inland and affecting vulnerable communities. These effects can be exacerbated by geomorphological and bathymetric characteristics near coastlines, as well as by human activities impacting the coastal landscape.

The research question guiding this review is: how do oceanic–atmospheric variations influence coastal erosion in continental Latin America over time, and what are the implications for developing effective future management and adaptation strategies? Given the disparity in studies addressing physical processes in coastal areas that face similar risks, the results offer insights into historical variations leading to impacts such as those from extreme events. Furthermore, the review will address trends of these variations for a high-emission scenario, where impacts are expected to be greater in affected areas, and previously low-risk areas will also be affected. Additionally, the need for greater participation of at-risk coastal communities, alongside increased synergy between authorities and local scientific communities, is discussed.

2. Systematic Review Process

The methodology for the systematic review (Figure 1) follows the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines, ensuring a focused literature search [21–23]. Conducted in October 2023 using the Scopus database, it employed a search equation developed from global publications on oceanic–atmospheric variation and coastal erosion. Boolean operators and word truncation refined search queries, with non-impactful keywords removed during preliminary revision.

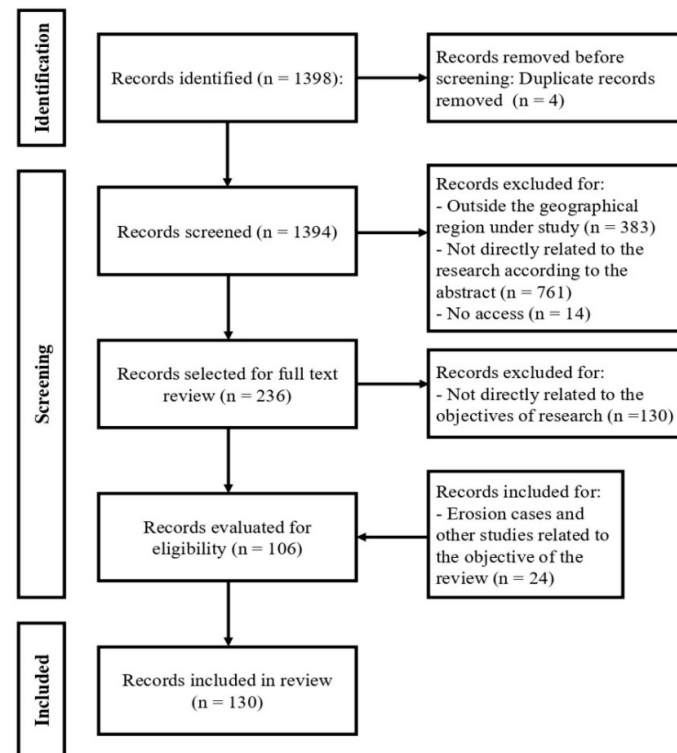


Figure 1. Flowchart of the records-selection-process methodology according to PRISMA guidelines.

The keywords equation used in the Scopus database were as follows: TITLE-ABS-KEY("Projected chang*" OR "Global chang*" OR "Teleconnection patterns" OR "Climate teleconnection*" OR "Climate Change" OR "Climate forcing" OR "Wave climate" OR "Wave climate projections" OR "Wind-wave climate" OR "Ocean-atmosphere" OR "El Niño-Southern Oscillation" OR "ENSO" OR "Meteo-oceanographic" OR "Atmospheric conditions" OR "Atmospheric patterns" OR "Oceanographic dynamic*" OR "Pacific Decadal Oscillation" OR "PDO" OR "Atlantic Multidecadal Oscillation" OR "AMO") AND ("Coastal erosion" OR "Beach erosion" OR "Shoreline erosion" OR "Coastal hazard*" OR "Coastal impact*") AND ("America" OR "Caribbean" OR "Latin America" OR "Central America" OR "South America").

The study's selection criteria encompassed all document types in the Scopus database, limited to English and Spanish documents. Initially, 1398 records were identified, with 1394 reviewed for compliance. After applying exclusion criteria, 236 records were evaluated for eligibility, with 106 focusing on oceanic–atmospheric variations and erosion processes. A total of 24 records were included, addressing the challenges faced by coastal communities exposed to risks, specifically those derived from coastal erosion influenced by extreme events. These records also address specific cases of erosion on sandy beaches.

3. Global and Regional Trends of Ocean–Atmospheric Variations: The Case of Latin America

3.1. Climate Mode and Teleconnections

Climate change adversely affects coastal areas globally, particularly those with low elevation, where significant variations in wave systems occur under different concentration scenarios known as Representative Concentration Pathways (RCPs). These pathways represent various levels of greenhouse gas concentrations in the atmosphere, which subsequently influence the extent and impact of climate change. These impacts are not solely attributable to climate change but are also influenced by regional climatic patterns that trigger meteorological phenomena, leading to intense waves, high tides caused by storm surges, floods, and coastal erosion. In coastal regions of Mexico, and Central and South America, atmospheric patterns and long-distance climate anomalies known as teleconnections significantly impact coastal areas of the Pacific and Atlantic Oceans, causing coastline fluctuations over interannual and multidecadal periods [10,24,25].

Variations in wave systems and sea-level rise in global ocean basins may result from climatic modes, climate teleconnections, or climate change. However, identifying the predominant cause in specific regions remains a research challenge. According to [26], large-scale variability complicates the discernment of the causes of an impact, as it could result from long-term changes associated with global warming, internal variability linked to climate cycles like El Niño–Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO) (Figure 2), and changes in climate variability modes associated with climate change. Despite the observed increase in the intensity of climate events like El Niño in the central equatorial Pacific, this rise does not appear directly linked to a general increase in sea surface temperatures [26,27]. Additionally, Palanisamy et al. (2015) [28] suggest that the recent sea-level rise in the western tropical Pacific region could be attributed to notable internal variability, exacerbated by strengthened trade winds, possibly influenced in part by anthropogenic forcing.

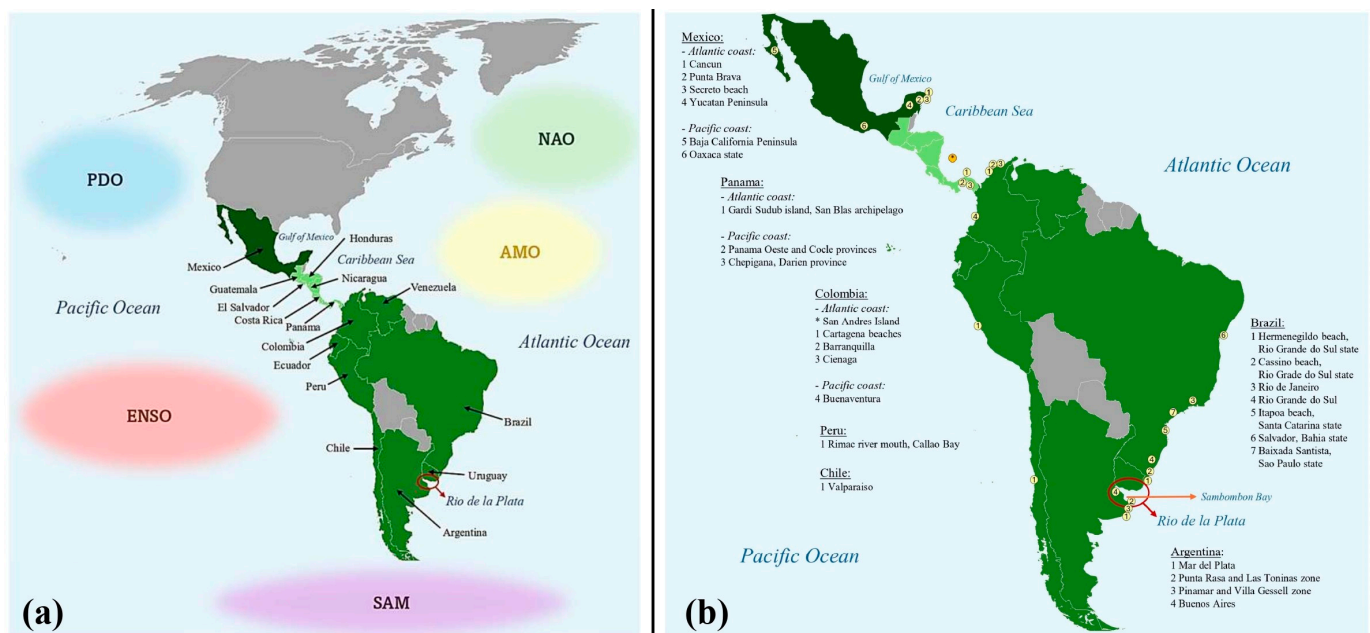


Figure 2. (a) Climate modes and teleconnection patterns; (b) points of interest mentioned in the different sections. Base map obtained from Microsoft PowerPoint database.

The Pacific Ocean interacts with various climatic phenomena, notably ENSO, which significantly impacts Latin America [29]. Extreme weather phenomena are most pronounced during the warm phase, with events classified as weak (W), moderate (M), strong (S), or very strong (VS) occurring cyclically [30,31]. Climate change may increase the

frequency of extreme El Niño events, heightening warm and dry conditions and Eastern Pacific weather events [32].

During the El Niño phenomenon, warm temperatures near the coasts of Peru induce changes in the climate of the eastern equatorial Pacific, triggering more frequent and intense storms along with stronger winds that influence wave systems. However, it has been identified that along the Colombian Pacific coast during La Niña, both wind speeds and conditions associated with significant wave heights from wind-driven waves, swell, and combined significant wave heights are greater for most of the time compared to El Niño [33–35]. ENSO phases influence wave systems along the Eastern Pacific coasts, with wave power increasing during El Niño in some areas and decreasing in others [24,36]. In winter, El Niño impacts the tropical northeast, reducing trade winds and intensifying wave activity, while in summer it affects the tropical northwest, increasing tropical cyclone activity and extreme waves [35,37]. Tropical Atlantic temperature, linked to ENSO, affects La Niña conditions in the North Tropical Atlantic, altering trade winds and storm intensity [10,34,38,39]. Along the Colombian Caribbean coast, trade wind speed varies seasonally during El Niño and La Niña, with higher values in certain seasons [40].

Interest in understanding the impacts of the El Niño-Southern Oscillation (ENSO) phenomenon on coastal areas has grown due to its global influence on climatic patterns. According to Oderiz et al. (2020) [24], ENSO analysis employs climatic indices that include measurements such as sea-level pressure like the Southern Oscillation Index (SOI), sea surface temperatures (i.e., Niño 3.4), Outgoing Longwave Radiation (OLR), and wind measurements or other parameters, often combining variables. For more accurate analyses, indices such as wave power, ONI (Oceanic Niño Index), MEI (ENSO Modoki Index) and, to a lesser extent, Niño 3.4 are used due to their ability to provide robust results and a more accurate representation of the phenomenon.

The phases of ENSO, especially during El Niño, cause significant climatic impacts in coastal areas, influencing global climate and affecting precipitation and weather events worldwide. During the positive phase of El Niño, the weakening of the trade winds shifts the energy flow northward below 20° S, resulting in a clockwise rotation along the Pacific coast of Mexico [10,41]. This leads to floods and mudflows in Peru, shaping dry coastal areas. Ecuador suffered severe impacts during the 1997–1998 El Niño, with intensified waves, rising sea levels, and coastal erosion, as did the Atlantic coasts of Colombia and the Rio de la Plata area between Argentina and Uruguay, especially in low-lying areas [42]. Nicaragua, Costa Rica, and Panama face coastal flooding, erosion, and saline intrusion in flat coastal plains [32]. Southern Brazil experiences intensified south and southeast waves and changes in sediment transport during El Niño, causing erosion and beach retreat in specific “hotspot” areas [29,43]. Conversely, La Niña led to hydrocoral loss on Panama’s coasts due to erosion during low tide events in 1988–1989 and 1993 [44].

In addition to ENSO, the Southern Annular Mode (SAM) is another significant driver of climate variability affecting various Latin American coasts. SAM influences temperature and precipitation in southern South America, correlating with sea surface warming in tropical latitudes, and heightened wave events in the southern Pacific at low latitudes [34,37,41]. A trend toward the positive SAM phase, possibly due to anthropogenic influence and climate change, has been observed in recent decades [27,45]. During December–January season, higher atmospheric pressures at high and low latitudes, especially on the coasts of the Eastern Pacific, reflect this trend, affecting wind conditions and leading to extreme waves. However, during the El Niño phase of this season, alterations in atmospheric circulation weaken pressure gradients in the southeastern Pacific Ocean region, potentially due to SAM’s influence on the position and intensity of the subtropical and Polar Jet Streams in the southern hemisphere [46,47]. Variations in the subtropical Jet Stream may also affect precipitation patterns and cold front propagation in southern Brazil [48].

El Niño and La Niña can intensify when coinciding with warm and cold phases of the Pacific Decadal Oscillation (PDO), which oscillates approximately every 20–30 years and influences regional trends and global mean sea level. During the warm PDO phase,

the western and central North Pacific regions remain cool, while sea surface temperatures increase in the Eastern Pacific. Conversely, during the cold PDO phase, temperatures decrease in the Eastern Pacific [29,33,41,49,50]. Recent decades have shown a negative PDO trend, suggesting a possible reduction in future extreme events [45]. At the regional level, the warm PDO phase leads to higher temperatures in northern South America, and to drier periods in the southern region, affecting precipitation variability. The impacts of the PDO are similar to those of ENSO but with less intensity. However, when both climate modes coincide, the effects of ENSO can be enhanced or diminished by the PDO, depending on their phase concurrence or inversion [25].

In the Atlantic, the Atlantic Multidecadal Oscillation (AMO) influences the climate of both the North and South Atlantic, affecting precipitation in northeastern Brazil and the formation of hurricanes [41,51]. During the warm AMO phase, there is an increase in the frequency of lower-intensity hurricanes in categories 1 and 2. Spanning a sea surface temperature oscillation of 60 to 90 years, the AMO differs from ENSO and PDO. When ENSO and AMO are in opposite phases, the effects of ENSO are intensified in the South Atlantic; for example, the warm AMO phase enhances dry periods in northeastern Brazil during La Niña [25,41,52].

ENSO and the North Atlantic Oscillation (NAO) significantly influence wave systems and wind patterns in the Caribbean region, impacting the coasts of Colombia and other coastal areas [40].

3.2. Oceanic-Atmospheric Variations and Projections

Over the past 150 years, greenhouse gas (GHG) emissions have accelerated climate change, contributing to increased occurrence and intensity of extreme weather events and rising sea levels in different regions of the world [53]. Therefore, to understand and predict how these changes will evolve and what negative impacts they may generate, General Circulation Models (GCMs) have been used. These models allow for the projection of future scenarios and the analysis of the effects of climate change globally [54]. However, utilizing these models requires expert judgment in the selection process of climate models and the consideration of factors such as ocean thermal expansion and glacier melting, which play a significant role in projections such as those related to sea-level rise [55]. Limitations of GCMs are associated with the resolution and simplifications used for representing climatic processes [56,57]. Therefore, to address these limitations, downscaling techniques are employed to obtain more detailed information at a regional scale [27,49,58].

In the analysis of climate projections based on General Circulation Models (GCMs), two approaches can be utilized: statistical scaling models and dynamic scaling models. Statistical models, while efficient and bias-reducing, require predictor and predictand data for a lengthy period and assume the persistence of past statistical relationships into the future, potentially resulting in an underestimation of extreme values. Additionally, their spatial resolution and representativeness depend on observational reference data. Conversely, dynamic models more accurately replicate the physical processes projected by GCMs, rendering them valuable in regions lacking available observations. Nonetheless, they necessitate greater computational resources and may require adjustments [8,56,58]. Generally, dynamic scaling is employed to model the impacts of climate change at a regional scale by refining data from large-scale models to smaller scales with higher resolution [49,59]. Furthermore, challenges to regional-scale projections arise from internal climate variability, including climate mode such as El Niño-Southern Oscillation (ENSO), which poses difficulties in discerning external signals such as greenhouse gas emissions. Climate models encounter challenges in accurately reproducing this variability, potentially leading to regional projections diverging from observed data [26]. To address this challenge, the Multiple Model Ensemble (MME) technique is employed to mitigate the impact of internal climate variability [28].

Climate change has triggered significant environmental impacts such as sea-level rise, which is associated with the thermal expansion of the oceans and the melting of land

ice [53]. Various studies worldwide have been conducted to identify trends that enable the projection of this rise under different emission uncertainty scenarios of RCPs. However, particularly in the study of sea-level rise, it is necessary to consider regional or local factors that may influence these variations, such as land subsidence, changes in seawater density, effects on ocean circulation, and redistributions of mass on the Earth's surface due to ice melting and changes in land water storage [60–63]. Therefore, according to [64], global projections of sea-level rise depend on three main factors: (1) changes in greenhouse gas emissions, (2) the response of the air and sea surface to higher levels of greenhouse gases, and (3) uncertainty in future rates of thermal expansion and polar ice melting.

The current global sea level is rising at a rate of approximately $\sim 3\text{--}4$ mm/year, but projections suggest it could increase from 0.3 to 2.0 m by the year 2100, depending on the emission scenario [61]. However, there is a 95% probability that the increase will not exceed 180 cm by the year 2100 in the RCP8.5 scenario [65]. By 2050, this is expected to significantly affect the frequency of extreme sea level events in coastal areas. According to Boumis et al. (2023) [66], these events, which result from a combination of mean sea level, tides, and non-tidal residuals due to extreme weather, could increase by 6 to 11 times under the RCP4.5 and RCP8.5 scenarios, respectively [66]. This would result in significant impacts on coastal areas of Latin America and the Caribbean, which are highly vulnerable regions to sea-level rise exceeding 1.00 m in elevation [67]. Therefore, to obtain reliable results on the impacts of sea-level rise in coastal areas at a regional or local scale, it must be addressed through the analysis of relative sea-level rise (RSLR). This considers both the global rise in sea level and local ground movements, including changes in coastal morphology [7,27,61,68]. In regions prone to subsidence events generated by tectonic plate activity, such as the coasts of Chile and Colombia, this type of study becomes especially relevant. Additionally, these studies also include internal sea-level variability due to natural climate patterns such as ENSO cycles, which can cause significant variations on the order of $\pm 10\text{--}20$ cm in sea level at a local scale [28,69]. This can increase risks associated with coastal erosion and flooding, especially along unprotected coasts, as observed water levels may exceed previous expectations [60,70].

Some examples of how regional sea level variations may differ from the global level are evident in the coastal regions of Brazil and the Gulf of Mexico. Along the Brazilian coast, the sea level has increased at a rate of 4 mm/year over the past 50 years, surpassing the global rate of 3.2 mm/year between 1993 and 2010, according to the Intergovernmental Panel on Climate Change (IPCC) [71,72]. However, a study of the southeast coast of Brazil suggests an increase of 7.30 mm/year by the end of the century, differing from the global average rate of 6.1 mm/year for the RCP4.5 scenario [59,72]. In the northern Gulf of Mexico, tide gauge records since 1930 show a relative average sea-level rise ranging from approximately 2.37 mm/year to 3.6 mm/year [73]. These regional increases can deviate by approximately $\pm 30\%$ from the global mean sea level, as evidenced by tide gauge records spanning over 55 years in various regions worldwide, demonstrating both positive and negative trends [62,66].

The risks of erosion and flooding in coastal areas are exacerbated by the occurrence of extreme sea levels. In the future, sea-level rise, together with cyclonic surges, intense waves, and high tides will be of particular concern globally [66,67,69]. One of the main regions where greater impacts are projected is Latin America and the Caribbean, although these regions are already experiencing significant negative impacts (Figure 3). Sea-level rise contributes to higher waves penetrating areas beyond the surf zone, which could lead not only to an increase in coastal flooding events but also to higher erosion rates and challenges in coastal planning. Therefore, the effects of climate change on coastal climate drivers may amplify future variations in sediment transport rates along the coast in the short term, resulting in significant negative impacts on beach profile stability and, consequently, the coastline [4,69,73]. Because of this, the study of wave climate variations has gained significant importance in recent decades, as it plays a crucial role in dynamic sea level elevations, mainly at the local scale, driven by factors such as wind waves and swells.

Along the tropical coasts of western America (mostly between 20° N and 20° S), runup has been projected to contribute significantly, exceeding 30% of the contributions to sea-level variations in the RCP8.5 scenario by the end of the century [62].

At a global level, variations in wave intensity and direction have been observed, which can be generated by regional climate modes, climate teleconnections, or climate change. For example, an increase of approximately 6 kW/m in wave power has been recorded in extratropical regions of the South Pacific (during ENSO± and SAM+ phases, it can vary between 5–10 kW/m) and the South Atlantic (during ENSO+ and SAM+ phases, it can exceed 4 kW/m) over a period between 1985 and 2018 [74]. Internal variability associated with climate phenomena such as ENSO and the Southern Annular Mode (SAM) complicates the attribution of these changes to climate change. According to Camus et al. (2017) [8], limitations in quantifying the impact of climate change on wave climate include the lack of high-resolution data, the need for downscaling models, biases in climate models, uncertainty in the analysis process, and simulating multiple combinations of climate forcing variables, which can result in significant cost and effort.

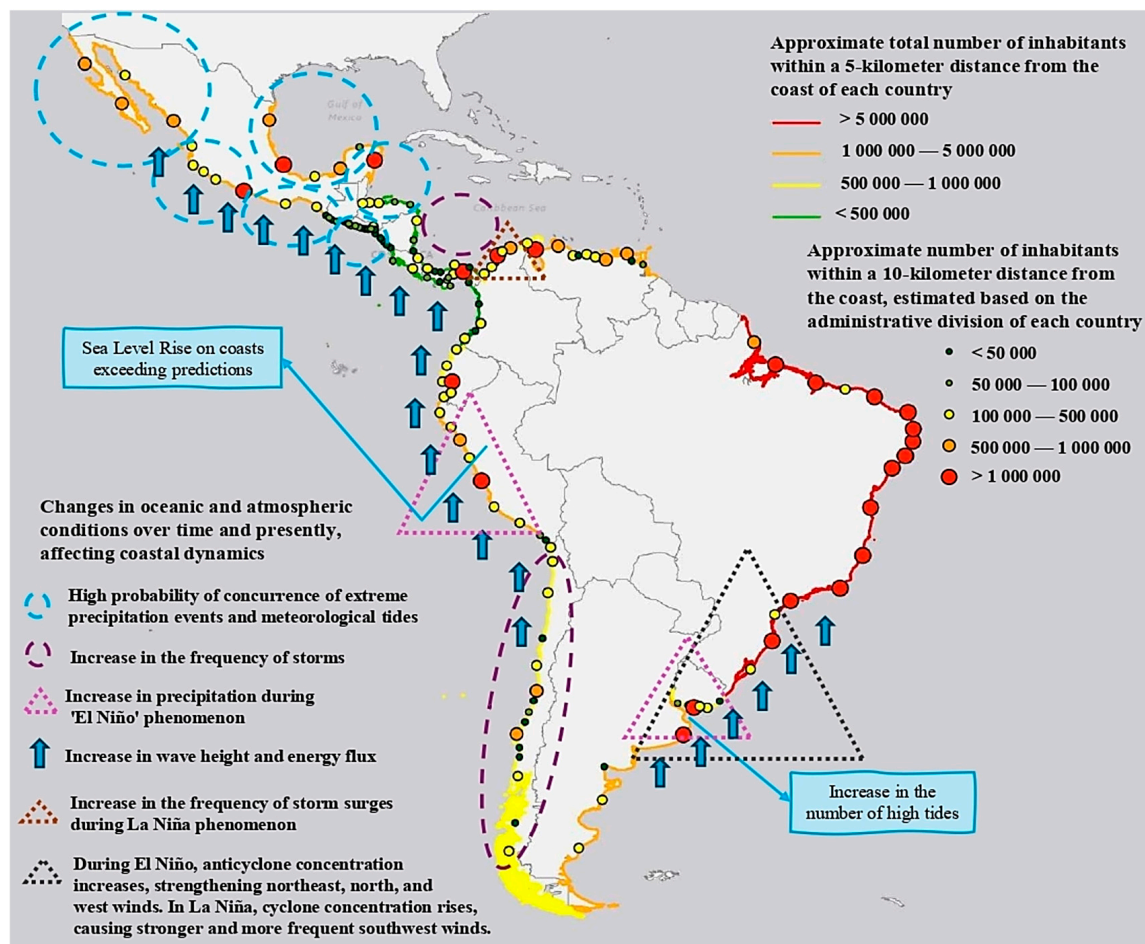


Figure 3. Historical and present variations across the coastal regions of Latin America, incorporating population counts within 5 km (at the national level) and 10 km (at the administrative division level) from the coastline. Population data within the 5 km coastal zone sourced from [75], and within the 10 km coastal zone from [76]. Base map obtained from the ArcGIS-ArcMap database.

In recent years, the spectral approach has gained attention in wave climate studies, providing a more detailed insight into how waves can affect specific regions, particularly in complex wave systems, such as tropical [35,77]. This type of analysis allows for the separate assessment of changes in variables like wave period and direction, contrasting with integrated approaches that may mask variations in individual wave systems. By

analyzing wave systems separately, information on variations in the sign and magnitude of changes in different wave systems is obtained, providing more precise insight into how climate change may influence each. This allows for identifying changes in different wave systems that periodically reach a specific area, which is crucial for evaluating the risks of coastal flooding and erosion. However, this approach faces challenges, such as limited availability of full spectrum data, uneven coverage of spectral buoys, and high data-storage requirements for high-frequency spectra [56,78].

Across various regions worldwide, trends have been observed indicating an increase in wave energy fluxes, particularly in their extreme values, which suggests a potential link with global warming. It is anticipated that by the end of the century under RCP8.5, there will be a heightened frequency of extreme wave events, with a 100-year event occurring at least every 50 years along the subequatorial–tropical eastern Pacific and South Atlantic coasts [34]. Additionally, an analysis of global climate patterns from 1979 to 2019 reveals the significant influence of swell waves in the eastern equatorial region of the Pacific Ocean. From December to February, there is a notable contribution of swells observed across a broad band spanning from the northeastern equatorial Pacific Ocean, between latitudes 30° N and 30° S. This region experiences a distinct rise in wave height, generating areas potentially dominated by swells, with extreme wave height exceeding >2.1 m due to the North Pacific and East Pacific trade winds [47]. Global climate patterns and climate teleconnections also play a crucial role in wave system variability. Climate modes such as SAM and ENSO impact the Latin American region, including the Caribbean [3,10,74]. For instance, the positive phase of the SAM climate mode has been linked to an increase in storm-wave-event duration in the southern hemisphere [79]. Additionally, factors like remote wind systems and local weather conditions, such as hurricanes, significantly affect wave climate, particularly in regions like the Caribbean [80]. The consequences of these phenomena on coastal areas highlight their destructive potential, with significant variations in wave intensity observed during their passage, including a decrease in more distant zones and an increase in those near the hurricane center. This disruption in dynamic equilibrium, particularly evident on sandy beaches, underscores the importance of studying how the evolution of oceanic wave climate and its interaction with the seabed can impact coastal geomorphology in local analyses [24,40]. An estimated 50% of coastlines worldwide are expected to undergo modifications in at least one wave climate variable, such as height, period, or direction, with approximately 40% experiencing changes in all these variables. This includes areas like the western coasts of Central and South America. Changes in the primary wave direction will play a critical role in coastal erosion, affecting around 21% of coastlines globally [4].

Regionally, projections suggest a significant decrease in wave height and energy in the tropical North Atlantic, attributed to reductions in both extratropical waves and those generated by northeast trade winds. Conversely, an uncertain increase in wave height is anticipated in the tropical South Atlantic, driven by projected swells from the Southern Ocean, similar to the trends seen in the tropical–subequatorial Pacific region [4,56]. These findings align with Camus et al. (2017) [8], projecting a rise in wave height in the Tropical Pacific by the end of the century, ranging between 0.06 m and 0.09 m under the RCP8.5 scenario. Results from a study based on data from 1986 to 2005 indicate significant increases in wave height along the eastern Pacific coast from Mexico to Peru, the Atlantic coast from southeastern Brazil to Mar del Plata in Argentina, and to a lesser extent along the Colombian Caribbean and Venezuelan coasts [62]. Furthermore, in the Southern Hemisphere, an increase in storm-wave-event duration is projected, reaching up to between 50% and 100%, especially along the Pacific coasts of Central and South America, by the end of the century under the RCP8.5 scenario [79]. Additionally, for this emission scenario, projections show an increase in the frequency of extreme wave events in the eastern tropical-subequatorial Pacific region, and a roughly 10% rise in extreme wave energy flux along the coasts of Brazil, Uruguay, and Argentina by the end of the century [34]. Regarding wave direction, the projections presented by Morim et al. (2019) [4] for the 2080–2100 period under the

RCP8.5 scenario reveal variations exceeding 2° counterclockwise along the Baja California Peninsula in Mexico and the central–southern region of Chile. Clockwise deviations of over 2° are anticipated in the tropical North Atlantic region, except in the Gulf of Darien area, between Panama and Colombia, where counterclockwise variations of 1° are projected.

Furthermore, toward the end of the century (RCP8.5), there are projections indicating an increase in the frequency of concurrent extreme events of precipitation and meteorological tides in specific coastal regions, such as North America, northwest South America, and southern Chile. There remains some uncertainty along most of the coasts in the Central American Pacific region. However, it is expected that the probability of these concurrent events will be lower in northern and central Chile, with uncertainties prevailing in the Caribbean and northeastern South America [2]. Additionally, under future scenarios where sea surface temperatures rise by 1.5 °C, there could be a 40% increase in the frequency of hurricanes in the eastern Caribbean region. Similarly, a higher density of storm tracks in the central and eastern Pacific, across all future scenarios, is observed, which would likely lead to an uptick in flooding and coastal erosion events [81,82]. Projections also suggest a potential increase of up to 30% in the height of cyclonic surges for a 100-year return period (RCP8.5) along the Pacific coasts, including Mexico, Costa Rica, Panama, Colombia, Ecuador, and certain areas of Peru. Moreover, such increases are expected in the Caribbean region, encompassing the coasts of Panama, Colombia, and some areas of Venezuela [83]. In the eastern Caribbean region, an increase in the frequency of extreme wave heights is expected, possibly attributed to remote swells of extratropical origin, rather than to tropical storms. This could be driven by the influence of wave height variability at mid-latitudes, resulting in 50% more variability in swell periods in the tropics [84].

The increase in the frequency of extreme events, such as tropical and extratropical cyclones, can lead to more frequent flooding in low-lying coastal areas and have a significant impact on the recovery of sandy beaches, as observed in some beaches in Mexico [42,80]. These events generate more intense waves, and their most significant impacts occur when they occur in short periods [4,67]. Therefore, to accurately predict coastal flooding caused by extreme events, high-resolution models that consider the physical processes in these areas are required [85]. Limitations to analyzing these risks on a larger scale are due to long processing times and a lack of land use and hydrology data at the global level [63,86]. Additionally, it is essential to consider the effects of climate influenced by weather patterns and remote connections, such as the El Niño phenomenon (warm phase of ENSO), which produces significant variations, such as in wave climate on the Pacific coast of Mexico. During the El Niño phase, notable changes in wave characteristics are observed, increasing the risk of coastal erosion [36].

4. Oceanic-Atmospheric Variations and Their Influence on Coastal Hydrodynamics and Shoreline Changes in Latin America

The sandy coasts of Latin America face extreme events linked to oceanic-atmospheric variations, posing significant risks due to their low elevation, dense population, and infrastructure concentration along the coastline [87]. Despite studies revealing shoreline retreat trends from coastal erosion across the region, local-level investigation remains limited or absent in some countries (Figure 4). Coastal erosion, coupled with increased extreme events and rising sea levels, alters beach morphology primarily through changes in coastal dynamics [26,87]. This leads to more areas becoming vulnerable to coastal flooding, and property loss, particularly in regions prone to high-intensity waves and cyclonic surges, as observed on various Latin American beaches [7,88,89]. A sea-level rise of 5–10 cm could double flood frequency on the eastern Pacific and southern Atlantic coasts of Latin America between 2030 and 2050 [69]. Local hydrodynamic factors drive coastal erosion on sandy coasts, necessitating a comprehensive exploration of how oceanic-atmospheric variations will affect them. These oscillations influence air and sea surface temperatures, precipitation patterns, hurricane/storm activity, sea-level rise, and wave system variations [38,69,90].

Approximate Rural and Urban Population in Low Elevation Coastal Zone (LECZ) below 10-meters

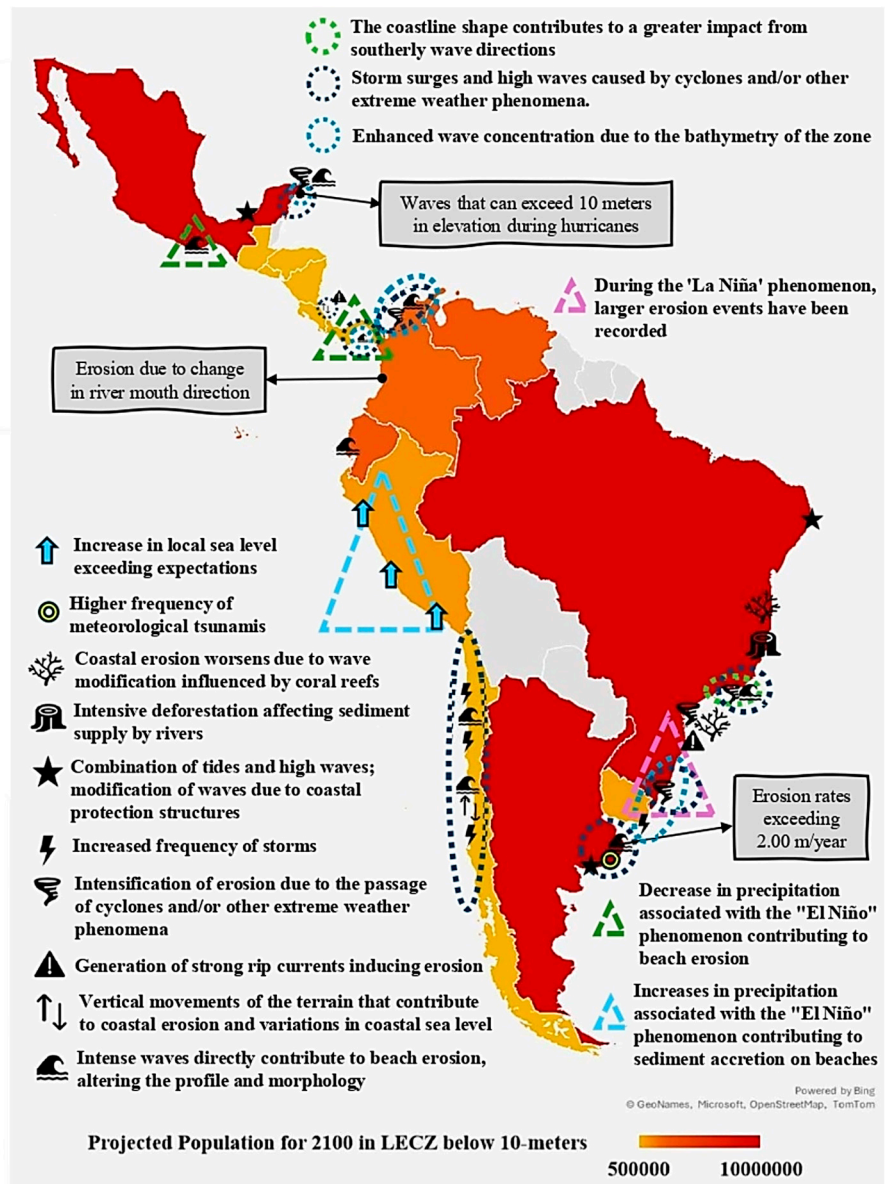
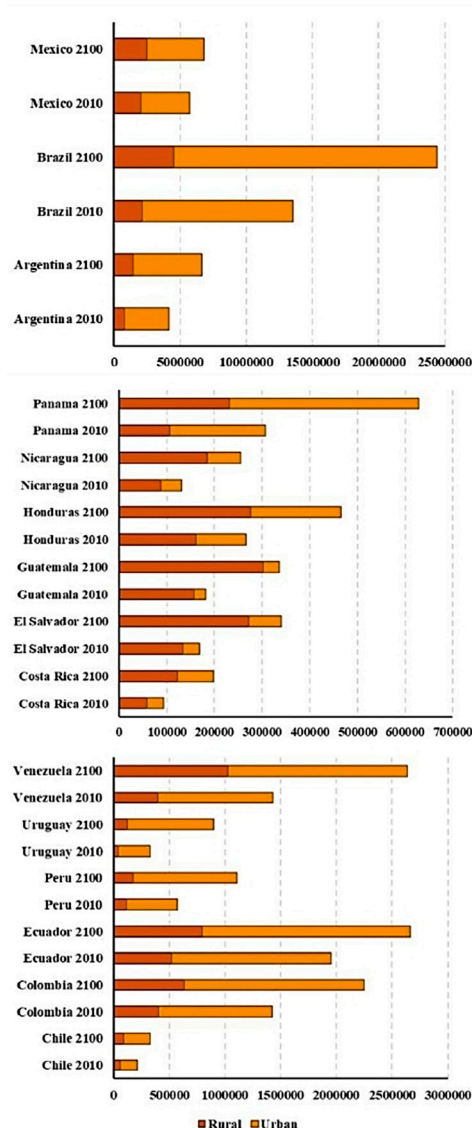


Figure 4. (Left Panel) Population for the year 2010 in rural and urban communities located in coastal areas with elevations below 10 m. Projections of population increase for the year 2100 are also displayed. (Right Panel) Identified causes of coastal erosion, based on evidence presented in various case studies throughout the continental Latin American region, from Vallarino et al. (2023) [88]. Population data in LECZ below 10 m from [91]. Icons and map obtained from Microsoft PowerPoint database [92].

4.1. Extreme Events and Sea-Level Rise

In recent decades, rising sea surface temperatures have increased both tropical and extratropical storms, leading to more extreme wave events [15,83,90]. These high-intensity wave systems, combined with elevated water levels, are closely linked to warm-core tropical cyclones and cold-core extratropical cyclones [93]. The destructive potential of coastal flooding from these events depends on various factors, such as atmospheric pressure, cyclone speed, direction, and scale. Additionally, friction with the seabed and coastal shape can amplify storm surge heights, particularly in bays or estuaries like the Rio de la Plata (RdIP), Argentina [16,46,93,94]. Changes in the seabed can alter wave angles in the surf zone, especially when combined with human interventions along the coast, affecting

sediment transport. For example, in Pinamar towards Punta Rasa, Argentina's eastern coast, this has led to accretion in the south and erosion in the north [95].

Extratropical cyclones between Argentina and Uruguay have increased 'Sudestadas' events in the Río de la Plata. This rise has resulted in a 7% increase in storm surges, with sea levels rising from 100 to 300 cm in the estuary [5,95]. A study analyzed wave patterns in the estuary from 1980 to 1990, noting changes in regional wind patterns [96]. Other research focused on the Bay of Samborombón, revealing an increase in high waves from the E and ESE directions, contributing to water elevation rises of 1.62 mm/year (Buenos Aires area, 1905–2010) and 1.72 mm/year (Mar del Plata area, 1953–2009) [97,98]. Cyclone-formation-event trajectories, especially originating from Uruguay's southern coast and moving eastward (28° S to 43° S), are closely linked to coastal erosion. Events heading southeastward (32° S to 57° S) generate intense storm tides [99,100].

The southern region of Brazil is known for its erosive process, designating certain areas as erosion "hot spots" due to an accelerated shoreline retreat on various beaches in Rio Grande do Sul (RS) state [88]. This could be related to the increase in the number of extreme events resulting from the observed increase in wind speed since 1990, with relevance to the extratropical cyclone that occurred in April 1999. This erosion trend may stem from an uptick in extreme events, notably a cyclone in April 1999, which deviated from typical trajectory and speed, leading to substantial sediment loss at Hermenegildo Beach. This event caused significant damage, including the destruction of 22 beachfront houses and coastal protection structures in the dunes area [99,100]. A study by Parise et al. (2009) [101] analyzed the impact of three cyclone events on Cassino Beach in Rio Grande do Sul, noting that the events' duration and proximity to the coast significantly affected beach morphology. Moreover, the area experiences increased anticyclone occurrences during El Niño winters, strengthening north and west winds, while La Niña years witness more cyclones in winter, intensifying southwest winds [48].

In the Western Tropical Atlantic, significant variations in hurricane activity are expected due to increasing global oceanic and atmospheric temperatures. This rise could prompt hurricane formation at higher latitudes in the Caribbean, amplifying impacts by 60% in the Gulf of Mexico [102]. These events can swiftly reshape sandy coasts, leading to long-term morphological changes [103]. For instance, Hurricane Wilma's devastation in October 2005 lingered for 48 h in the Caribbean region of Mexico, causing waves of up to 13 m high and beach retreats ranging from 10 m to 20 m. Beaches like Cancun, Punta Brava, and Playa del Secreto in the Northeast Yucatan Peninsula suffered significant damage [104,105].

In the Caribbean, Hurricanes Eta and Iota in 2020 caused human losses and damage to coastal infrastructure [106]. Evidence suggests an increase in tropical storm frequency over the past two decades, notably on San Andres Island in Colombia, where they occur approximately every 3 years [107]. Moreover, Cartagena's beaches experienced erosion in 2010–2011 due to a combination of regional climatic patterns, transitioning from a "strong" El Niño to a "moderate" La Niña, alongside a significant sea-level rise [108,109]. Numerical models projecting increased wave intensity and sea level indicate a 65% and 69% rise, respectively, in floods and coastal erosion in Cartagena de Indias [110]. This exacerbates erosion rates in the Colombian Caribbean, where rates exceeding −10 m/year have been recorded on various beaches [111]. For instance, erosion with average rates of −5.5 m/year occurs between Barranquilla and Cienaga, affecting 95% of the area, rendering it vulnerable to the impacts of extreme events. Additionally, extreme waves of up to 1.00 m were observed between 2014 and 2016, impacting the region's main road, coinciding with an ENSO year and necessitating an analysis of its influence on hydrodynamic variations in the Caribbean [18,112].

The passage of cold fronts, storms, and hurricanes in the Caribbean generates significant economic losses due to the destruction of beaches, essential assets for the region's tourism sector [18,103]. Variations in wave height, period, and direction result from changes in atmospheric circulation and surface winds due to internal climate variability and climate

change. However, not only can increasing wave parameters harm the region, but decreasing wave height and roughness can also cause coral reef death (as seen in the Caribbean of Costa Rica), both potentially leading to coastal erosion [62,113].

Furthermore, changes in Tropical Pacific Ocean temperature, especially the sudden increase in 1976, may have added more heat to the global atmosphere, potentially intensifying storms and coastal climate waves in Latin America [100]. This has contributed to intensified erosion, particularly along the Colombian Pacific coast, where approximately 22% of the coastline is experiencing erosive processes that could result in the accelerated retreat of the coastline [111]. In Costa Rica, west and southwest waves are showing trends towards increasing height, leading to mangrove death due to sediment modification; specifically, the sediment is becoming sandier and less silty [114]. Conversely, in extratropical regions like Chile, extreme wave events have increased nationwide due to factors such as storm surges from extratropical cyclones and latitudinal gradients causing wave intensity variations across Chilean territory [45,115]. In the mid-century, Chile's average storm rate was around 5 per year; however, in the last decade it surged to 20 per year [116,117]. This exacerbates impacts due to high population density near coastal areas, mirroring the situation in many urban centers and coastal communities across Latin America.

According to a study by Boucharel et al. (2021) [37], waves from extratropical regions influenced by the polar jet stream can impact coastal areas at lower latitudes, such as tropical regions. For instance, waves generated by extratropical cyclones in the Southern Ocean can reach northern South American and Central American Pacific regions [78]. Conversely, waves generated in the tropical oceanic region tend to stay within low latitudes, but occasionally reach high latitudes, especially due to tropical storm formation. The study indicates that waves in coastal Pacific regions are locally generated 54% of the time, with 46% originating externally. Among the latter, 22% come from the opposite hemisphere due to activity in the southern hemisphere's polar jet stream and cyclonic basins in the northern hemisphere.

In general, changes are expected in various coastal areas of Latin America, as indicated by a study published by Reguero et al. (2013) [10]. Increases in wave height are reported in the northern Pacific of Mexico, Uruguay, southern Brazil, and the northern east coast of Argentina (Figure 5). Additionally, counterclockwise rotations of wave patterns are observed on the Argentine coast, while the rest of the Atlantic coast exhibits clockwise rotations. In the Caribbean Sea and the Pacific region of Central America, trends are slightly clockwise, except for the Caribbean coasts from Mexico to Costa Rica and the Baja California peninsula, where a slight counterclockwise rotation of wave patterns is projected. Such variations in coastal dynamics can lead to the formation of new sections of beaches experiencing erosion. For instance, the counterclockwise rotation of wave patterns is projected in the sandy beaches of Chile, although it is less intense than waves in the deep sea due to wave refraction near the coast. This could result in straight beaches experiencing erosion at their southern ends, and accretion at the northern ends [116–118].

These variations in wave system patterns could vary due to the influence of climate modes such as AMO, ENSO, and SAM. Since the 1990s, variability in sea surface temperature and its correlation with the AMO has been observed, influencing the temperature of the Southwest Atlantic and generating a higher frequency of storms, as well as variations in wind speed and direction [51]. Additionally, in the Southern Atlantic Ocean (SAO), an increase in anticyclone occurrence has been recorded during El Niño winters (warm phase of ENSO), intensifying north and west winds. Conversely, La Niña years (cold phase of ENSO) show increased cyclones during winter, resulting in intensified southwest winds [48]. In Chile, the increase in extreme events appears to be influenced by SAM, modifying wind intensity and direction at southern latitudes, and affecting wave conditions by increasing their intensity [45,115]. The increase in the duration of storms generated in the southeastern Pacific is consistent with the changes projected in tropical regions of the southern hemisphere, and it aligns with the shift towards the positive phase of SAM [79].

However, while evidence shows variations in waves and storms due to climate modes' influence, their relationship is not always clear [38,93].

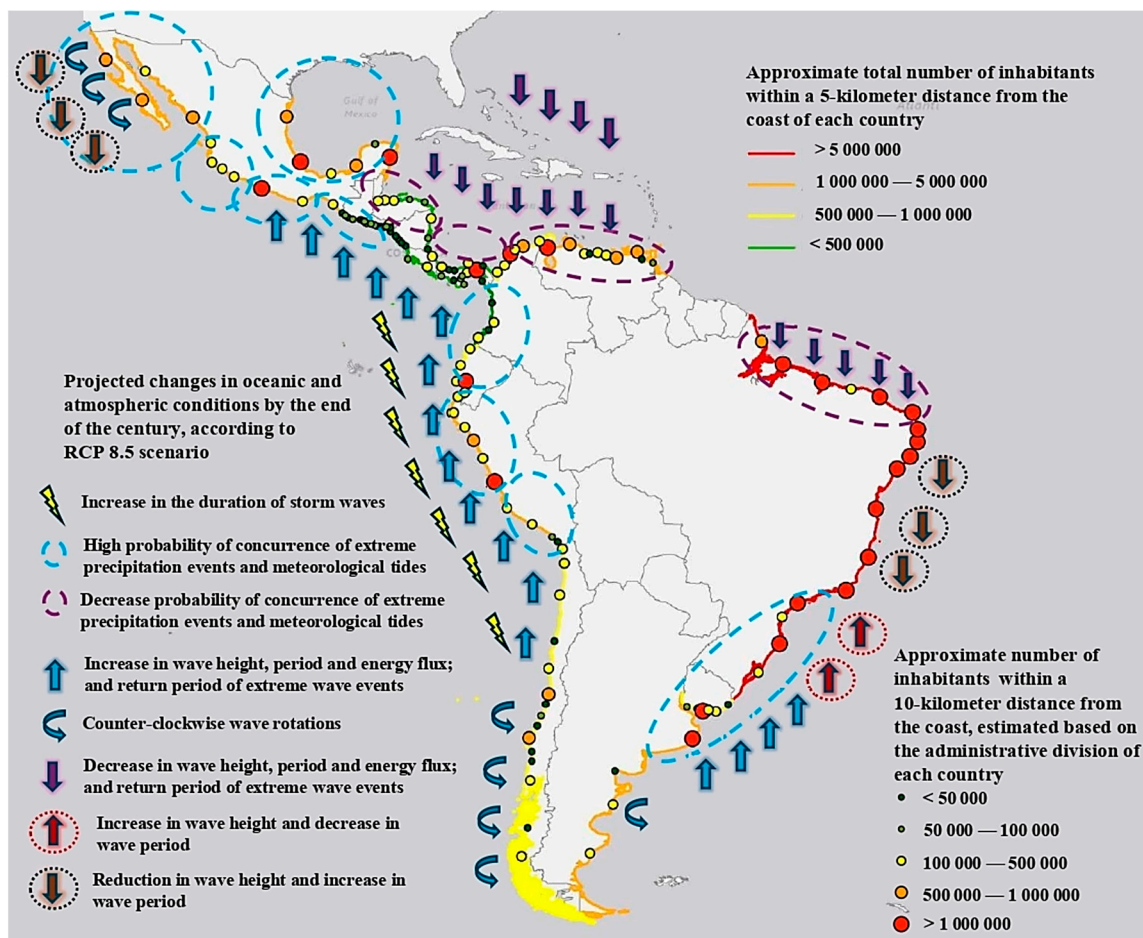


Figure 5. Variations in oceanic-atmospheric conditions projected for the end of the century under the RCP8.5 scenario. This information is derived from a review of literature from various global studies, with the consulted sources listed in Tables 1 and 2. Population data within the 5 km coastal zone sourced from [75] and within the 10 km coastal zone sourced from [76]. Base map obtained from the ArcGIS-ArcMap database.

4.2. El Niño-Southern Oscillation (ENSO)

The climate of Latin America is significantly influenced by the intensity of ENSO phases, impacting extreme events and precipitation patterns. Hydrological changes related to El Niño affect the sea level in the RdLP estuary, with river discharge having a greater effect than wind on coastal water levels. During warm ENSO phases, increased precipitation and southeastern winds can elevate water levels by over 1.00 m on the Uruguayan coast [5], leading to sediment accumulation. Conversely, during La Niña, reduced mid-current action allows waves to reach the upper estuary, decreasing friction in shallow waters [119]. Strong El Niño events in Samborombon Bay alter wave frequencies, with NE and E waves increasing by 30–50%, and W and NW waves decreasing by 40–60% [97]. Under normal conditions, waves from E and ESE have become more frequent in the area [120]. These wind and wave variations, coupled with increased cyclones and storms, have accelerated erosion along Argentina's eastern coast. Erosion rates exceeded -1.00 m/year (from Villa Gesell to Las Toninas) between 1985 and 2009, exacerbated by coastal protection works affecting south-to-north coastal drift [121,122].

The effects of ENSO in the southeastern region of Brazil impact coastal dynamics, notably in Rio de Janeiro and Rio Grande do Sul (RS). During strong El Niño years, sub-

tropical jets increase, accompanied by a decrease in southern quadrant waves. Conversely, strong La Niña periods see more waves from the south and southwest, linked to erosion due to shifts in littoral currents and short-period waves. In neutral years, southeast Brazil's littoral current tends southwestward [48,123]. During the El Niño event in 1997, there was an increase in the energy of incident waves, contributing to coastal retreat in RS that occurred in November. In the winter of 1998, following El Niño, it was characterized by less intense winds and storm surges, leading to the recovery of the coastline. However, during La Niña in 1998, there was more intense cyclogenesis and an increase in the frequency of high waves, contributing to a period of erosion that extended from 1998 to 1999. This was evidenced in the beach profile observed in March 2000 at Itapoa Beach, Santa Catarina state, which retreated by an average of -8.13 m due to the effects of both climatic phenomena [124]. Moreover, during the period of 2010–2012, the La Niña phenomenon induced extreme events that resulted in an estimated 20 m of beach retreat in the southern sector of Rio de Janeiro. This study indicates that storm events during La Niña are approximately 18% stronger than those during El Niño, emphasizing the greater impact of La Niña on erosion in the southeastern region of Brazil. [125]. Another example is the city of Salvador in Bahia state, where within the set of erosion events recorded between 1967 and 2006, most are associated with La Niña events [126]. In Baixada Santista, coastal flooding events and cyclonic storm surges between 1928 and 2016 are associated with El Niño and La Niña events, especially those of moderate to weak intensity. However, the effect of additional local factors, such as winds, bathymetry, and the previous state of the beach, which can affect wave conditions and littoral currents during extreme events, should also be considered [16,88,127,128].

In Uruguay, during La Niña events, southwest to northwest winds are more frequent (especially between April and September), contributing to coastal erosion. Conversely, during El Niño, the decrease in this wind direction's frequency leads to increased sediment in the region [123,129]. Another study suggests a correlation between positive anomalies in Atlantic Ocean sea surface temperature and the AMO, possibly leading to water advection by the Brazil Current and a warmer phase since 1997. This has increased storm frequency in Uruguay's coastal region. Wind speed anomalies have further heightened dissipative beach susceptibility, increasing swash width and raising the risk of erosion and intertidal species loss [51].

Furthermore, in semi-closed ocean basins like the Caribbean Sea, oceanic-atmospheric variability is closely linked to changes in the Caribbean Low-Level Jet (CLLJ) during ENSO events. This creates a climate pattern influenced by local wind conditions where, during El Niño, the sea level rises above normal values, while during La Niña it tends to be lower (similar to coastal areas of South America's Pacific). Additionally, during La Niña, an increase in cyclonic-storm-surge events is observed, especially in the Colombian Caribbean (as well as in Brazil) [130].

Variations in coastal dynamics in the Eastern Pacific due to ENSO primarily involve increases and changes in wave direction. Along the Pacific coast of Mexico in Oaxaca, El Niño leads to decreased precipitation and a unimodal wave pattern. Conversely, La Niña increases precipitation patterns and sediment availability, resulting in a bimodal wave climate with winds from the west and south [131]. In other coastal regions, such as Panama in the Pacific coast of Coclé and Panama Oeste province, beaches near densely populated areas experienced shoreline retreat of approximately 25 m over a 5 km stretch from 1981 to 2021. This erosion is partly attributed to decreased precipitation during El Niño, which reduces sediment input and impacts sediment-dependent beaches [132]. In Peru, El Niño brings increased precipitation, leading to greater sediment input from river channels. For instance, a sedimentation peak of 60 m was recorded in 2017 at the mouth of the Rimac River in the Bay of Callao [133]. Additionally, a study by Jigena-Antelo et al. (2022) [70] indicates sea-level rise trends on the Peruvian coast are 4 mm/year higher than IPCC predictions for 2006–2015. This study suggests a cycle of at least 30 years, possibly related to PDO, with shorter phases due to the increased influence of extreme atmospheric events.

An increase of 3 to 5 cm has been observed in the lowest cycle levels, coinciding with El Niño events of “Mega-Niño” or “strong” categories, except during the 1997–1998 period, classified as “Mega-Niño”, coinciding with the onset of the negative PDO phase.

The high-intensity waves on the coast of Chile associated with the El Niño phenomenon during the period 2015–2016 reached wave height values exceeding 3.00 m. This increase in wave height appears to be related to storms generated southwest of the region during the austral winter. Considering that Chile’s coasts are vulnerable to the effects of ENSO, variations in mean sea level can fluctuate by up to ± 30 cm [45,116]. According to a recent study [118], an increase in mean sea level of 0.14 m is projected for 2050, and one of 0.58 m for 2100, under the high emissions scenario (RCP 8.5) in the Valparaíso area.

The increasing frequency of (extra-)tropical cyclones and storms alters wave systems, potentially leading to more intense wave conditions near coastlines. Additionally, the closer proximity of these large storms could potentially result in cyclonic surge events near vulnerable coastal areas, potentially contributing to coastal erosion on Latin American sandy beaches. This potential trend, influenced by climate phenomena such as ENSO, could intensify pressure on coastal systems. For instance, research by Odériz et al. (2020) [24] highlights ENSO’s impact on global wave climate from 1979 to 2018, indicating a low response in Argentina, Uruguay, and southern Brazil’s coastal regions [16,97]. Conversely, El Niño events amplify wave power and induce the clockwise (counterclockwise) rotation of wave patterns along the southern coast of Brazil (Caribbean of Panama and Colombia). La Niña events result in increased wave power and induce the counterclockwise (clockwise) rotation of wave patterns along the Pacific coast of Panama and the eastern coast of Brazil (Chile, Peru, and the Caribbean off the Yucatan Peninsula, Mexico) [24].

Understanding the intricate interplay between extreme events, sea-level rise, and climate patterns is crucial for grasping their impact on coastal erosion in Latin America. Much of the sandy coastline in this region accommodates urban infrastructure, including residences and hotels, located within 30 m from the shoreline [88,102,118]. During extreme events like cyclonic surges or high-intensity waves, there is an elevated risk of partial or total damage to these properties, a risk that may escalate in future scenarios.

The compilation of evidence regarding coastal erosion cases on the sandy shores of the Pacific (Chile, Colombia, Mexico, and Panama), the Atlantic (Argentina, Brazil, and Uruguay), and the Caribbean (Colombia, Costa Rica, and Mexico) provides valuable insights into diverse coastal dynamics in these regions. These data can serve as a starting point for researching coastal erosion and its drivers in neighboring countries that have not yet initiated similar studies. The need for this research arises from the fact that many Latin American countries have developments directly on the shoreline, with little or no coastal protection, and decreasing beach width in recent decades, a trend expected to continue under different climate change scenarios. This has been evidenced in global studies (see [134–136]), highlighting the importance of local studies to compare results and future trends [112,115].

Presented below are Tables 1 and 2, which provide a comprehensive summary of the findings and references discussed in the preceding sections. These tables are designed to offer an integrated view of the data and information depicted in Figures 3–5. Specifically, Tables 1 and 2 consolidate the historical impacts on coastal regions and the coastal climate, along with projections for the RCP8.5 scenario pertaining to oceanic-atmospheric variations that may influence changes and exacerbate the impacts of coastal erosion. Furthermore, these tables include references to key studies cited in Sections 4.1 and 4.2, facilitating a deeper understanding of the analyzed aspects.

Table 1. Summary of historical/current impacts and end-of-century projections under RCP 8.5 scenario for the Atlantic Ocean region near the coastlines of Latin America.

Regions	Historical/Current Impacts and End-of-Century Projections under the RCP8.5 Scenario	Sources
Northern Atlantic	Historical/current impacts:	
	Increase in wave energy of approximately greater than 1.00 kW/m in the tropical region.	Odériz et al., 2021 [74]
	Increases in the frequency of concurrent extreme precipitation events and meteorological tides (over a period of 4–8 years) in the Gulf of Mexico.	Bevacqua et al., 2020 [2]
	Projections:	
	Increase in the frequency of concurrent extreme events of precipitation and meteorological tides along the coasts in Gulf of Mexico.	Bevacqua et al., 2020 [2]
	Decrease in wave height ranging from 0.06 m to 0.09 m (including a decrease in peak period).	Camus et al., 2017 [8]
	The 100-year return period event will occur twice as often by the end of the century in the North Atlantic tropical region for wave energy flux along the coastline.	Mentaschi et al., 2017 [34]
	Projected decreases in the days of intense waves (~10–30%) and in the duration of storm waves (~10–20%).	Morim et al., 2021 [77]
	Decrease in the wave period extending to areas of the Gulf of Mexico and the Caribbean region of the Yucatan Peninsula.	Morim et al., 2019 [4]
	Decrease in the annual significant wave height by up to ~10%.	Morim et al., 2019 [4]
Caribbean	Historical/current impacts:	
	High probability of concurrent extreme precipitation events and meteorological tides (within a period of 4–8 years) in the northern regions of the western and eastern Caribbean.	Bevacqua et al., 2020 [2]
	Negative impacts lasting over half a decade due to the degradation of the marine ecosystem and beach loss caused by Hurricane Wilma and subsequent hurricanes in the northern part of the Yucatan Peninsula in Mexico.	Silva Casarín et al., 2012 [104]; Mulcahy et al., 2016 [105]
	Increase in the frequency of tropical storms, evidenced by a rate of 1 tropical storm every 3 years on the island of San Andrés in the last two decades.	Bernet et al., 2022 [107]
	During the La Niña phenomenon, there is an increase in the occurrence of storm surges in the Caribbean of Colombia.	Genes et al., 2021 [130]
	Projections:	
	Clockwise wave rotations reaching up to 2° in Venezuela and some Caribbean islands.	Morim et al., 2019 [4]
	Decrease in the frequency of concurrent extreme events of precipitation and meteorological tides.	Bevacqua et al., 2020 [2]
	Increases in wave height between the coasts of Nicaragua and Venezuela.	Camus et al., 2017 [8]
	Increase in the frequency of extreme wave heights due to the influence of waves of extratropical origin.	Belmadani et al., 2021 [84]

Table 1. Cont.

Regions	Historical/Current Impacts and End-of-Century Projections under the RCP8.5 Scenario	Sources
Southern Atlantic	Historical/current impacts:	
	Tropical cyclones have increased the number of positive tides in the Río de la Plata and raised sea levels between 100 cm and 300 cm due to “Sudestadas”.	Verocai et al., 2015 [5]
	Increase in wave energy of approximately greater than 2.00 kW/m in the subtropical region, and greater than 5.00 kW/m in the extratropical region.	Odériz et al., 2021 [74]
	Accretion in the south and erosion in the north of the east coast of Argentina due to anthropogenic interventions and changes in wave approach angles.	Dragani et al., 2013 [95]
	Cyclones forming along Uruguay’s southern coast, moving eastward (28° S – 43° S), cause erosion, while those tracking southeastward (32° S – 57° S) generate intense storm surges.	Machado et al., 2010 [99]
	During El Niño years, there is an increase in the concentration of anticyclones in the Southern Atlantic Ocean, resulting in strengthening of the northeast, north, and west winds. Conversely, during La Niña years, there is an increase in cyclone concentration, leading to more frequent and stronger southwest winds.	Esteves et al., 2006 [48]
	During the warm phase of ENSO, positive anomalies in rainfall occur along with strengthening southeastern winds, which can elevate the water level in the Río de la Plata estuary, occasionally exceeding 1.00 m in height along the Uruguayan coast.	Verocai et al., 2015 [5]
	In the La Niña phase, the most significant impacts on coastal areas occur, resulting in significant losses of beachfront in the southern sector of Rio de Janeiro, as well as increased erosion in the southeastern region of Brazil.	Dutra et al., 2014 [126]; Campos Carvalho et al., 2020 [125]
	Projections:	
	The 100-year return period event is projected to occur approximately every ~35 years for wave energy flux along the coastline in the eastern region of Brazil.	Mentaschi et al., 2017 [34]
	Increases in wave height from southeastern Brazil to Mar del Plata in Argentina, along with reductions in wave period.	Melet et al., 2020 [62]
	Increase in extreme wave energy flux by 10% along the coasts of Brazil, Uruguay, and Argentina.	Mentaschi et al., 2017 [34]
	Increase in wave height due to the influence of swells from the Southern Ocean.	Morim et al., 2019 [4]
	Counterclockwise wave rotations exceeding 17° in southern Argentina.	Morim et al., 2019 [4]
	Increase in the frequency of concurrent extreme events of precipitation and meteorological tides on the southern coast of Brazil up to the northern coast of eastern Argentina.	Bevacqua et al., 2020 [2]

Table 2. Summary of historical/current impacts and end-of-century projections under RCP 8.5 scenario for the Pacific Ocean region near the coastlines of Latin America.

Regions	Historical/Current Impacts and End-of-Century Projections under the RCP8.5 Scenario	Sources
Northern Pacific	Projections:	
	Counterclockwise wave rotations reaching up to 3° on the Baja California Peninsula.	Morim et al., 2019 [4]
	Increased frequency of concurrent extreme events of precipitation and meteorological tides on the coasts of Mexico.	Bevacqua et al., 2020 [2]
	Decrease in wave height of between 0.06 m and 0.09 m (including increases in peak period).	Camus et al., 2017 [8]
	Increases in wave height with reductions in wave period in Baja California Peninsula.	Melet et al., 2020 [62]
	Projected decreases in days of high wave activity (~10–30%) and storm wave duration (~10–20%).	Morim et al., 2021 [79]
Tropical and subtropical Pacific	Annual significant wave height decreases of up to ~10%.	Morim et al., 2019 [4]
	Historical/current impacts:	
	Increase in wave energy of approximately greater than 2.00 kW/m in the tropical Pacific region.	Odériz et al., 2021 [74]
	Waves reaching heights up to 2.00 m during the months of December to February, generated by westerly winds in the North Pacific and easterly trade winds between latitudes 30° N and 30° S in the eastern equatorial Pacific	Kumar et al., 2022 [47]
	Increase in wave height from the West and Southwest in Costa Rica has led to mangrove loss due to sediment modification towards a sandier and less silty composition.	Lizano, 2016 [114]
	During El Niño, a decrease in precipitation and a unimodal wave pattern are observed on the Pacific coast of Mexico in Oaxaca. During La Niña, there is an increase in precipitation and a bimodal wave climate due to West and Southwest winds.	Godwyn-Paulson et al., 2021 [131]
	High probability of concurrent extreme precipitation events and meteorological tides (with a return period of 8–16 years, mainly during the months of May to November) along the coasts of Central America and Mexico.	Bevacqua et al., 2020 [2]
	Projections:	
	The 100-year return period event is projected to occur approximately every ~54 years for wave energy flux along the coastline in the eastern subtropical–tropical Pacific region	Mentaschi et al., 2017 [34]
	Significant increases in wave height and period, with height increases ranging from 0.06 m to 0.09 m.	Camus et al., 2017 [8]
	Increased wave height exceeding 2.10 m during December to February due to swells.	Kumar et al., 2022 [47]
	Increased duration of storm surges along the coasts of Central and South America.	Morim et al., 2021 [79]
	Increase in wave period and significant wave height in the eastern tropical region.	Morim et al., 2019 [4]
	Uncertain increases in the frequency of concurrent extreme events of precipitation and meteorological tides.	Bevacqua et al., 2020 [2]

Table 2. Cont.

Regions	Historical/Current Impacts and End-of-Century Projections under the RCP8.5 Scenario	Sources
Southern Pacific	Historical/current impacts:	
	• Increase in wave energy of approximately greater than 6.00 kW/m in the extratropical region.	Odériz et al., 2021 [74]
	• Significant increase in the frequency of storms in Chile, rising from an average rate of 5 per year to 20 per year in the last decade.	Martínez et al., 2018 [116]
	• During El Niño in Peru, there is an increase in precipitation, resulting in a higher contribution of river sediments to the coast.	Muñoz et al., 2022 [133]
	• Along the coast of Peru, sea-level rise is more pronounced than IPCC predictions, possibly due to the influence of the PDO, with shorter phases in the 21st century.	Jigena-Antelo et al., 2022 [70]
	• During the 2015–2016 El Niño event, the coast of Chile experienced intense waves with heights exceeding 3.00 m, possibly originating from storms to the southwest of the region during the austral winter.	Martínez et al., 2018 [116]
	Projections:	
	• Counterclockwise wave rotations ranging from 1° to 5° in central and southern Chile.	Morim et al., 2019 [4]
	• Increase in concurrent extreme events of precipitation and meteorological tides on the southern coast of Chile, and a decrease on the northern and central coasts.	Bevacqua et al., 2020 [2]
	• Increases in the frequency of concurrent extreme events of precipitation and meteorological tides are anticipated in Northwest South America.	Bevacqua et al., 2020 [2]

5. Implications for Coastal Management and Planning

Coastal erosion worsens with increased intensity and frequency of tropical cyclones, particularly impacting low-lying sandy coastal areas due to rising sea levels [93]. While rising sea levels do not directly cause erosion, they increase the likelihood of events like high tides and intense waves reaching further inland, displacing sediments [64]. Additionally, the expansion of ocean sinks, such as riverbeds and deltas, will prolong sediment retention within these areas [137]. The combination of more extreme storms and rising sea levels could exacerbate coastal squeeze in poorly planned hard structure areas, like beach walls, reducing the coast's adaptive capacity and increasing vulnerability to flooding [63,117,138,139].

A study revealed a 5.3% population increase in flood-prone coastal areas in Latin America from 1970 to 2010, ranking it fourth globally [86]. In Nicaragua, Colombia, Uruguay, and Venezuela, the risk of coastal area loss due to sea-level rise exceeded 3.0%, while in Mexico it surpassed 6.0% by the end of the century under the RCP8.5 scenario. Most Latin American countries face a risk exceeding 2.0%, according to a recent study [140]. Results from the analysis of Cassino Beach in Rio Grande do Sul, Brazil, suggest that coastal topography has a limited impact on beach response to low rates of sea-level rise, but this changes with higher rates. Simulations projected for the year 2030 show average shoreline retreats of 3.60 m for the RCP2.6 scenario, increasing to 42.80 m for RCP8.5, especially near river mouths [5,141,142]. In Chile, a retreat of 2.00 m to 13.00 m is projected by 2050, and one of 10.00 m to 53.00 m by 2100 under the RCP8.5 scenario, exacerbating coastal infrastructure exposure to extreme events. The reduction in beach width would also impact tourism, with economic losses estimated at over USD 5 million per year by 2050, and over USD 10 million per year by 2100, with some beaches possibly disappearing by the end of the century [118].

Low-Elevation Coastal Zones (LECZ) in Latin America and the Caribbean have witnessed increasing population settlement. The research by Neumann et al. (2015) [143] revealed that by 2000, these zones housed over 30 million people, projected to exceed 40 million by 2030, and 50 million by 2060. Significant population surges are anticipated in countries like Argentina, Mexico, and Brazil, with expected increases of 4 to 7 million inhabitants [17]. This growth exacerbates current population exposure conditions, especially in densely populated low-elevation coastal areas of Central and South America. Moreover, the region's vulnerability to extreme events and sea-level rise is poised to intensify due to ENSO variations, particularly affecting countries such as Peru, Ecuador, and Panama [144]. The heightened frequency and intensity of extreme events, alongside population expansion in LECZ, will escalate costs from losses of exposed assets in these risk areas [26].

Furthermore, the impacts of extreme events and sea-level rise on the sandy coasts of Latin America will negatively affect socio-economic activities in various coastal areas, especially in the Caribbean, vital for recreational sun and beach tourism [7,63,92,112,145,146]. However, sea-level rise will vary across regions due to vertical land movements observed in cases like Chile, Colombia, and Venezuela [102,115,147]. These movements may result from human activities such as groundwater or oil extraction, as well as soil compaction due to civil engineering infrastructure construction, and vertical land motion during both inter-seismic and intra-seismic periods. Therefore, developing comprehensive coastal planning and management policies is crucial [102,137].

The economic impact on each beach in the continental Latin America region can vary according to factors such as exposure to extreme events, the frequency and intensity of these impacts, and erosion rates. An example of this is seen in the beaches of Cancun, Mexico, which, due to their geographical location, are highly exposed to hurricane impacts [148], similar to the beaches in Colombia [40]. While the number of visitors can provide insight into future economic losses due to coastal landscape degradation, in some cases the busiest beaches may not experience the greatest economic losses, as this depends on the effectiveness of coastal management plans in implementing rapid mitigation measures [149]. In this regard, certain tourist areas in Brazil are better prepared to cope with coastal erosion impacts due to fund allocation and socioeconomic factors [150].

Insights from the study by Lincke et al. (2022) [9] inform adaptation policies, such as limiting urban development in vulnerable coastal areas with community participation in management plans, reducing risk through planned infrastructure removal, and conducting comprehensive studies considering various factors to avoid inaccurate impact estimates. This is particularly relevant in high-risk areas identified in Latin America, where reducing risk through planned infrastructure limitation/removal is fundamental to avoiding inaccurate long-term impact estimates [151]. Additionally, minimizing errors in coastal impact estimations in continental Latin America requires the consideration of factors such as local sea-level rise, regional trends, tectonic movements affecting coastline position (especially in Chile), and the cumulative effects of extreme climatic events altering hydrodynamic conditions (especially in the Caribbean region and extratropical regions of South America) [88,142].

For instance, the Pacific coast of Buenaventura in Colombia, where potential losses affecting tourism (one of its main economic activities [152]) have been identified, could benefit from studies conducted in nearby regions, such as the one developed in Chepigana-Darién in Panama. Given that, in this coastal erosion study, the use of permeable barriers and oyster reef constructions were identified as alternatives, these nature-based coastal protection measures are feasible to implement and maintain with the support of affected community residents [153–156]. In tourist areas, residents and local business owners must understand the risks and benefits of protection strategies, as some may affect the landscape and tourism [103]. For example, protective structures could limit ocean views and beach access, potentially reducing profitability and the attraction of tourists, as observed in certain coastal areas of the Pacific in Panama.

In this context, the project developed in Chepigana-Darién (Panama) [153] engaged community members in a participatory research process. They were integrated into the study, prioritizing identified issues and considering potential adaptation and mitigation plans that could be implemented based on their perspectives and concerns. The methodology applied to this community, threatened by coastal erosion due to strong waves and anthropogenic causes, illustrates how effective risk communication is crucial for raising local awareness of specific threats and preparation needs [71,152]. In the Central American region, which has a limited number of studies on coastal risks, the development of such studies could be promoted through research agreements between regional universities and state institutions responsible for environmental and coastal issues. This could facilitate the subsequent implementation of early warning systems in high-risk populations, in collaboration with organizations like the Coordination Center for the Prevention of Natural Disasters in Central America (CEPREDENAC).

Furthermore, as economic growth attracts migrants in search of opportunities, population exposure may increase, particularly in cities in developing countries located in low-lying coastal areas vulnerable to extreme events and sea-level rise, such as in Ecuador and Central America [20,152]. Therefore, in areas with evident erosion trends known as “hot spots”, institutions must take assertive measures to prevent the expansion of coastal urbanization or facilitate migration to safer inland locations [86]. However, this latter approach should be carefully evaluated in the decision-making process, considering its significant sociological implications. Displaced populations, such as the recent community from the coastal island of Gardi Sugdub in Panama, may face challenges in adapting to a new environment, especially if their homes hold cultural significance [142,154,157].

Another aspect to consider is recognizing that socio-ecological systems do not respond linearly to changes; impacts result from cumulative effects leading to rapid and significant changes [63]. Disrupted ecological balance can affect economic development, as observed in sandy beaches affected by erosion in several countries in Latin America. For instance, intertidal habitat species such as clams, crabs, and crustaceans may lose their value due to imbalances in coastal dynamics, impacting tourism and ecological equilibrium [158]. Degraded coral reefs and mangroves result in the loss of assets and natural protective barriers, increasing economic losses and future costs during extreme events, as could be the case in Costa Rica and Panama [113,154,155,159].

The assessment of vulnerability at the local level involves the consideration of socio-economic and demographic aspects, encompassing not only activities such as tourism and fishing, but also institutional risk management measures such as planning and the availability of shelters for affected residents [154,160,161]. This significant challenge entails mobilizing resources at multiple scales, particularly economic resources that are often limited, to provide options that reduce the likelihood of unplanned migration. Therefore, promoting early communication and coordination among stakeholders, such as coastal managers, emergency planners, and crisis managers, is crucial for effective risk management. This requires expediting the development of policies and laws related to coastal management, which are currently in the early stages and are transitioning toward Integrated Coastal Zone Management (ICZM) development. This ensures the continuity of protection measures, operational protocols, funding, and institutional frameworks, especially in many countries in continental Latin America where such infrastructure is not fully developed, except for in Brazil [150]. Institutional strengthening is essential for developing and implementing coastal adaptation measures, enhancing monitoring capacity, and growing scientific databases through research and development programs [88]. Additionally, involvement of the private sector, especially the hotel sector due to its high vulnerability in coastal areas, can contribute to adaptation and coastal mitigation plans supported by national governments, potentially generating synergies in later stages [73,162].

Climate change vulnerability and adaptation capacity assessments in continental Latin American countries can be approached using two distinct methodologies: “top-down” and “bottom-up”. The “top-down” approach prioritizes large-scale assessments and global climate change projections, whereas the “bottom-up” approach focuses on specific local factors determining communities’ resilience to climate change impacts. However, the “bottom-up” approach encounters challenges due to the requirement for detailed local information and the difficulty of aligning with global projections owing to insufficient local-scale resolutions [160,163].

Strategies to address coastal risks vary significantly, depending on the resilience approach adopted in different countries of continental Latin America [164,165]. For example, in Chile, where vertical land movements are pronounced, reactive measures strengthen the system to withstand sudden changes and recover from disturbances [166], while in Brazil, a proactive approach involves anticipating changes, planning, and preparing to face them, including preventive and early response measures [167]. In Argentina, especially in the Buenos Aires and Mar del Plata regions, coastal adaptation strategies may include protection through coastal structures and artificial dunes to mitigate erosion, as well as management and adaptation, promoting sustainable land use, constructing climate-resilient infrastructure, and strategic retreat in critical areas [168,169]. In Peru, particularly in Lima and the northern coast, adaptation strategies may focus on protection through mangrove reforestation to protect against erosion, and management and adaptation by regulating coastal urban development [170,171].

Adaptation strategies in coastal management rely on accurate predictions of shoreline changes. These projections are essential for assessing the feasibility of maintaining natural coastlines, implementing engineering solutions, or regulating coastal development. Long-term predictions are crucial due to the extended implementation period. Methodologies ranging from remote monitoring to hydrodynamic models, including deterministic or probabilistic models, can identify areas experiencing coastal erosion and assess variations in shoreline and potential impacts [142,172–175]. However, according to Vitousek et al. (2017) [173], the most credible predictions will integrate assimilated data, validation, and projections from various models with different assumptions about future wave climate and sea-level rise. Overcoming challenges related to local-scale projections is necessary, as current projections primarily focus on global and regional scales. The assessment and adaptation to coastal risks require reliable tools to mitigate current impacts and to predict future erosion and inundation. The development of these tools faces challenges due to uncertainties in global projections. Accurate predictions of sea level, wave climate, and the frequency of extreme events are fundamental for designing coastal protection structures. Decision-makers must choose between ignoring potential changes or preparing for extreme conditions [137]. Additionally, despite advances in climatic and dynamic analyses in coastal areas, uncertainties remain regarding how elements vulnerable to coastal erosion, such as populations, ecosystems, socio-economic activities, and infrastructure will be affected in a cascading manner, and how these impacts will interrelate. This requires integrated evaluations that consider the analysis of all elements in vulnerable areas (Figure 6).

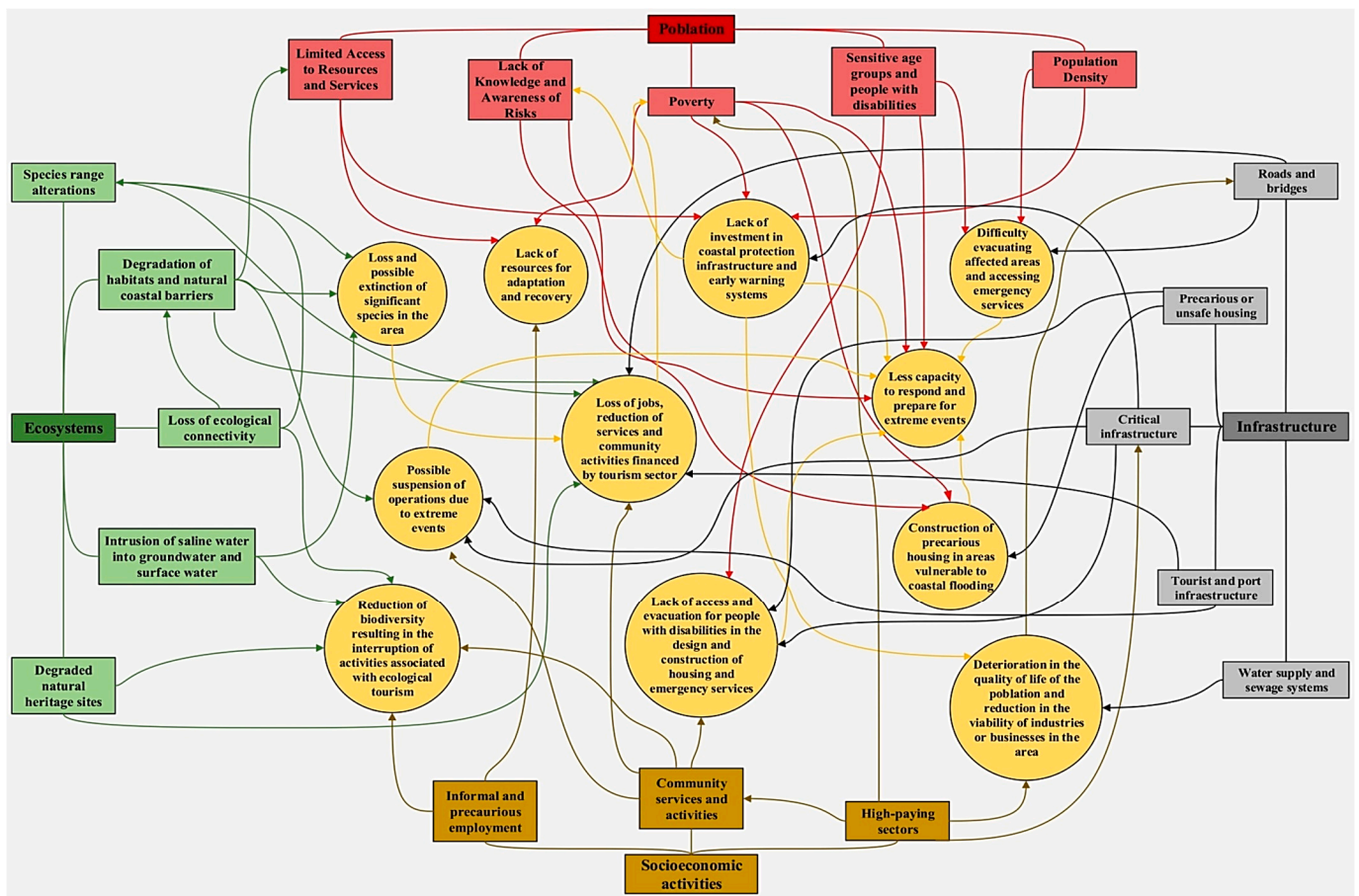


Figure 6. A depiction of vulnerable elements and their potential impacts linked to coastal erosion. The vulnerable elements are categorized into population (red), ecosystems (green), infrastructure (gray), and socioeconomic activities (light brown). Impacts or consequences (yellow) and their interrelations (indicated by arrows) are presented within the scenario emphasizing the substantial role of coastal erosion.

6. Discussion and Conclusions

Oceanic and atmospheric variations will exert a significant influence on the coastal areas of continental Latin America. This impact is exacerbated by population growth in low-lying areas near beaches, which have already experienced erosion due to extreme events and rapid sea-level rise. An increase in the frequency and intensity of events such as storms and intense waves is projected, especially along the Latin American Pacific coasts, posing a considerable challenge for decision-makers in these countries. General Circulation Models (GCMs) provide insights into the past and allow for future projections regarding global climate change. However, they have limitations in terms of the resolution and simplification of climatic processes, which complicates the detailed understanding of regional coastal climates. Moreover, the lack of detailed data on local marine dynamics, especially wave patterns, necessitates the use of downscaling techniques through specialized software, posing a challenge due to varying levels of available expertise in Latin American countries.

Regionally, under the RCP8.5 emission scenario, a significant increase in the frequency of extreme events is expected, which will heighten coastal risks, particularly in terms of already threatened coastal erosion due to rising sea levels. These impacts are not uniform across the region, varying considerably among different areas such as Brazil, the Gulf of Mexico, and Peru, where sea-level rise rates have exceeded global averages during certain periods. This rise, combined with cyclonic tides and changes in wave energy and direction, will exacerbate flood risks and accelerate coastal erosion by affecting beach profile stability.

Consequently, the increasing frequency of simultaneous extreme events involving precipitation and meteorological tides, particularly under the RCP8.5 scenario, underscores the urgent need to enhance predictive models and adaptive planning in vulnerable coastal areas. The complexity of ENSO climate variations and their influence on coastal dynamics in continental Latin American regions has been extensively studied only in specific areas, separated by significant distances. Evidence shows that this climatic phenomenon significantly affects wind patterns and storm frequency, modifying wave conditions and intensifying coastal erosion processes. For instance, during El Niño events, occurrences of anticyclones increase, affecting wind intensity and direction in the South Atlantic and Pacific regions. Meanwhile, during La Niña events, cyclonic activities intensify, particularly impacting southwest winds in these areas. Climate variations induced by teleconnections in the Atlantic have significant effects in localized regions, such as the area between Uruguay and Argentina, where El Niño increases precipitation and southeast winds, raising water levels and promoting sediment accumulation. In contrast, La Niña intensifies cyclonic surges, exacerbating coastal erosion. Along the southeast coast of Brazil, El Niño reduces southern wave energy, whereas La Niña intensifies southern and southwestern waves, increasing wave approach angles and favoring beach erosion. Although some general patterns have been identified, such as increased precipitation and southeast winds during El Niño in the Atlantic region, and intensified cyclonic surges during La Niña, a deeper and more specific understanding is still needed regarding how these teleconnections differentially affect diverse coastal zones across continental Latin America.

Furthermore, in semi-enclosed oceanic basins such as the Caribbean Sea, there is evidence that changes in the Caribbean Low-Level Jet (CLLJ) due to the El Niño-Southern Oscillation (ENSO) phenomenon affect local winds, directly impacting sea levels and the frequency of cyclonic surges. During El Niño events, sea levels tend to rise, increasing the risk of coastal erosion. Conversely, La Niña events lead to an increase in cyclonic surges, which are particularly detrimental to coastal areas like the Colombian Caribbean. It is crucial to investigate how climate variations in the Caribbean region influence the intensity of cyclonic surges in different parts of the Caribbean, especially in the Central American region. In addition to the immediate effects of ENSO phases on sea levels, identifying how these changes could affect the long-term stability of beaches and coastal infrastructure in the Caribbean is necessary. This would allow for future comparative studies between Caribbean countries and other areas of Latin America where ENSO effects are significant, revealing common patterns and differences in how different coastal communities respond to these climate phenomena.

Along the Pacific coast of Mexico and in Central American countries, during El Niño, reduced precipitation and unimodal wave patterns decrease sediment availability, contributing to coastal erosion. In contrast, during La Niña, increased precipitation and sediment input generate a bimodal wave climate that differentially affects coastal erosion. Significant sedimentation increases have been recorded at river mouths in Peru during El Niño events, altering coastal morphology and sediment availability. However, future studies could explore various approaches to quantify these effects in different geographical and climatic contexts, especially in countries with numerous beaches influenced by river mouths or estuaries.

The incorporation of advanced technology, such as drones, remote sensors, and advancements in remote sensing (e.g., multispectral and optical satellite imagery for coastline mapping, InSAR for measuring vertical ground movements) could significantly enhance data collection and the accuracy of studies on coastal erosion and sedimentation. Especially in Latin American coasts where local data collection may be limited, these tools offer an economical and effective solution for monitoring changes in the coastal landscape. This approach not only allows for broader and more frequent spatial coverage but also facilitates risk assessment and adaptation planning against the effects of climate change and human activities in these vulnerable areas. Additionally, it would enable comparative analysis with

regions where both beach line variation and changes in the coastal profile are studied in situ, providing a more comprehensive understanding of coastal processes at different scales.

Moreover, internal climate variability from ENSO, SAM, AMO, and PDO cycles adds complexity to attributing changes in regional coastal climates to climate change. Further studies are needed to address the interaction between these climate modes and teleconnections to identify combined impacts on coastal dynamics and erosion processes. However, this represents a significant challenge in highly anthropized coasts and those where activities such as sand extraction occur. Inconsistencies in the availability of this information hinder the creation of accurate models and reliable predictions. Furthermore, the lack of detailed historical data and variability in the quality of existing records complicates the assessment of past changes and the projection of future trends. To overcome these challenges, it is crucial to implement more robust and standardized monitoring networks at the local level and to promote international collaboration in coastal data collection and analysis. Human activities, such as urbanization and the construction of coastal protection and infrastructure, also play a significant role in coastal erosion. These activities can exacerbate the effects of climatic and oceanic factors, altering natural sedimentation dynamics and further eroding coastal zones. For example, in Argentina and the Pacific coast of Panama, the construction of ports and coastal protections has altered the stability of nearby beaches due to changes in coastal currents and sediment distribution. This situation is exacerbated by combined actions such as sand extraction and the influence of ENSO on precipitation, which can reduce sediment availability that is necessary to maintain beach stability, and thus intensifying erosion in many regions.

Despite the existing global information, the scarcity of data on the influence of oceanic-atmospheric variations on the regional coastal climate in continental Latin America, and therefore on local erosion events, hinders a precise understanding of their overall impact. This lack of understanding sets off a chain reaction, as without adequate information on historical trends, projecting reliable future scenarios for affected coastal areas becomes challenging. This could lead to the implementation of ineffective long-term mitigation and adaptation measures. Initially, these measures may protect coastlines, but they could exacerbate issues like coastal erosion, particularly on sandy shores, resulting in significant losses to homes, businesses, and natural landscapes, thereby devastating the economies of tourist regions and their cultural assets. Hence, there is an urgent need to promote further research that not only addresses the physical impacts on coastal morphology but also provides insights into potential socio-economic impacts on populations. Developing coastal management policies that include community participation and the implementation of appropriate risk adaptation and mitigation strategies is crucial. Challenges in implementing these strategies include the need for accurate predictions of changes in the coastline and overcoming limitations in local-scale projections. Additionally, it is essential to consider all contributing factors, including socio-economic aspects, to formulate effective coastal management solutions.

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