# THE CHANGING COASTLINES OF SOUTH AMERICA

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## ABSTRACT

South American coasts are subject to different natural hazards. In general terms, the Pacific coast is tectonic and therefore earthquakes and tsunamis are likely to occur. The Caribbean coast is constantly subject to trade winds and episodically to hurricanes and tsunami-triggered waves. The Atlantic coasts of Brazil, Uruguay and Argentina suffer the action of storms surges coming from the south (southeasterlies).

At the same time, the South American coast is particularly exposed to ENSO-triggered effects. These effects were different in different regions: in Colombia the seasonal increase of the mean sea level alter the dynamics of barrier islands. In Perú, ENSOs are responsible for sudden inputs of sediments to the coast; similar processes impact the estuarine complexes of Lagoa dos Patos (Southern Brazil) or Paraná-Rio de la Plata floods (Argentina-Uruguay). In northern Brazil, on the other hand, dry conditions induce the migration of dunes landwards.

In several countries of South America, population is concentrated at or near the coast, and therefore some natural coastal processes increase their impacts. In the recent years, erosion effects are more severe due to the action of man.

## Key words

Coastal hazards – storms – hurricanes- ENSO – tsunami – sea level

## INTRODUCTION

In South America, as well as in most regions of the world, people tend to concentrate in coastal areas (Fig. 1).

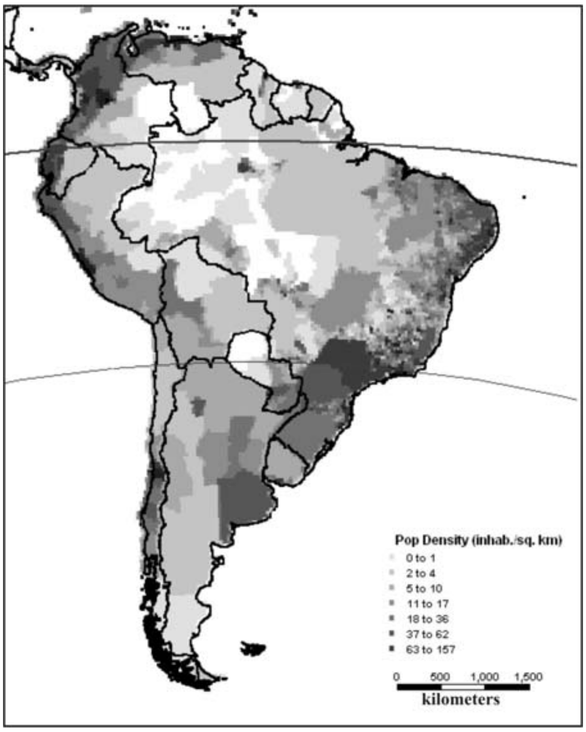

Figure 1. Population density in South America. Source data from: Gridded Population of the World (GPW), Version 3. Center for International Earth Science Information Network (CIESIN), Columbia University; http://sedac.ciesin.columbia.edu/gpw.

Because of the diversity of coastal environments and of the physical factors resulting from the ocean-atmosphere interactions, the coast of South America is exposed to the effects of different processes. Tropical cyclones (hurricanes) occur in the Caribbean region, while extratropical storms are typically produced in the Southwest Atlantic Ocean, from southern Argentina to southern Brazil. While wave action is dominated by west coast swell environments and ENSO effects from central Chile to Colombia, storm waves are predominant in southern Chile. East coast swell environments prevail along much of the east-facing coast of Brazil and trade winds generate low energy waves on the northeast-facing of South America from Brazil to Guyana (Fig. 2). In addition, the Pacific and Caribbean coasts are exposed to tsunamigenic events.

One of the most direct consequences of the land-sea interactions along the South American coast is their impact on shorelines, resulting in coastal erosion, loss of wetlands, salt intrusion in coastal aquifers, among other effects. Even considering the global change scenarios, many of them forecasting a temperature increase leading to the melting of glaciers and a rise in sea level, and an increase in the frequence and intensity of storms (IPCC 2001), anthropogenic causes are to be considered a major contributor to coastal change.

Figure 2. Major physical approaches on the South American coast (modified from Davies, J.L., 1980. *Geographical Variation in Coastal Development*, Hafner Publ. Co., New York, 204 p.).

## 1. SEA LEVEL TRENDS. PAST, PRESENT AND FUTURE

In general terms, the Atlantic coastline is on a trailing-edge margin, the Pacific coast is subject to tectonism in a similar way that the Caribbean coast (Fig. 3). Sea level rise in the order of 1-2 mm/year is dominant in the whole continent as well as worldwide (Church et al.2001; Munk, 2003; Alley et al. 2005). On the Pacific coast, only certain tectonic blocks, subject to earthquakes, seem to be uplifting: Tumaco (Colombia), Matarani (Perú) and Antofagasta (Chile). These uplifted areas are surely related to the oceanic ridges (Carnegie, Nazca, X) subducting below the South American Plate. This fact makes difficult an estimation of sea level trends.

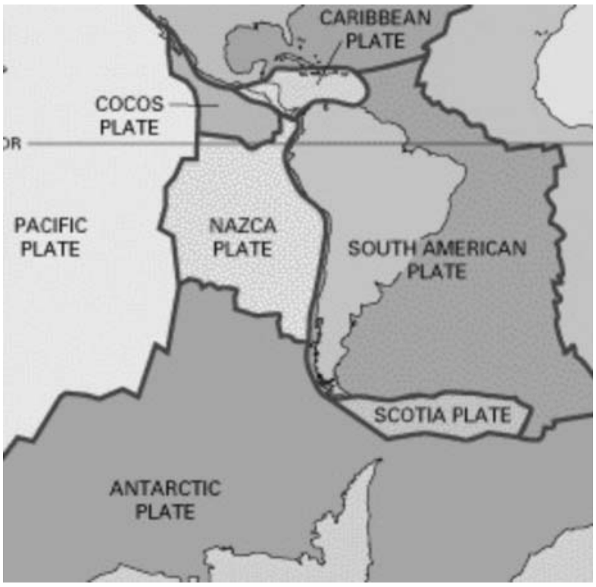

Figure 3. Tectonic setting of South America and adjacent regions (from USGS, http://geology.er.usgs.gov).

Although the Pacific coastline of Colombia is subject to tsunamis and El Niño effects, a subsidence of 1.2-1.5 m in the last 500 years in the San Juan river delta is explained by coseismic effects (González and Correa 2001). Within this tectonic domain, and considering a mesotidal regime, 62 barrier islands evolve in a climate dominated by rainfalls and with dense vegetation dominated by mangrove swamps and rain forest (Martínez et al., 2000). These islands are very low (less than 2 m over the spring tide level), of short lengths (5.8-8.6 km) and dominated by beach ridges and washovers. They formed due to a high sand supply from rivers and a littoral transport from south to north (Martínez et al. 2000).

Sea level trends along the seismic coast of northern Perú are not clearly explained. Tide gauges from Libertad and Talara are indicating subsidence (Emery and Aubrey 1991). Beach-ridge plains related to river deltas can be assigned to the Holocene glacioeustatic sea-level fluctuation (Isla 1989) or to co-seismic uplifting trends (Patagonia). The beach ridge plains of the Chira and Piura rivers were surely conditioned to the availability of sediment related to former strong El Niño events (Ortlieb and Macharé 1993).

For the coast of Venezuela a sea level rise of 2 mm/yr was estimated for the last 20 years (Almeida 1995).

South America is a plate moving westwards, and away from the Mid-Atlantic Ridge. It is coliding mostly against the oceanic Nazca Plate, and its ridges (Malpelo, Carnegie, Nazca, **X**, Juan Fernandez, Selkirk, Mocha and Chile). To the north, the plate interacts with the Cocos and Caribbean plates. To the south, the South American Plate is also interacting with the Antarctic and Scotia plates. Within this tectonic settings, the trailing-edge continental shelf of Argentina has a minimum uplift of 8-9 cm/kyrs (Guilderson et al. 2000). There are evidences of a lowest sea level of -105 m about 15.000 years (Guilderson et al. 2000) and a sea level highstand during the Mid-Holocene (Isla, 1989; Ota and Paskoff 1993; Martin et al. 2003; Angulo et al. 2005).

Over the last century, sea level rose globally ~ 1.0 to 2.0 mm/year, with water expansion from warming contributing 0.5 ± 0.2 mm (steric change) and the rest from the addition of water to the oceans (eustatic change) due mostly to melting of land ice (Church et al. 2001). Different sea-level rise scenarios have been proposed in relation to greenhouse concentrations. From different climate scenarios and model uncertainties, the loss of the Greenland Ice Sheet plus the contributions from thermal expansion and a partial collapse of the West Antarctic Ice Sheet (WAIS) over the coming millenium would lead to an increase in sea level of 1m per century (Nicholls and Lowe 2005). However, other models show that Greenland is largely the main contributor to sea-level rise, while the East and West Antarctic ice sheets appear to be nearly balanced (Alley et al. 2005).

Considering the tide-gauge records, three facts should be stressed:

1. Some tidal stations are located in estuaries. Although in these stations the seasonal changes are not so evident (Emery and Aubrey 1991), some of them may be subject to signicant interannual ENSO effects.
2. South America is less subject than other regions of the Northern Hemisphere to glacioisostatic effects. Although some rebound is expected and some tectonic uplift estimated (Fuenzalida and Harambour 1984; Gordillo et al., 1992), the highstand evidences of Tierra del Fuego were mainly produced by glacioeustatic effects.
3. The records in South America are usually scarce, discontinuous and/or very short, less than 100 years some time ago (Pirazzoli 1986; Emery and Aubrey 1991)**.**

Even considering these contraints, it should be noticed that about 20 years have passed since the latter references, and a few records from the Southwest Atlantic can be considered a reliable reference for relatively stable areas on a subcontinental basis. Hourly sea level measurements from the Mar del Plata (Argentina) tide gauge station for the period 1954-2002 have been used as the rough data to calculate a filtered series of absolute annual mean sea levels. The linear regression analysis of this series shows a trend of +1.4 ± 0.01 mm/yr (Pousa et al., 2006; Fig. 4a). An even longer record for Quequén estuary tide gauge shows a

1.6 ± 0.2 mm/yr rise in sea level (Lanfredi et al. 1998). Moreover, an almost 100 years old record for the Rio de la Plata at Buenos Aires shows a 1.6 ± 0.1 mm/yr rise (Lanfredi et al. 1998). These values are agreeable with eustatic worldwide trends.

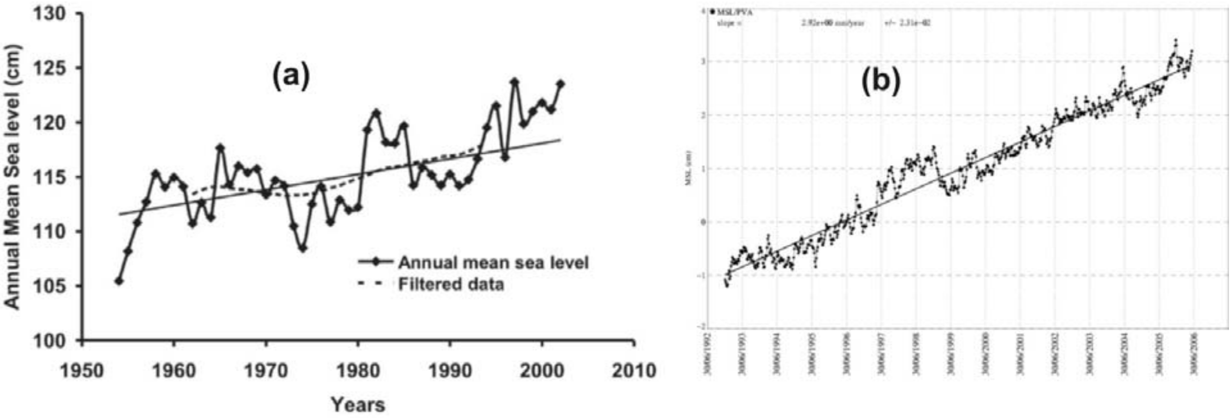

Figure 4. a) Linear regression calculated from filtered data of absolute annual mean sea levels at Mar del Plata for the period 1954-2002 (after Pousa et al. 2006). b) Global mean sea level since October 1992 as seen by the altimetry satellites. Seasonal variations have been removed (source: http://www.aviso.oceanobs.com/)

Because of the highly-dense population living along coastlines, or in the hinterland, sea-level rise as indicated by historical trends, or its acceleration between roughly 0.09 m/yr and 0.9 m/yr according to different scenarios (IPCC 2001) would produce severe damage along the South American coast, particularly on low-lying areas. The more exposed areas are extended along the east and northern coasts of South America (Schnack 1993, Brooks et al. 2006). Increases in coastal flood risks will manifest in Orinoco, Amazon, Paraná-La Plata basins, as well as an exacerbation of erosion in beach systems, demanding varios types of responses to ameliorate the exposure of human populations to sea-level rise hazards (Brooks et al. 2006).

In conclusion, future sea-level rise would result in an increase of coastal erosion and inundation, groundwater intrusion, migration and loss of coastal wetlands (salt marshes, mangrove swamps), among other effects.

## *2.* STORM SURGES

A storm surge is a rise in sea level above normal tidal variations due to the action of strong winds blowing towards the land. When storm surges are the result of severe storms such as hurricanes, the low atmospheric pressure at the center of the depression can additionally raise the sea level. Thus storm surges are usually the result of two different physical processes, namely wind shear stress acting on the water surface and changes in the atmospheric pressure. Storm surges have been responsible for extensive flooding of low-lying regions in many coastlines, and have caused great loss of lives and property damage. Storm surges can be more severe if they coincide with a high tide or if they bracket several tidal cycles, particularly in the case of a perigean tide. The term storm tide is used by some researchers to denote the sum of the astronomical tide and storm surge.

According to their origin, storms are classified into tropical and extra-tropical (Figure 2). Tropical storms are generated in low latitudes, approximately between 5° and 25°, from where they move toward the coast in a somewhat unpredictable trajectory. Usually they are of small extension, with strong pressure gradients and winds which, as in the case of hurricanes, can reach speeds over 240 km/h. These storms cause extreme flooding when reaching the coast, with water levels above 8 m in open coasts, or even higher in bays and estuaries.

Extra-tropical storms, on the other hand, are generated at higher latitudes, between 25° and 60°, and cover much more extensive regions, in the order of hundreds of kilometers, around a low pressure center not as clearly defined as in tropical storms, and with a slower displacement. In addition, the winds around the low pressure center show a less symmetric scheme than in the case of tropical storms. Although low pressure and wind stress are the two main factors in any storm, wind stress is the primary factor in tropical storms; on the other hand, both low pressure and wind stress have similar importance in extra-tropical storms. These are typical of the North Sea, the northeast coast of USA and Canada, and the southwest Atlantic Ocean.

### *2.1 Hurricanes*

A hurricane is a severe tropical storm that forms in the North Atlantic Ocean, the Northeast Pacific Ocean , or the South Pacific Ocean east of 160° E. Hurricanes need warm tropical oceans, moisture and light winds above them. The Saffir-Simpson hurricane scale, which has been used for over the past 25 years, groups tropical storms (hurricanes) into five major categories as a function of wind speed alone (Dolan and Davis 1994).

Hurricanes have a great variation in frequency and intensity. From historical accounts, the coastal region with the greatest hurricane activity is South Florida (15% annual chance), while many areas in Latin America and the Caribbean have a 10% annual chance of experiencing a hurricane, and areas with smaller risk of impacts (1-5% annual chance) are located in the southern part of the Caribbean, including northern Venezuela and northern Colombia (Pielke et al. 2003).

These intense storms originate in the Atlantic Ocean, off the northwest coast of Africa north of the equator (Fig. 5). They track from east to west and exhibit counter-clockwise wind circulation around a center of low barometric pressure. As a result of this pattern, coasts facing east and north are the most exposed to impacts. Exceptionally, Hurricane Lenny (1999) formed within the region tracking from west to east.

The Atlantic basin shows a very peaked season from August through October, with 78% of the tropical storm days, 87% of the minor (Saffir-Simpson Scale categories 1 and 2) hurricane days, and 96% of the major (Saffir-Simpson categories 3, 4 and 5) hurricane days occurring then. Maximum activity is in early to mid September. Once in a few years there may be a tropical cyclone occurring out of season - primarily in May or December.

Although most of the hurricane tracks do not experience landfall on the northern South American coast, Hurricane Joan (October 1988) produced impacts in Venezuela and Colombia, with no precise data on economic damage or human impacts (Pielke et al. 2003).

Hurricane winds generate and propagate deep-ocean swell that can cause substantial coastal change far from the storm center. This breaking waves from distant storm sources can transport sediments inland, as documented by sandy overwash deposits observed in a village on Tierrabomba, an island south of Cartagena, Colombia, from Hurricane Lenny ~~(1999)~~, which was centered more than 500 km north of the Caribbean coast (Morton et al. 2006).

During El Niño events (ENSO warm phase), tropospheric vertical shear is increased inhibiting tropical cyclone genesis and intensification, primarily by causing the 200 mb (12 km or 8 mi) westerly winds to be stronger. La Niña events (ENSO cold phase) enhance activity. Recently, Tang and Neelin (2004) also identified that changes to the moist static stability can also contribute toward hurricane changes, with a drier, more stable environment prevailing during El Niño events.

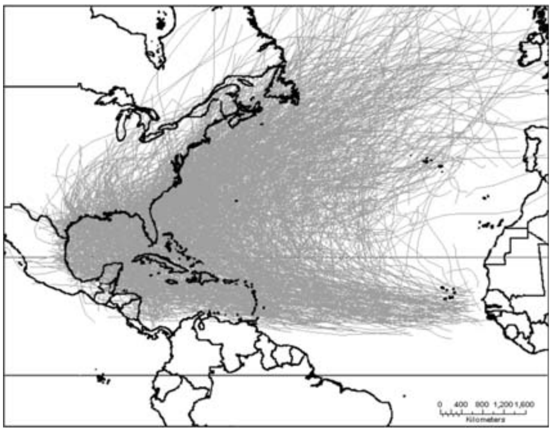

Figure 5. Historical North Atlantic Tropical Cyclone Tracks, 1851-2005 (source: National Oceanic and Atmospheric Administration; http://www.csc.noaa.gov/hurricane_tracks).

A common question is if tropical cyclones are getting stronger and more frequent in the last several years. In this respect, there is no evidence globally. However, for the Atlantic Ocean there has been an increase in the number of strong hurricanes since 1995, with a record of 33 hurricanes between 1995 and 1999. The extreme impacts from Hurricanes Marilyn (1995), Opal (1995), Fran (1996), Georges (1998) and Mitch (1998) in the United States and throughout the Caribbean attest to the high amounts of Atlantic hurricane activity lately (Central Pacific Hurricane Center, from various sources).

However, there is no evidence of a long-term increase in the intensity or frequency of Atlantic hurricanes. In fact, 1991-1994 marked the four quietest years on record (back to the mid-1940s) with just less than 4 hurricanes per year. Instead of seeing a long-term trend up or down, we do see a quasi-cyclic multi-decade regime that alternates between active and quiet phases for major Atlantic hurricanes on the scale of 25-40 years each. The quiet decades of the 1970s to the early 1990s for major Atlantic hurricanes were likely due to changes in the Atlantic Ocean sea surface temperature structure with cooler than usual waters in the North Atlantic. The reverse situation of a warm North Atlantic was present during the active late-1920s through the 1960s. It is quite possible that the extreme activity since 1995 marks the start of another active period that may last a total of 25-40 years (Central Pacific Hurricane Center, from various sources).

Hurricanes affecting the coast of South America are basically within the Atlantic Basin, at low latitudes and can be active on the northern coast of South America (Colombia, Venezuela). However, the first hurricane ever reported in the South Atlantic, Catarina, hit the southern coast of Brazil on March 28, 2004. This unprecedented event led some Brazilian meteorologists to deny that it was a hurricane at all; further analysis, however, has shown that it was (Pezza and Simmonds 2005). In a detailed study of the storm, the authors describe its evolution from genesis on March 20 2004 as an extra-tropical cyclone, through its strengthening to a category I hurricane before it drifted over land. This hurricane developed in an unusual combination of high sea surface temperatures, low vertical wind shear, and strong mid-to-high latitude blocking (which interferes with normal east-west atmospheric flow).These conditions are functions of largescale atmospheric circulation patterns in the region and could be related to climate change (Pezza and Simmonds 2005).

### *2.2 Extratropical storms*

Many storm surges have been recorded along the Argentine coast simultaneously with the northward traveling tidal wave. The duration of these storm surges range from a few hours up to two or three days. They are basically produced by the combined action of an anticyclone located to the west of Argentina (semi-permanent Pacific anticyclone) and a cyclone located over the Atlantic to the southeast of Argentina, the latter moving towards the east or northeast. Because of this situation, strong winds from the south or southwest and high water levels affect the whole Argentine coast, as well as the Rio de la Plata shores, Uruguay, and southern Brazil. The most conspicuous and worse floods in the Rio de La Plata shores and the eastern, sandy coast of the Province of Buenos Aires are due to southeasters. These are very strong winds from the southeast, often caused by an anticyclone located over southern Argentina and the adjacent ocean. But in order that water might attain an extraordinarily high level it is necessary, among other factors, that a depression forms to the north of Buenos Aires, over Uruguay and southern Brazil. Figure 6 illustrates the weather chart corresponding to the flood of 15 April 1940, when the predicted tidal level in Buenos Aires was overcome by 3.18 m, the highest level in Buenos Aires since the beginning of records in 1905. Twenty five people were killed. Similar floods were experienced in 1958 and 1959, and more recently in 1989 and 1993.

Coastal plain flooding due to storm surges can be particularly destructive in areas where topographic gradients are extremely low, such as the Rio de La Plata shores, the Salado basin, and around the Bahía Blanca estuary. Every time this phenomenon has taken place very many inhabitants have suffered severe property loss and other damage. Flooding is exacerbated by the Coriolis force piling up water as the storm surge travel along the Argentine coast, particularly within the Rio de La Plata.

Erosion processes on the sandy barriers of northern Argentina, Uruguay and Brazil are typical. The coincidence of a storm surge with spring tides has been regarded of being of the utmost importance in coastal erosion. Storm surges (southeasters) are considered the most significant natural agent for coastal erosion on the eastern coast of Buenos Aires (Schnack et al. 1998). However, it must be considered that their effects are more severe on areas of heavy human intervention (beach sand mining, urbanization, coastal construction). The effects of one such storm are shown in Figure 7b.

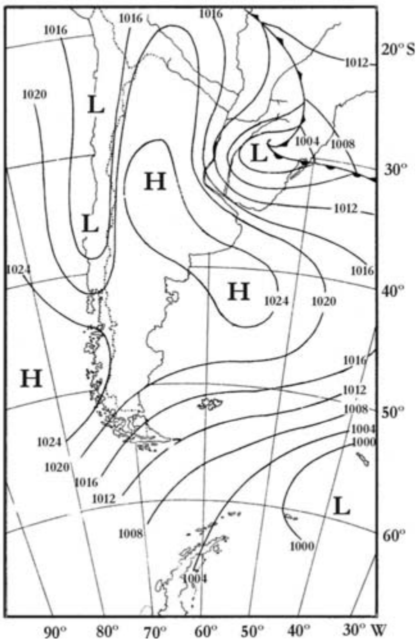

Figure 6. Synoptic chart of the severe southeasterly of 15 April 1940 in the southwest Atlantic Ocean (From Balay, M.A., 1961)

Isla and Cortizo (2005) state that the Patagonian coastline, mostly composed of cliffs, is receding at a rate of ca. 0.5 m/year. Many authors have mentioned variable rates of coastal retreat for the Buenos Aires coastline, ranging from a few meters/year to less than 1m/year (Cortelezzi et al. 1973; Schnack 1985, and others). However, a reliable regional pattern has not yet been determined. Some examples of eroding coastlines are shown in Figure 7.

Figure 7. Eroding beaches in Argentina. a) cliff showing mass movements in Patagonia. b) barrier sand with severe erosion after a southeasterly, Santa Teresita (Buenos Aires).

Beach erosion rates along the shoreline vary due to temporal effects of the refraction of storm waves induced by linear shoals (Isla and Bértola 2005). A similar situation seems to occur along the Uruguaian coast (Pivel et al. 2001).

In the State of Paraná, the pocket beach of Praia Brava in Caiobá is located between the capes of Caiobá and Matinhos. Between 1951 and 1969 this beach had a progradation of 42.1 m, it receded 1.8 m between 1969 and 1980, and the retreat increased to 14.9 m between 1980 and 1997 (Bessa and Angulo, 2001).

Logarithmic beaches from the north of the Santa Catarina island are subject to different erosion rates along their lengths. Between 1938 and 1994 Ingleses Beach, subject to waves coming from the north, receded 0.5 m/yr at the northern end and 0.95 m/yr at the southern end. The Aemacao beach is open to the east. Beach retreat is 0.1 m/yr to the northern part of the beach, and 0.5 m/yr to the southern end (Abreu de Castilhos and Gré 1997).

In the State of Rio Grande do Sul, 81.3% of the beaches are subject to erosion, 11.5% are stable and only 7.2% are accreting (Esteves et al., 2001). In Farol da Conceiçao (north of the Lagoa dos Patos inlet), coastal dunes were receding at a rate of 2.5 m/yr between 1975 and 1995 (Tomazelli et al., 1997). Further south, at Concheiros do Albardao (close to Hermenegildo), beach profiles were surveyed between 1991 and 1993. The coastline was approximately stable between 1991 and 1992; but in the interval May-June, 1993, the shoreline retreated to 13-14 m per month (Klein and Calliari 1997). Much of the erosion of the south of the State is caused by the ephemeral location of gullies (locally called “sangradouros”) that drain ponds and wetlands located between beach ridges. These sangradouros cause the erosion of frontal dunes, are are surely increasing the action of rip currents. They distribute between 0.5 to 1 per km but they are much densely spaced during the Autumn (Figueiredo and Calliari 2001).

In a similar way that hurricanes seem to be statistically more frequent, or stronger, in the last years, it is not yet known if extratropical storms in the southwestern Atlantic Ocean are more frequent or stronger. For the northwestern Atlantic Ocean, extratropical storms were more frequent in the North Carolina coast during the sixties (Dolan and Hayden 1981). In the Mid-Atlantic coast of USA, for example, a storm with waves of 3.4 m occur every 3 months (in winter months they are more frequent); waves of 5 m occur every 3 years, and waves of 7 m happen every 25 years (Dolan et al., 1987). Statistical data is (are?) crucial to forecast the threat of the sand barriers of mid-latitude coasts of South America (Argentina, Uruguay and Southern Brazil).

## 3. TSUNAMIS

Typical tsunamis consist of a series of high-energy, long period waves of small steepness usually caused by ocean floor displacements. Most tsunamis are produced by co-seismic seafloor displacements, others are generated by underwater landslides, and a small number are the result of volcanic eruptions. Actually, tsunami generation involves complicated interactions among earthquakes, landslides, and sympathetic vibrations between the quake and the ocean above it. In general, scientists believe that it requires an earthquake of at least magnitude 7 to produce a tsunami. Calving of glaciers and the extremely rare meteorite or asteroid impact in the open ocean should also be considered among possible generation mechanisms. Of all 2250 tsunamigenic events historically known, only 223 (about 10%) resulted in human fatalities.

### *3.1 Trans-oceanic tsunamis*

Trans-oceanic tsunamis, capable to transmit their energy far away from the source area, are quite rare events as compared to local and regional events, however, they are responsible for a considerable part of damage and fatalities resulted from all tsunamis.

The 11 trans-oceanic tsunamis that occurred in the World Ocean during the last 250 years are responsible for 372,000 fatalities (Table 1). Among them, 280,000 people were killed during just one event - the December 26, 2004 Indian Ocean tsunami. The signal of this tsunami was felt in several areas around the globe (Titov et al. 2005), reaching the east coast of South America at several localities within 20-24 hours, with maximum wave heights ranging from 0.15 m (Mar del Plata, Argentina) to 1.22 m (Imbituba Port, Brazil) (Table 2; Dragani et al. 2006). At Callao (Perú) and Arica (Chile) wave amplitudes >50 cm were recorded, indicating a close correspondence to the predominant directions of tsunami energy propagation (Titov et al. 2005).

Other 10 trans-oceanic tsunamis are responsible for 92,000 deaths that is only 13% of all tsunami-related fatalities. Three of them caused severe impacts on the coast of Chile, with a death toll of few thousand people altogether (Table 1).

**Table 1.** The list of historically known trans-oceanic tsunamis occurred in the World Ocean during the last 250 years (source: Tsunami Laboratory, Novosibirsk, Russia: http://tsun.sscc.ru).

| **Date and place** | **Magnitude** | **Max run-up near the source, m** | **Max run-up in the far-field, m** | **Fatalities** |
|---|---|---|---|---|
| November 1, 1755 Lisbon | 8.5 | 18 | 7.0 | 40000 |
| November 7, 1837 Chile | 8.5 | 8 | 6.0 | many |
| August 13, 1868 Chile | 9.1 | 18 | 10 | 3000 |
| August 27, 1883 Krakatau | | 36 | 1.5 | 36000 |
| February 3, 1923 Kamchatka | 8.3 | 8 | 6.1 | some |
| April 1, 1946 Aleutians | 7.4 | 42 | 18 | 165 |
| November 4, 1952 Kamchatka | 9.0 | 18 | 9.1 | >10000 |
| March 9, 1957 Aleutians | 9.1 | 15 | 10 | none |
| May 22, 1960 Chile | 9.5 | 18 | 12 | 1180 |
| March 28, 1964, Alaska | 9.2 | 68 | 6.0 | 123 |
| December 26, 2005 Sumatra | 9.3 | 34 | 9.1 | 280000 |

The characteristics of the Chilean transoceanic tsunamis are described below:

**November 7, 1837: Valdivia, Chile**

An 8.5 Ms destructive earthquake hit the southern coast of Chile on November 7, 1837 with epicenter near Valdivia, Corral and Ancud. Waves reached 8 m at the nearest Chilean coast. 6-m waves were observed in Hilo, Hawaii after almost 14 hours of propagation time *(Walker,* *1994*). There is no quantitative data on the number of victims in Chile, but in Hawaii it caused 58 fatalities.

### August 13, 1868 Arica, Chile

A destructive 9.1 Mw earthquake with epicenter near Arica, northern Chile resulted in 18-m tsunami waves that in 20-30 min after the quake hit the nearest Peruvian and Chilean coast. Data on resulted fatalities are fragmentary, but one can guess that at the nearby coast the tsunami took several thousand victims. Outside the source area, the largest waves (up to 10 m) were observed at the Chatham Islands at the distance almost 10,000 km (DeLange and Healy, 1986). Along the east coast of New Zealand waves were of 3 to 5 m in high. These waves turned out to be the most severe far-field tsunami observed in New Zealand during the 160-year period of available observations. DeLange and Healy (1986) list this tsunami as having caused loss of life in New Zealand, however, they do not give any numbers for fatalities. Five-meter waves reached Hawaii causing 47 fatalities (O'Loughlin, Lander, 2003).

### May 22, 1960 Chile

On May 22, 1960 a magnitude 9.5 Mw earthquake, the largest earthquake ever instrumentally recorded, occurred in Southern Chile **(Fig.8a)**. The earthquake ravaged the vast area along nearly 1000-km of the Chilean coast. The main shock generated a destructive tsunami that hit the nearest coast with 8-10 m waves. The maximum waves, reaching 15 m in high, were observed along the 350-km section of the coast between Corral and Concepción. Number of reported fatalities varies in different sources from 490 to 5,700; 1000 fatalities is a reasonable assumption. In 15 hours, 8-10 m waves reached Hawaii (reported maximum was 12.1-m wave observed at Ahukini Point on the Kauai Island) and caused 61 fatalities in Hilo, despite the advance warning was given and warning sirens sounded more than 3 hours before the first wave arrived. In 22 hours, the waves reached the east coast of Japan, still having 5-6 m in high. More than 10,000 houses were destroyed and 122 people died (Tsunami Laboratory, Russia 2006).

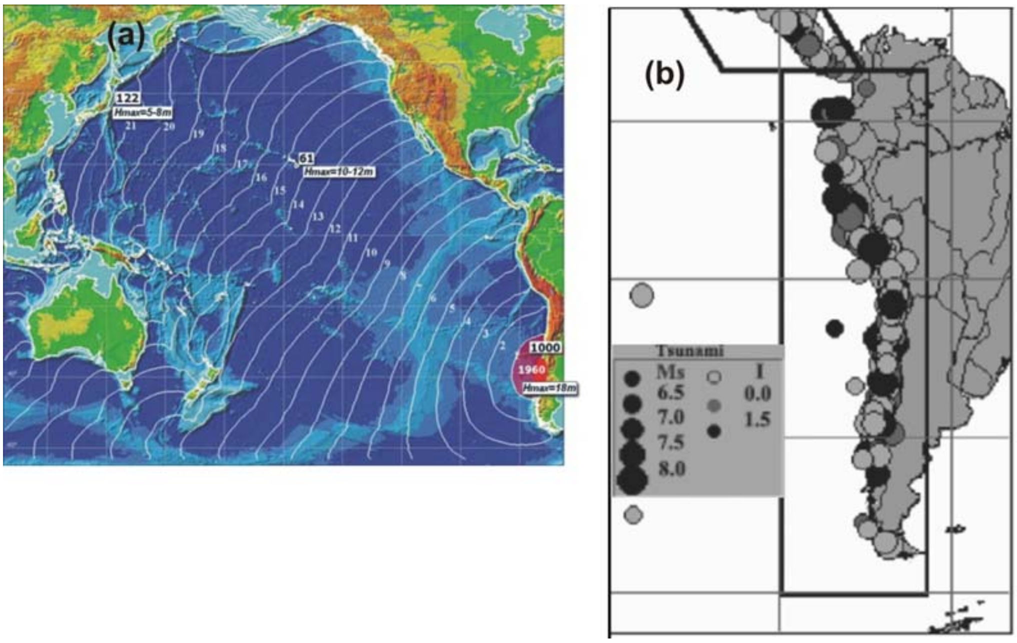

**Figure 8**.a) Travel time chart for the 1960 Chilean tsunami (source: Tsunami Laboratory, Novosibirsk, Russia: http://tsun.sscc.ru). b) Boundaries of the main tsunamigenic regions in the Pacific coast of South America. Circles show source positions of the tsunamigenic earthquakes that occurred in the Pacific from 1901 to 2000. The size of circles is proportional to the magnitude Ms, density of grey tone–to the tsunami intensity I (adapted from Gusiakov, 2004).

### *3.2 Regional tsunamis*

All historically known tsunamis sources are located within the continental slope or the shelf at the average distance of 150-200 km of the coastline.

#### *Pacific coast of South America*

Due to seismotectonic features of the region, the sources of all tsunamigenic events are located within the area with 20-min propagation time limit. For many South America tsunamis, their sources were located partly in-land, so the first wave arrived almost simultaneously or shortly after the end of seismic shaking caused by the fault rupture

**Table 2**. Arrival time (UTC), travel time (h), maximum wave height (m) and duration of sea level activity (h) obtained from the sea level records gathered at stations located in the Southwestern Atlantic Ocean (after Dragani et al. 2006).

| **Station** | **Arrival time (UTC)** | **Travel time (h)** | **Max. wave height (m)** | **Duration of sea level activity** |
|---|---|---|---|---|
| Cananeira, Brazil[1] | Dec. 26, 20:45 | 19.77 | 0.20 | 54 |
| Ubatuba, Brazil[1] | Dec. 26, 22:00 | 21.02 | 1.20 | 53 |
| Port Stanley[2] | Dec. 26, 22:23 | 21.40 | 0.44 | ~48 |
| Arraial do Cabo, Brazil (22º57´S, 42º01´W)[a] | Dec. 26 22:57 | 21.97 | ~0.90 | ~48 |
| Mar del Plata | Dec. 27, 00:15 | 23.27 | 0.15 | 40 |
| Santa Teresita | Dec. 27, 00:48 | 23.82 | 0.27 | 54 |
| Imbituba Port (28º13´S, 48º39´W)[b] | Dec. 27, 03:20 | 26.35 | 1.22 | ~40 |
| Puerto Belgrano | Dec. 27, 04:45 | 27.77 | 0.20 | [c] |

[a] Candella 2005 http://www.pmel.noaa.gov/tsunami/indo20041226/IEAPM.html

[b] Mello and Rocha 2005 http://www.pmel.noaa.gov/tsunami/indo20041226/tsunami-southernbrazil.pdf

[c] Truncated record – the tide gauge did not work after December 28, 2004, 02:00 UTC.

[1] Franca and de Mesquita 2006 (see Refs.)

[2] Woodworth 2005 (see Refs.)

(Gusiakov 2004; Fig. 8b). In other cases, they are produced within the same basin, which in the case of the Pacific is large enough to permit tsunami waves traveling over long distances.

A few historical events are described :

On July 9, 1589, a tsunami affected the coasts of Lima. The level of the ocean rose 4 fathoms destroying properties in the 300 m close to the shoreline (22 victims in Lima). The tsunami was triggered by an eartquake (intensity VII) close to the coasts of Lima.

The coast of Pisco (Ica) was shocked (earthquake VI) on May 12, 1644. The coast was flooded and 70 inhabitants died. Another earthquake on June 17, 1678 (intensity VII), north of Lima, cuased severe damages at El Callao harbour; the sea receded before advancing. In

October 20, 1687, another earthquake north of Lima (intensity IX) destroyed much of that city (200 inhabitants died).

A confirmed tsunami was recorded on November 26, 1705. Large waves hit the shoreline between Arequipa (Perú) to Arica (Chile) where the damages were more severe.

An intense earthquake (IX) that took place in Camaná caused significant damages in Pisco on February 10, 1716.

The worst tsunami affecting the coast of Perú was recorded at El Callao harbour on October 28, 1746. Waves of 7 m caused the sinking of 19 ships (one of these was found 1.5 km to the interior). Diseases were estimated in about 5-7 thousands. Other harbours affected were Chancay and Huacho.

Another tsunami affected El Callao on December 1, 1806. Waves higher than 6 m transported several ships to the shoreline, including a ancor of 1,5 tons.

Several coastal cities were destroyed the morning of March 30, 1828. The tsunami was triggered by an earthquake intensity VII.

A very detailed account of the effects of the earthquake that affected the Chilean localities of Valdivia, Concepción and Talcahuano, among others, on February 20, 1835, was provided by Charles Darwin (1845):

*"February 20th. -- This day has been memorable in the annals of Valdivia, for the most severe earthquake experienced by the oldest inhabitant. I happened to be on shore, and was lying down in the wood to rest myself. It came on suddenly, and lasted two minutes, but the time appeared much longer. …. The tides were very curiously affected. The great shock took place at the time of low water; and an old woman who was on the beach told me that the*

*water flowed very quickly, but not in great waves, to high- water mark, and then as quickly returned to its proper level; this was also evident by the line of wet sand.*

*March 4th. -- We entered the harbour of Concepcion. While the ship was beating up to the anchorage, I landed on the island of Quiriquina. The mayor-domo of the estate quickly rode down to tell me the terrible news of the great earthquake of the 20th: -- "That not a house in Concepcion or Talcahuano (the port) was standing; that seventy villages were destroyed; and that a great wave had almost washed away the ruins of Talcahuano." Of this latter statement I soon saw abundant proofs -- the whole coast being strewed over with timber and furniture as if a thousand ships had been wrecked. Besides chairs, tables, book-shelves, etc., in great numbers, there were several roofs of cottages, which had been transported almost whole. The storehouses at Talcahuano had been burst open, and great bags of cotton, yerba, and other valuable merchandise were scattered on the shore. During my walk round the island, I observed that numerous fragments of rock, which, from the marine productions adhering to them, must recently have been lying in deep water, had been cast up high on the beach; one of these was six feet long, three broad, and two thick….. Shortly after the shock, a great wave was seen from the distance of three or four miles, approaching in the middle of the bay with a smooth outline; but along the shore it tore up cottages and trees, as it swept onwards with irresistible force. At the head of the bay it broke in a fearful line of white breakers, which rushed up to a height of 23 vertical feet above the highest spring-tides.”*

An earthquake originated in the coast of Chile on May 9, 1877, caused a tsunami that affected the shorelines of Japan, New Zealand, Samoa islands, California and Hawaii. In the Eastern Pacific Ocean, high waves arrived from Pisco (Perú) to Antofagasta (Chile). Tha maximum wave measured was of 23 m in Arica.

On January 10, 1878, the ocean flooded several coastal cities between Arequipa and Iquique. Maximum wave height was recorded at Tanna Island (12 m).

On January 31, 1906, an earthquake occurred in Ecuador at a depth of 25 km and with a magnitude of 8.6 (Melcalli). The area shocked was about 1200 km between Guayaquil and Medellín. Towards Bogotá the width of the earthquake was evaluated in about 350 km, covering an area of 300.000 km$^2$. Half and hour after the shock a tsunami arrived at Tumaco (Colombia); 20 minutes later arrived the second wave, and the situation continued for about 4 hours. Fortunately, these waves arrived during the low tide. Water levels of 2-5.9 m above the islands were estimated in the Colombia coastline (Herd et al., 1981). The low-lying coasts were more affected. Buildings settled close to the beach or at the estuarine areas of the rivers Santiago and Mataje were destroyed. 1000 to 1500 inhabitants died. In Tola, 23 houses were destroyed. In Esmeraldas, the river flooded the village. In Bahía Caraquez, the level of the water rose 0.8-1.0 m in only 20 minutes. On the oposite hand, in Manta and Buenaventura the sea level dropped 2 m.

On October 2, 1933, another earthquake (6.9 Richter magnitud) occurred offshore Ecuador. Significant waves occurred at La Libertad, Santa Elena Peninsula. A submarine cable broke 25 km south of Salinas. Sea level dropped inmediately to the land movement (10.30 AM), but after and hour the level rose to the high-tide mark. At mid-day the level dropped again to the low-tidel level, and rose again at 14.00 hours. Fluctuations of about 2-2.5 m occurred in only 3.5 hours.

A submarine movement occurred close to Pisco on August 24, 1942, causing damages in Matarani and El Callao. The original earthquake had a magnitude 8.1 and occurred at 60 km.

The earthquake that took place on April 1, 1946, on the Aleutian islands, affected the American coast from Colombia to Chile. Long-period waves were more significant in Iquique where sea level rose 5 m. In Valparaíso, the ocean extended 100 m landwards. Great alarm was caused although there were no deaths.

On November 4, 1952, another tsunami coming from Kamchatka, Siberia, affected the Pacific coast from Ecuador to Chile; most severe impacts were registered at the coastlines of Antofagasta (waves arrived at 8 AM) and Talcahuano (11 AM). In Chile, the sea level rose 3.7 m while the sea extended 500 m inlands, without victims. Tide gauges recorded 1.9 m in Libertad (Ecuador), and 2.0 in El Callao.

Another earthquake produced close to the border between Perú and Ecuador affected La Libertad coast on December 12, 1953. The magnitude of the event was about 7.3, and non-destructive oscillations were only 0.2 m in height.

The tsunami that originated in the North Pacific on March 9, 1957, did not cause signficant damages in Chile (1.0 increase in tidal gauges) or El Callao (only 0.25 m).

On January 19, 1958, an earthquake (7.8 degrees Mercalli) occurred close to the border between Colombia and Ecuador; the areas affected were the coasts of Tumaco and Esmeraldas. Tsunami waves of 2.0 to 5.9 m caused 4 deaths.

The energetic Chilean earthquake of May 22, 1960, produced a huge tsunami at the northern Pacific Ocean (Hawaii and Japan). The sea withdrew for 10-20 minutes and then returned; similar behaviour of the sea was reported in Cumberland Bay, Juan Fernández archipielago, 480 km offshore the continent. The third and fourth waves were reported as the highest. A ship of 3000 tons was washed onto the beach in Mocha island. In some places (Bahía Mansa, Maullín) the first action was a rise in sea level (Saint-Amand, 1961). In Lebu, Arauco Peninsula, a beach uplifted 1.5 m but in the last 5 months it turned to its original level. In Perú the sea level increased 2.2 m in El Callao.

The earthquake of Alaska (Kodiak, March 28, 1964) also affected the coasts of Perú and Chile; in El Callao a wave of 1.5 m was recorded.

On October 3, 1974, a seismic movement occurred at the sea in front of El Callao. The sea flooded some bays north of Lima (Chimú, Tortugas).

About 3-4 tsunami waves also occurred in Esmeraldas (Ecuador) on December 12, 1979. The so-called Tumaco earthquake was triggered at the frontier between Colombia and Ecuador. These movement took place 33 km deep. As the waves arrived during low tide, no significant damages were recorded (Herd et al. 1981).

On February 21, 1996, a seismic movement (6.9 Richter scale) originated 210 km to the SW of Chimbote caused 15 deaths at this town.

On November 12, 1996, an earthquake 6.4 degrees magnitude was recorded 93 km to the SW of San Juan de Marcona, and at a depth of 46 km. A tsunami was triggered causing damages and human losts.

In this century, a tsunami generated from an earthquake (6.9 degrees in the Richter scale) that occurred at the ocean close to Ocoña (June 23, 2001). Only 3 waves were remembered but with a height of 8 m. 23 persons died and 69 dissapeared.

*Caribbean Sea*

The Intra-Americas Sea (IAS) plate is characterized by subaerial and submarine active volcanoes, steep continental slopes and frequent earthquakes. Some of the submarine earthquakes, eruptions and subaerial or submarine slumps can generate tsunamis. In the central Lesser Antilles several collapses have occurred in the last 10 000 to 20 000 years at volcanic sectors. The region has experienced tsunamis since at least from the 16th century.

The origin of these events has been both local and from distant sources, and one or more events per century have been recorded: Venezuela, 1530; Jamaica, 1692; Martinique, 1755; St. Thomas, 1867; Puerto Rico, 1918; Dominican Republic, 1946). In addition, as mentioned before, the Lisbon earthquake of 1755 generated a tsunami with 6 to 7 m waves in the Lesser Antilles.

In the last 150 years, tsunamis have caused about 2000 in the IAS. The 1867 event in the US Virgin Islands is a true precedent to the 1998 event that occurred in Papua New Guinea: superimposed earthquake epicenters, a great instantaneous tsunami, and densely populated coastal settlements. Historical events are shown in Figure 9 and Table 3 provides a list of tsunamis that affected the coast of Venezuela.

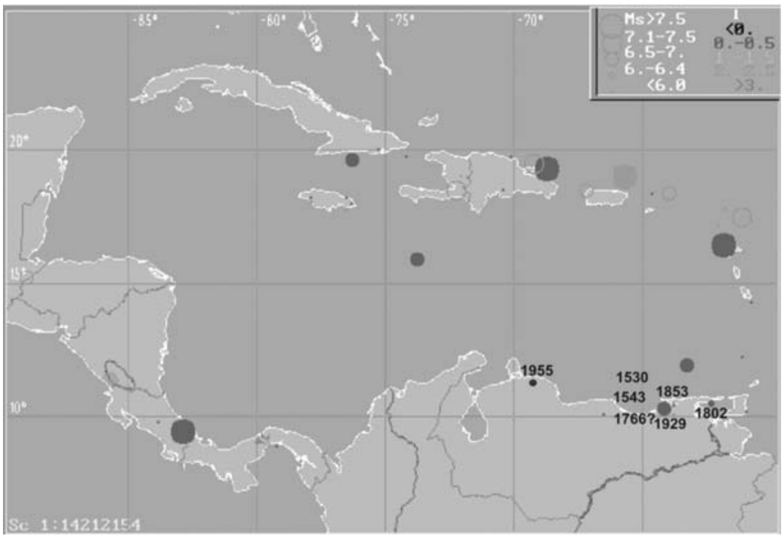

Figure 9. Historical tsunamigenic events in the Caribbean region from 1530 to 1991. Recorded events number 57. However, not all events are presented on this map, because 11 events lack their source coordinates. The dates are only shown for the South American coast where tsunamis with reliable information are indicated. The size of circle is proportional to the event magnitude. However, in the case of Cumaná there are 5 events recorded with different magnitudes (sources: Lander and Whiteside 1997; Schäffers, 2002; Tsunami Laboratory, Novosibirsk, Russia: http://tsun.sscc.ru).

**Table 3**. List of Caribbean tsunamis affecting the coast of Venezuela (selected from Lander and Whiteside, 1997).

| | | |
|---|---|---|
| 1530 09 01 | Paria<br>Cumaná<br>Cubagua | Sea rose 7.3 m and sank again near coast of Paria and at Cumaná and near Island of Cubagua. Ground opened emitting black salt water and asphalt. Mountain at the side of the Gulf of Cariaco was cleft (earthquake). A fort and many houses destroyed, but not clear whether due to the wave, the earthquake or both. |
| 1543 | Venezuela | Waves noted. City of Cumaná destroyed by earthquake? |
| 1766 10 21 [9:00 UT] | Cumaná, Venezuela | Very violent shocks raised Cumana and caused the island of Orinoco to sink and disappear. In many places the water surface was disturbed. This is a possible tsunami report. |
| 1802 08 05 | Orinoco River, Venezuela | Earthquakes at Cumaná caused the water of the Orinoco River to rise so high as to leave part of the bed dry. This could describe wave action near the mouth of the river, or bore action. The rudder of a vessel was broken |
| 1853 07 15 | Cumaná, Venezuela | A violent earthquake (MMI=X) in Cumaná was followed by a tsunami |
| 1929 01 17 | Cumaná, Venezuela | City was destroyed by an earthquake (Ms=6.9) and a steamer off shore was endangered by a huge wave. The tidal wave following the earthquake caused much damage. Many sailboats were wrecked. |
| 1955 01 18 | La Vela, Venezuela | A wave was reported; four ships were wrecked and four waterfront buildings damaged. An earthquake (Mb=5.5) off the coast of Panamá is listed for this time. |
| 1968 09 20 [6 09 UT] | | A report of a tsunami has not been verified. Hurricane Edna was passing north of Venezuela at this time and an earthquake (Ms=6.2) occurred near the coast of Venezuela |

### *Southwest Atlantic Ocean*

No evidence is yet available for tsunami events in the southwest Atlantic Ocean. However, the southernmost portions of the ocean (Scotia Plate and Tierra del Fuego) are tectonically-active areas. In addition, glacial calving and submarine slumps can occur in the southern ocean. Hence exposure to tsunami should not be disregarded in certain areas located in the southernmost region (Schnack and Pousa, 2004). On December 17, 1949, an earthquake affected the island of Tierra del Fuego. The epicenter was located in Dawson Island, southern Chile (7.75 Richter scale). At the Atlantic coast of the Grande Island (close to Rio Grande), the San Pablo lighthouse tilted 15 degrees (Isla and Bujalesky 2004). In Punta Arenas (Chile), 3 deaths were reported as a consequence of the earthquake.

## 4. ENSO EFFECTS

ENSO (El Niño-Southern Oscillation) cycle is a fluctuation between anomalous warm (El Niño) and cold (La Niña) conditions in the tropical Pacific with a 2-7 years recurrence. ENSO is the strongest and most predictable natural variation of Earth´s climate on year-to-year time scales and has impact on physical, geological, biological and chemical processes in the oceans and atmosphere, and on terrestrial ecosystems. In addition, socio-economic impacts are very important on a global scale (McPhaden et al. 2006).

Changes in precipitation patterns in response to El Niño warming in the central and eastern Pacific cause drought in Australia, Indonesia and other areas in the region, while the islands of the central Pacific and the west coast of South America are frequently affected by heavy rains and flooding.

South America is particularly subject to inter-annual changes triggered mainly by the humidity and temperature transport from the western to the eastern Equatorial Pacific. They severely impact either in coasts of high slopes (Perú, Chile, Ecuador) and in low-lying coastal plains (Argentina, Brazil, Uruguay); but the main direct effects on the coastline occur in the Pacific region. Along this region, a positive phase (El Niño) usually results in heavy rainfall and the occurrence of mass movements on the slopes facing the coastal zone. Other effects are the flooding of rivers draining onto the shore, erosive processes and other morphological changes at the shore and nearshore, as it was registered in Ecuador during the 1982-1983 event (Tutivén Ubilla 1998).

A sea level anomaly is also registered during El Niño events, causing an increase in global mean sea level (Fig. 4b).

The coastal and island populations of Ecuador were dramatically affected during the 1997-98 El Niño season. Increases in sea level and wave action, due to Kelvin waves from storms in the northern Pacific, caused coastal erosion at the shoreline, destroying any structures near the beaches.

Historically, El Niño causes a high increase in wet conditions on the Paraná-La Plata basin, and severe flooding takes place during strong events, such as in 1982-1983 and 1997-1998 (Andersen and Díaz 1993; Arntz and Farbach 1996; McPhaden et al. 2006).

The mud derived from the Amazon river seasonally affects the coast from northern Brazil to Venezuela. In Cayenne (French Guiana), pocket beaches can be protected from wave attack when this mud is embanked. Without this "mud protection" these beaches are subject to wave attack ("interbank phase") and washover phenomena (Dolique and Anthony 2005).

The barrier island of El Choncho, is related to the San Juan river delta (Western Colombia). During the 1997 El Niño event there was a rapid beach retreat, the opening of a new inlet, flooding of small villages with destruction of coastal-protection structures (Morton et al. 2000). During this period, ocean waves were less than 1 m, and onshore wind speed was less than 2 km/hr. The occurrence of non-storm washovers were therefore assigned to the regional increase of 20-30 cm in the sea level triggered by the thermal expansion of the Pacific Ocean (Morton et al. 2000).

## 5. ANTHROPOGENIC EFFECTS

Although shorelines in South America are affected in various ways by natural processes, the human action has exacerbated erosion processes. One example is the beach erosion along the

Buenos Aires coastline. Many localities have evolved in the past decades with an increasing number of seasonal and permanent residents, resulting in unplanned urbanization, development of resort facilities, beach mining for building purposes, and salt intrusion into coastal aquifers, among other problems. The most noticeable response has been the emplacement of hard structures to protect the beaches and the coastal facilities. But many of these structures have caused a diminished suply of sand to areas located northward (direction of the net littoral drift). One remarkable case of rapid shoreline retreat was observed at Mar Chiquita beach, north of Mar del Plata (Argentina), where a more than 6 m/year retreat was registered from 1957 to 1979 (Schnack et al. 2005) (Figure 10).

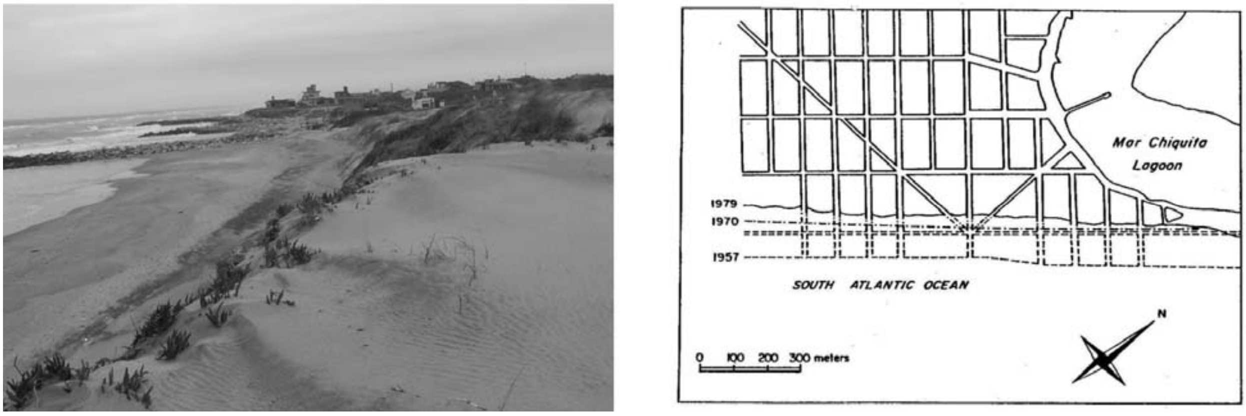

Figure 10. Erosion at Mar Chiquita beach between 1957 and 1979 (after Schnack 1985). The retreat was controlled by defense works of local effect. Photograph showing present situation.

In other places along the Buenos Aires coastline erosion rates are variable, depending on sand supply and degree of human intervention, whereas in other localities without occupation the coastal systems seem balanced or even accreting.

The shoreline of the Unare coastal lagoon (Venezuela) has retreated at a rate of 7.5 m/year (150 m between 1961 and 1980; Pacheco and Suárez, 2004). The Unare river arrived to the Caribbean Sea between the coastal lagoons of Unare and Piritu (Fig. 11**),** supplying sediments to the longshore spits where the villages of El Hatillo and La Cerca were settled. As this coast is not significantly impacted by physical effects (storms, hurricanes, earthquakes, sea level rise), these authors concluded that much of the erosion is caused by the sediment trapping by the 12 dams of the Unare river, whose accumulation was estimated in about 2,260.000 $m^3$/year (Pacheco and Suárez 2004).

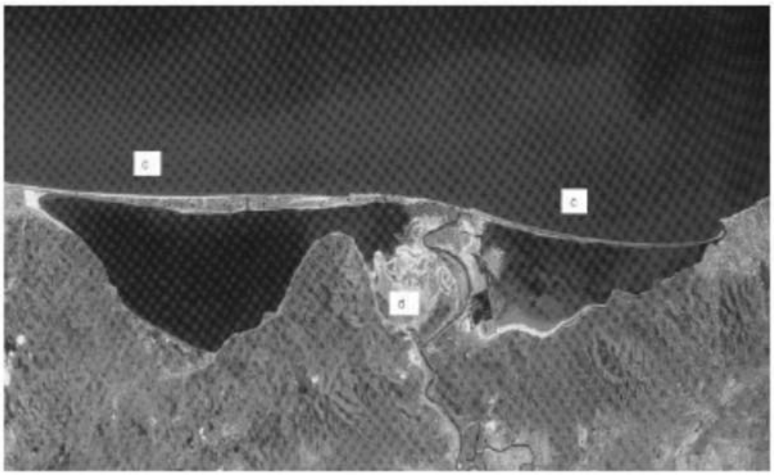

Fig. 11. The costal lagoons of Unare (west) and Piritu (east) are separated from the Caribbean Sea by coastal spits (c). The river Unare discharges between both lagoons forming a delta (d) (from Pacheco and Suárez 2004).

Coastal erosion along the coastline between Ilheus and Vitória, Eastern Brazil, is subject to strong trade winds from the NE. Old inhabitants from Alcobaça pointed that this erosion increased in the last 30 years, when beaches receeded 30-40 m. It was concluded that this erosive dissequilibrium should be assigned to the peak in the deforestation activities (Addad and Martins-Neto, 2000). At the same time, at the city of Ilheus the construction of a jetty in 1971 provoked the progradation of 340 m of the Praia do Porto ( 13 m/yr on the updrift side) and the erosion of 80-150 m at Praia do Norte (3-5.7 m/yr at the downdrift side; Apoluceno et al. 1997).

The preceding few examples are just to show the influence of man in coastal systems. There are additional consequences of human intervention, resulting in the degradation of coastal salt marshes and mangrove swamps, or the exhaustion of water resources on dune fields. All those interventions exacerbate the vulnerability of the coastal environments to natural hazards.

## CONCLUDING REMARKS

There have been speculations about the future occurrence of episodic processes associated with global warming and the rapid sea-level rise scenario. Tropical cyclones and extra-tropical storms, as well as, for example, ENSO-linked processes, may increase their frequency and intensity, and most likely their impact would affect larger coastal areas in South America.

1. It is widely accepted that global **sea-level rise** (between 1 and 2 mm/year) is causing impacts on coastal systems, whose effects can be seen in many sandy barriers around the world. An acceleration of sea-level rise, which could reach a global average between 0.1 m and 0.9 m during the twenty-first century, would certainly exacerbate erosion processes and would provoke serious constraints on coastal systems, particularly along the east and north coasts of South America.
2. Inter-annual processes (**ENSO**) affecting the Pacific coast, are also responsible for coastal changes in the east South American coast, and perhaps many effects of the teleconnection are still unknown.
3. Although independent from climate-driven mechanisms, the more unpredictable **tsunamis** may also pose an increasingly serious threat to coastal populations in densely-populated areas, both on the Pacific and Caribbean shores. An unlikely but yet possible coincidence of a storm surge, spring tide, and tsunami on a major coastal city would cause devastating consequences on human lives and property. Such an event could be possible in the Caribbean Sea, where coasts are exposed to tsunami and also to tropical storms. Another case could be the Pacific shore if a tsunami occurs during a strong positive El Niño.
4. On a regional perspective, the **vulnerability** of coastlines to episodic processes will increase, particularly because coastal systems are already subject to human occupation and intervention. Statistical data about storm waves would permit to be better prepared for the climate change affecting our coasts.  Ecosystems, human lives and property can

be severely damaged, thus response strategies must consider the development of predictive tools, public education, alarm systems and evacuation plans. Some of these procedures are already in place in many areas vulnerable to storm surges and tsunamis.

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