ENSO-triggered floods in South America: correlation between maximum monthly discharges during strong events

Federico Ignacio Isla

Instituto de Geología de Costas y del Cuaternario (UNMDP-CIC)

Instituto de Investigaciones Marinas y Costeras (UNMDP-CONICET)

Funes 3350, Mar del Plata 7600, Argentina, +54.223.4754060, fisla@mdp.edu.ar

Abstract

ENSO-triggered floods altered completely the annual discharge of many watersheds of South America. Anomalous years as 1941, 1982-83, 1997-98 and 2015-16 signified enormous fluvial discharges draining towards the Pacific Ocean, but also to the Atlantic. These floods affected large cities built on medium-latitudinal Andes (Lima, Quito, Salta), but also those located at floodplains, as Porto Alegre, Blumenau, Curitiba, Asunción, Santa Fe and Buenos Aires. Maximum discharge months are particular and easily distinguished along time series from watersheds located at the South American Arid Diagonal. At watersheds conditioned by precipitations delivered from the Atlantic or Pacific anti-cyclonic centers, the ENSO-triggered floods are more difficult to discern. The floods of 1941 affected 70,000 inhabitants in Porto Alegre. In 1983, Blumenau city was flooded during several days; and the Paraná River multiplied 15 times the width of its middle floodplain. That year, the Colorado River in Northern Patagonia connected for the last time to the Desagûadero – Chadileuvú - Curacó system and its delta received saline water for the last time. During strong ENSO years the water balances of certain piedmont lakes of Southern Patagonia are modified as the increases in snow accumulations cause high water levels, with a lag of 13 months. The correlation between the maximum monthly discharges of 1982-83 and 1997-98 at different regions and watersheds indicates they can be forecasted for future floods triggered by same phenomena. South American rivers can be classified therefore into ENSO-affected and ENSO-dominated for those within the Arid Diagonal that are exclusively subject to high discharges during those years.

Keywords: floods, El Niño-Southern Oscillation, South America, maximum monthly discharges

1. Introduction

El Niño events were known before the Spanish colonized the Peru region because of their consequences on the anchovy fishery. They were also known by seasonal heavy rainfalls and rapid floods in tropical South America. Their origin is well known: immense volumes of water transported across the Pacific Ocean during certain anomalous years, the so-called "*El Niño*" or ENSO years (Vargas et al. 2000; Andreoli and Kayano 2005).

Bjerknes (1969) postulated that ENSO originates when Sea Surface Temperatures (SST) anomalies in the Pacific Ocean cause trade winds to strengthen or slacken driving ocean circulation changes that induce changes in the SST. Although much information has been collected from different projects (TOGA, TAO-TRITON, ECMWF) there is still some doubts about the interactions that triggered ENSO events (Kleeman and Moore 1997; Neelin et al. 1998; Sheinbaum 2003, Dijkstra 2006). Although this interannual anomalous years are known by their climatic and oceanographic consequences, their hydrological responses in South American rivers have not been carefully reported. One to the main reason is the lack of information about rains records (Sun et al., 2015) and also of long and continuous hydrological records (Ward et al. 2016).

Rapid floods at the Andes watersheds occur during strong ENSO years, impacting in Peru, Ecuador and Northern Chile. They are significantly recorded when they affect arid watersheds comprised within the South American Arid Diagonal. However, these interannual floods also affect extended Atlantic watersheds of rivers as the Paraguay, Bermejo, Pilcomayo and Salado. This manuscript reports the available records of these floods -in their monthly periodicity-, compiled at national agencies of different countries (Ecuador, Peru, Chile, Paraguay, Brazil, Argentina and Uruguay). Environmental and social impacts of these floods in South America were reported considering especially that the floods triggered by El Niño-La Niña are significantly important (Ward et al. 2016).

2. Climate

Central South America has a subtropical to temperate climate. Humidity is provided from the east by trade winds from the anti-cyclonic center of the South Atlantic. Further south, humidity is also provided by westerly winds from the South-Pacific anti-cyclonic center. Between both humid areas, the Arid South American Diagonal (ASAD) extends from N to S, connecting the Atacama and Patagonian deserts (Fig. 1). Climate is considered as the main variable governing the suspended sediment yields from catchments located to the E of the Andes between Ecuador and Bolivia, either in its variability or indirectly conditioning the vegetation cover (Pepin et al. 2013). Along the coast of Chile, rainfall increases from north to south (Valdés-Pineda et al. 2014; Araya Ojeda and Isla 2016). On the other hand, along the Eastern Patagonia coast, rainfall increases northwards (Coronato et al. 2008).

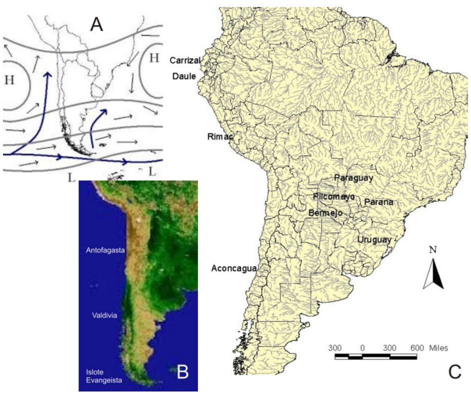

Fig. 1. A. Anti-cyclonic centers ejecting winds from the east and west. B. South America is characterized by the ASAD connecting Atacama and Patagonia deserts. C. Major rivers of South America.

South America has significant temporal changes in its interannual precipitation. Precipitation has a linear response to El Niño occurrences (Andreoli and Kayano 2005). With regard to long-term precipitation, south of 15°S, there were positive jumps east of the Andes, with a negative trend toward the west (Minetti and Vargas 1997). Historical positive jumps occurred between 1946 and 1960, while the negative trend diminished from north (Antofagasta station) to south (Islote Evangelista meteorological station; Fig. 1B).

In Southern Chile, and according to records measured at Valdivia (Fig. 1B), there was a significant decrease in precipitations between 1901 and 2005 (González-Reyes and Muñoz 2013). On the other coast, at the Argentine Pampas, there was an increase of 50-200 mm in the annual rains comparing two intervals: 1947-1976, and 1977-2006 (Forte Lay et al. 2008). The Pampa Region reports increments in precipitation rates during the last decades of the 20th century (Scarpatti and Capriolo 2013). Several authors point to the early 70's as the epoch of significant increases in runoffs of the rivers Paraguay and Paraná (Pasquini and Depetris 2007). Notwithstanding this natural climatic influence, significant variations in South America should be assigned to changes in land use and land covers (Clark et al. 2012).

3. Methods

Monthly hydrological records were compiled and analyzed from the databases of different South American countries (Table 1). As some of these hydrological stations are located in areas subject to floods, there are some gaps in coincidence with strong ENSO events. In this sense, the quality of the data is difficult to discern for each country and region. Some countries were successfully to achieve data bases with monthly records that can be downloaded in digital formats; other countries have their records as printed tables. From some areas, there are automatic gauges while some systems take several months to disseminate the information. Some countries require specific permissions from the administration authorities.

Peru	http://www.senamhi.gob.pe/
Ecuador	http://www.serviciometeorologico.gob.ec/caudales-datos-historicos/
Chile	http://snia.dga.cl/BNAConsultas/reportes
Brazil	http://hidroweb.ana.gov.br/HidroWeb.asp?TocItem=4100
Bolivia	http://www.senamhi.gob.bo/web/public/sige
Argentina	http://www.mininterior.gov.ar/obras-publicas/rh-base.php

Table 1. Web pages for hydrological records of different countries of South America.

Historical maps and TM images (30 m pixel resolution) from Landsat satellites were compared in order to discriminate the extension of flooding episodes from normal conditions.

4. Results

4.1. Ecuador and Peru

According to the Instituto Nacional de Meteorología e Hidrología from Ecuador, the largest floods connected to strong El Niño phenomena occurred in 1977-78, 1982-83 and 1997-98. The floods of 1983 were triggered by enormous amounts of rainfall at Western Ecuador (Rossel et al. 1996). The impacts caused by the strong ENSO of 1997-98 were estimated for different economic sectors: agriculture (43.6 MU$S), infrastructure of the sanitary sector (27.5 MU$S), housing (3.2 MU$S) and industry (9.5 MU$S; Vaca 2010).

The Daule River (Fig. 1) produced floods in 1965, 1983, 1997-98 and 2012 (Fig. 2). Normally these maximum discharges occur during the first months of the year (January to May). The worst floods occurred during the first months of 1998. with discharges over 1300 $m^3 s^{-1}$ (Fig. 2). At the boundary between Ecuador and Peru, the Zarumilla River produced discharge peaks during the years 1965, 1973, 1983 and 1998.

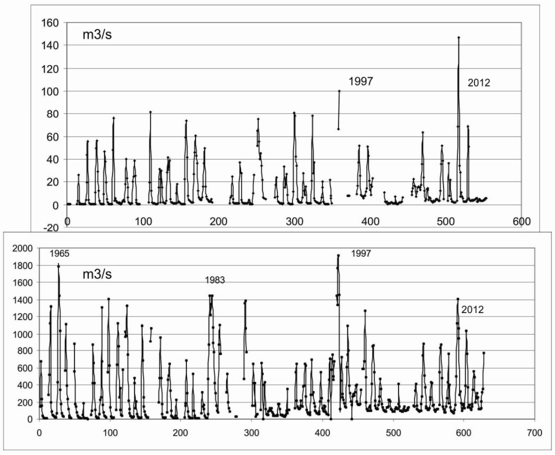

Fig. 2. Monthly discharges of the Carrizal River (top) and Daule River in La Capilla showing peaks in 1965, 1983, 1997 and 2012.

Perú hydrological statistics are published every year by the SENAMHI (2016). The Rimac River (Fig. 1) flooded in 1925 with a maximum daily discharge of 600 $m^3 s^{-1}$, an event considered the first "meganiño" of the 20th century (Rocha Felices 2011). It also produced a flood in 1941 (385 $m^3 s^{-1}$) and 1955 (380 $m^3 s^{-1}$). Historical data from Perú indicates that there is a patchy distribution between different basins (Waylen and Caviedes 1986).

4.2. Chile

Although Chilean floods may have different origins, 71% are associated with rainfalls. However, rainfall is assumed to be diminishing in a long-term scenario (González-Reyes and Muñoz, 2013). Floods associated exclusively with strong ENSO events occur northwards of 36°S (Rojas et al. 2014). However, significant discharges also occur at the south, but masked to other floods triggered by local rains (Araya Ojeda and Isla 2016).

There is not a definite effect of ENSO anomalies along the whole Chile. Those rivers of Northern Chile comprised within the South American Arid Diagonal are specifically subject to anomalous precipitations. The two debris flow recorded in Antofagasta in 1940 (Vargas et al 2000) could have been connected to the strong ENSO of 1941. The 1982-83 and 1997-98 ENSO-related rainfalls significantly affected Northern Chile (Meza 2013; Vargas et al. 2006).

In Central Chile, the higher discharges of the Aconcagua River (Fig. 1) were related to ENSO events, but with a certain delay (Waylen and Caviedes 1990). For the interval 1901-2005 there was a significant reduction of annual precipitation for the Valdivia region, southern Chile (González-Reyes and Muñoz, 2013). It has been proposed that the reduction in water yields in South-Central Chile was caused by land-use changes due to the replacement of native forest by exotics (Little et al. 2009); afforestation significantly affected runoff at the Biobio Region (Iroumé and Palacios 2013).

4.3. Brazil

Anomalous years affected some cities of Brazil. The floods of 1941 affected 70,000 inhabitants at the riverine area of Porto Alegre (Fig. 3). City authorities constructed a dike in order to prevent another flood of the Guaiba fluvial complex (Loitzenbauer et al. 2012).

Fig. 3. A) Fluvial area of Porto Alegre flooded in 1941. B) Present area.

The floods of 1983 of the Itajaí-Açú River caused the destruction of 30,000 houses at Blumenau. The level of the river raised 16 m over normal level and stayed high for several days. 80% of Itajaí County was affected. The Iguaçú River, a tributary to the Paraná River (Fig. 1), flooded Curitiba in 1982 and 1983 signifying losses of 10,000 and 78 billion US Dollar respectively at some neighborhoods (Tucci and Petry 2006).

4.4. Bolivia

The Pilcomayo River (Fig. 1) has a maximum discharge of 3500 $m^3 s^{-1}$, about 45 times its minimum discharge (80 $m^3 s^{-1}$; Rabicaluc 1986). This river has an alluvial fan of 210,000 km^2 with several abandoned channels (Iriondo et al. 2000). The floods of the Upper Pilcomayo River of 1983 and 1984 increased 2-3 times the amount of sediment transported in suspension (Malbrunot 2006). During normal years the river transports less than 1 x 10^6 tons of sediments; in 1984 it transported between 2 and 3 millions of tons. The city of Villamontes (Tarija, Bolivia) is usually flooded by the Pilcomayo River. Although a hydrologic gauge was installed in 1941, it operated randomly. A maximum level of 7.98 m was measured in March 1984, with a maximum discharge of 7000 $m^3\ s^{-1}$ (Ribstein and Peña 1993). The last flood was recorded during the beginning of 2018.

The Bermejo River (Fig. 1) also flows from Bolivia to Argentina, to the Paraná River. Based on historical archives, its hydrological cycles have been reconstructed (Prieto and Rojas 2015). Floods progressively increased since 1800. The deforestation has increased the climatic effects. Floods occurred less frequently during the first half of the 20^{th} century but more frequently to the end of that century. These rivers flowing from the Andes to the Parana River (Paraguay, Pilcomayo, Bermejo) carried significant amount of particulate matter and dissolved substances. The plume of the Paraguay River persists isolated from the Upper Paraná water during approximately 225 km (Campodónico et al. 2015).

4.5. Paraguay

The Republic of Paraguay is located between three rivers (Paraguay, Paraná and Pilcomayo), all belonging to the Río de la Plata watershed (Baez et al. 2014). The Paraguay River (Fig. 1) is about 2800 km long, draining an area of about 1,095,000 km^2 (Collischonn et al. 2001). Two regions should be distinguished in this large basin: the northern related to the Amazonas River system, and the southern, subject to ENSO-triggered floods (Drago et al. 2008). This watershed is closely connected to the Patiño Aquifer (Monte Domecq and Baez Benítez 2007) and the Pantanal wetlands (Collischonn et al. 2001). During the winters of 1982 and 1983 the river had discharges of 9712 and 10663 $m^3\ s^{-1}$, respectively (Monte Domecq et al. 2003; Barros et al. 2004). The two largest floods of the riverine areas of Asunción occurred in 1983 (63 m over MSL) and 1992 (62.3 m). During the floods of 1997/98 24,975 inhabitants were evacuated from Asunción, and 54,000 inhabitants from the departments of Neembucú, Concepción, Cordillera and Chaco (Fig. 4). One of the major risks of the Paraguay River floods is that concerning the Cateura waste disposal of the Asunción city (Fig. 5). This dumping site is on the floodplain and very close to the international boundary with Argentina.

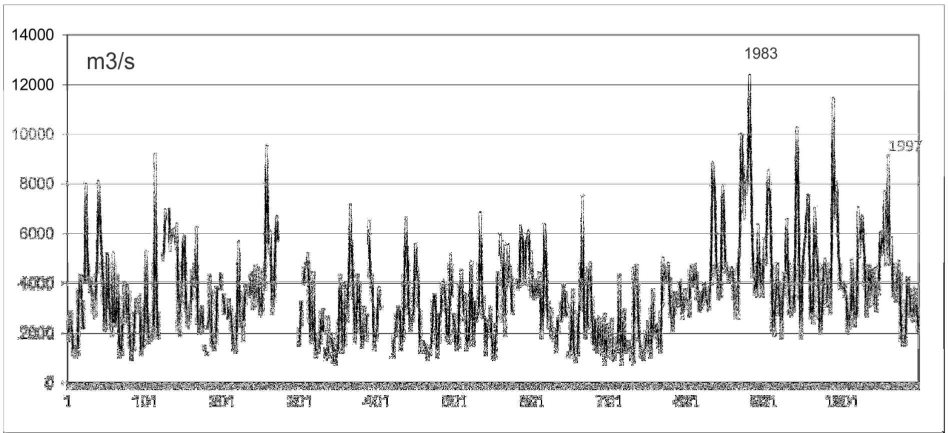

Fig. 4. Paraguay River floods at Puerto Pilcomayo with the peaks in 1983 and 1997.

Fig. 5. During the ENSO 2015-2016 the waste disposal site of Asunción, very close to the international boundary with Argentina, was flooded.

4.6. Argentina and Uruguay

The Rio de la Plata receives significant amounts of water from the Upper Paraná (83%), 20% from the Paraguay River, and about 7% from the rivers flowing from the west (Bermejo, Pilcaomayo and Salado; Pasquini and Depertris 2010). The Paraná River (Fig. 1) flooded systematically during the last strong ENSOs (1982-83, 1997-98 and 2015; Fig. 6), The width of its floodplain increased 15-fold during the floods of 1982-83 (Drago 1989). This extraordinary event was associated with high monthly streamflows in Corrientes during a year and half (Camilloni and Barros 2003).

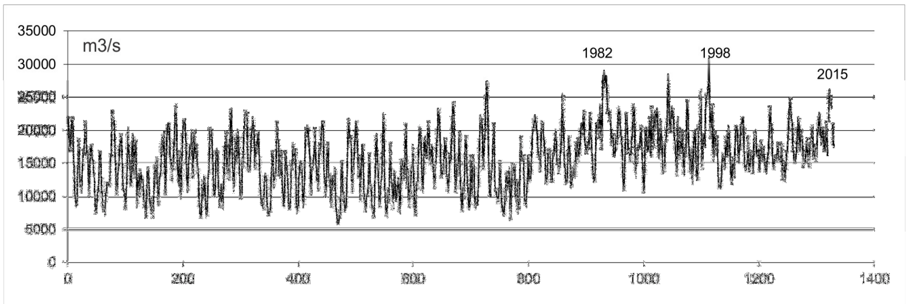

Fig. 6. Hydrological record of the Paraná River at Timbúes Station, 1901-2016 (modified after Isla and Toldo 2013)..

In Corrientes city, the discharge surpassed 10,000 $m^3 s^{-1}$ from July 1982 to December 1983 (Camilloni and Barros 2003), also affecting the localities of Resistencia, Barranqueras, Puerto Vilelas and Fontana (Fig. 7). The Paraná River at Barranqueras reached a maximum level of 8.6 m. Below the General Belgrano Bridge the discharge was 58,000 $m^3 s^{-1}$.

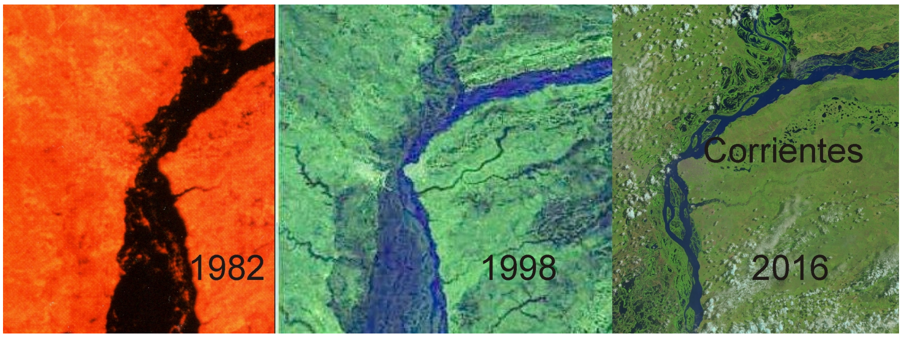

Fig. 7. The floods of of 1982, 1998 and 2016 affected the cities of Corrientes and Resistencia (Argentina).

These floods lead to the transport of subtropical floating plants (*Eichhornia crassipes*, also known as "water hyacinth") to temperate areas, which carried dangerous fauna with them (snakes, spiders and lizards). Several fluvial harbors as Rosario, Campana, Zárate and Buenos Aires were restricted in their operability during these events. At the floodplain close to Rosario, the peak flows of 1982-83, 1992, and 1997-98 exceeded 30,000 $m^3 s^{-1}$ (Fig. 8). During these extraordinary floods, the floodplain stored between 23 and 123 x 10^6 tons/year (García et al. 2015).

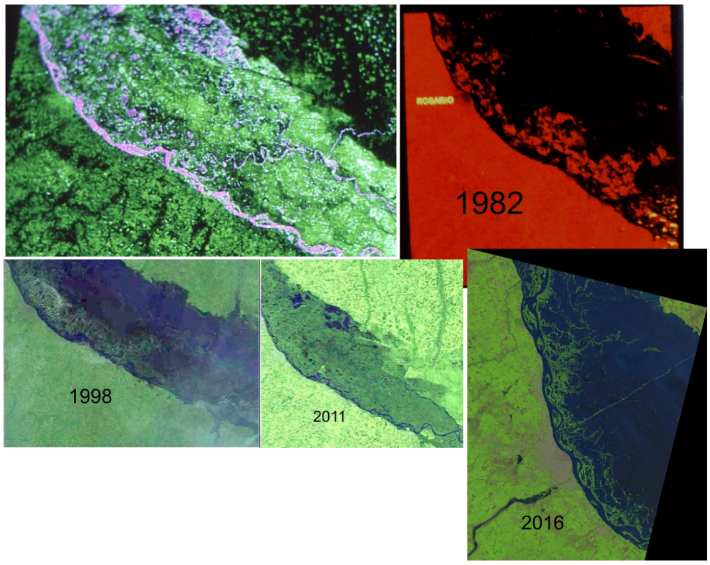

Fig. 8. The Paraná River flooded several times restricting the operation of the harbor of Rosario.

The Uruguay River (**Fig. 1**) flooded in 1941, 1983 and 1997-98 (Isla and Toldo 2013). It has a mean discharge of 4315 $m^3 s^{-1}$ (Evarsa 2006). Harmonic analysis shows a dry period during the 1950-1960 decade, recorded also at the Paraná watershed (Krepper et al. 2003).

The Colorado River (Northern Patagonia) is assumed to have disconnected from the northern portion of the watershed during the Holocene. During the floods of 1982-83, the whole watershed connected for the last time and saline water arrived to the delta plain (Isla and Toldo 2013). Proglacial lakes of eastern Patagonia were also affected during ENSO years: increases in the amount of snow during ENSO years produced high water levels of these lakes with a lag of 13 months (Pasquini et al. 2008).

5. Maximum floods

The best recorded strong ENSOs (1982-83 and 1997-98) produced similar maximum discharges in Chile (Araya Ojeda and Isla 2016). The strong ENSO of 1997-98 was stronger in Ecuador (Daule and Carrizal rivers). However, comparing their maximum monthly discharges, these floods are correlated (Fig. 9). This correlation is useful to forecast the maximum discharges expected for future strong ENSOs. During the last two centuries, three strong ENSOs occurred in less than 40 years (1982-82, 1997-98 and 2015-2016) and are therefore indicating a higher frequency compared to previous years.

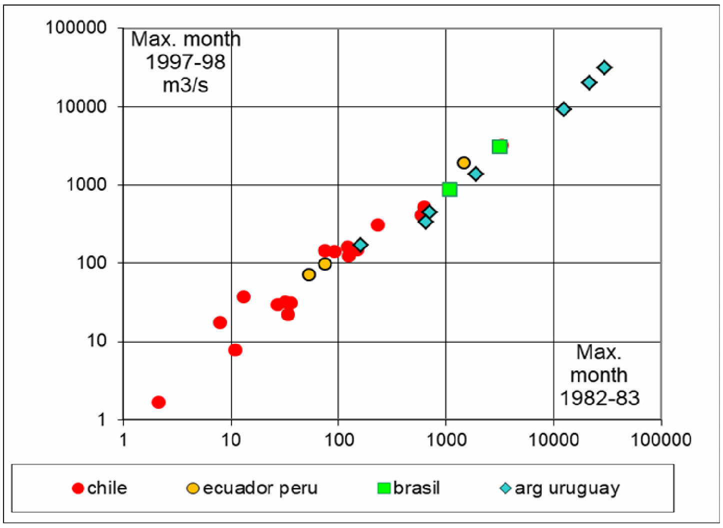

Fig. 9. Comparison of maximum discharges ($m^3\ s^{-1}$*) of the floods of 1982-83 and 1997-98.*

6. Discussion

This is the first attempt to summarize the environmental and social consequences in South American countries caused by the floods triggered during ENSO events, although meritorious analyses were performed in continents where their effects are not so direct or strong (Ward et al. 2016). In South America, flooding effects in one country could lead to consequences in another, i.e. the Cateura dumping site of Asunción city. At the same time, the impacts on some countries should only be reverted with improvements in regions at the headlands, e.g. the floods of the alluvial plains of the Bermejo and Pilcomayo rivers could be minimized constructing small dikes at the Bolivian watersheds.

The correlation found between the monthly maximum discharges of the strong ENSOs of 1982-83 and 1997-98 should be assigned in a first approximation to the size of the watersheds and the adaptative morphological changes at the bottom of the rivers. Dealing with tidal inlets, there is an empirical relationship between the tidal prism and the minimum discharge area (O'Brien 1969). Bedforms change in order to control the bed shear stress delivered by the currents (Bruun and Gerritsen 1959).

The ENSO events recorded during the Holocene are highly controversial (Clement et al. 2000). Although this review is based on hydrological measurements from countries with short series, there are some records that could be applied as historical and tree-ring records. Paleoclimatic studies indicate that in Northern Chile (north of 30° S) there was an absence of heavy rainfalls between 8400 and 5300 years BP in conjunction with a decrease in ENSO activities at the Eastern Pacific Ocean (Ortega et al. 2012). Based on tree rings from the Bermejo River region, it was stated that for the last three centuries there were significant increases in the frequency, intensity and duration of floods and droughts since the second half of the 20th century (Ferrero et al. 2015). The last five extreme wet events occurred since 1814, the last three in the last 40 years. However, there were significant droughts in the Western Pampas: the “Pampas Dust Bowl” occurred between 1930 and 1940 (Viglizzo and Clark 2006). Summarizing, for Northeastern Argentina 1901-1960 was a dry period while 1970-2003 was characterized by wet conditions (Lovino et al. 2014). ENSO floods occur with a different delay between the high-relief Andes watersheds draining towards the Pacific Ocean and those meandering towards the Atlantic Ocean. In Patagonia, the delay between the snow recharge and the raise in the piedmont lakes levels is about 13 months (Pasquini et al. 2008).

ENSO cycles do not only affect the hydrological records of South America (Ward et al 2016). They also affect rivers of China causing variations in their sediment discharge (Liu et al. 2017), and can therefore be considered a good predictor for flood-affected and flood-destroyed crop areas (Zhang et al. 2016).

ENSO cycles, either Niños or Niñas, have significant effects on the global price of wheat. Niños cause reductions of 1.4% in wheat production while Niñas cause reductions of 4% (Ubilava 2017). Niños have positive effects regarding crop yields at the Argentine Pampa; maize and wheat yields increase during ENSOs, while the increase in soybean only occurred along some areas (Magrin et al. 1998). On the other hand, sunflower yields diminish during ENSO years. These increments are more significant in the north of the Pampas region (Fernández Long et al. 2011). IN Paraguay, high-moisture content during ENSO years can depress yields by delaying planting, decreasing plant population, enhancing disease pressure, and causing harvest losses (Fraisse et al. 2008).

7. Conclusions

1. Strong ENSO-related floods affected South America in 1941, 1982-83, 1997-98 and 2015-16.
2. Rivers from the South American Arid Diagonal are only affected by ENSO floods. Those outside the diagonal can be also affected by anomalous precipitations derived from the Atlantic and Pacific oceans.
3. Comparing the monthly discharges of several rivers, the 1982-82 and 1997-98 floods were of similar magnitudes and should be considered to forecast future strong events and to organize mitigating plans.

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