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The fate of the Patagonian rivers: fluvial captures and climate trends

El destino de los ríos patagónicos: capturas fluviales y tendencias climáticas

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ABSTRACT

Patagonia and Tierra del Fuego are the only places to analyse climate changes at high latitudes in the Southern (Oceanic) Hemisphere. This region is totally dominated by westerly winds, although the altitude of the Andes Cordillera —transverse to these winds— modifies their effects. According to short meteorological records, air temperature is increasing slightly while precipitations are diminishing. Hydrologic records are longer; their trends are biased by geomorphological changes in the watersheds by fluvial and glacier captures. The discharges of the Negro, Chubut, Senguerr, Deseado, Santa Cruz and Gallegos rivers have decrease although some of them are not significantly modified by dams. The Santa Cruz River is the only example that is increasing the discharges due to significant variations at the upper watershed.

Palabras clave: Regional climate change; hydrology; watershed captures; Patagonia.

RESUMEN

Patagonia y Tierra del Fuego son los únicos sectores para analizar los cambios climáticos a altas latitudes del Hemisferio Sur (oceánico). Esta región es totalmente dominada por los vientos del oeste, aunque las alturas de la

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Cordillera de los Andes —perpendicular a estos vientos— modifican sus efectos. De acuerdo a registros meteorológicos cortos las temperaturas del aire están aumentando levemente mientras que las precipitaciones están disminuyendo. Los registros hídricos son más largos, sus tendencias están sesgadas por capturas geomorfológicas en las cuencas de drenaje fluviales como glaciales. Las descargas de los ríos Negro, Chubut, Senguerr, Deseado, Santa Cruz y Gallegos han disminuido, aunque algunas han sido modificadas por represas. El río Santa Cruz es el único que ha incrementado su descarga debido a variaciones significativas en la cuenca superior.

Palabras clave: Cambio climático regional, hidrología, capturas de cuencas, Patagonia.

INTRODUCTION

In regard to the worldwide forecasted climatic trends those concerning to Patagonia and Tierra del Fuego have no science-based assumed bearing. However, two simple facts should be stressed: 1) the lack of information expressed as long term records, due to a low number of reliable meteorological stations (Labraga and Villalba, 2009; Garreaud *et al*., 2013; Lenaerts *et al*., 2014; CIMA, 2015); and 2) the importance of this area as a monitoring site for climate changes of high latitudes of the Southern (Oceanic) Hemisphere.

Most of Eastern Patagonia is comprised on the Monte Desert, spanning from 25° to 45°S where some trends can bestated:

Warming intervals were recorded for the intervals 1920-1944, and 1997-2000, although cooling trends were observed for the Pacific coast between 37°S and 43°S for the 1950-1970 interval (Villalba *et al*., 2003).

Climate experiments and general circulation models indicate temperature increments (larger in summer than in winter) and more abundant precipitations in summer (Labraga and Villalba, 2009).

For the XXI century, models have predicted increments in arid conditions due to lower precipitation and higher temperatures (Nuñez *et al*., 2009). Models applied in Central and Southern Chile have also projected dryer conditions (Magrin *et al*., 2014; Boisier *et al*., 2018). Cattle overgrazing —a land-use trend—, is projected to accentuate desertification (Gaitán *et al*., 2014).

Some facts can be cited from local perspectives. Temperature increased significantly in Rio Grande, Tierra del Fuego (2004-2020 interval, EARG Station) and Punta Arenas (1976-2020 interval, 85934 station).

http://earg.fcaglp.unlp.edu.ar/meteorologia/tmedias.html
https://www.meteochile.gob.cl/

However, daily records of minimum and maximum temperatures do not denote trends except in Ushuaia. It was stated that temperature increments in the west of the Argentine Patagonia were triggered by the retreat of the glaciers (CIMA, 2015). On the other hand, increments of 0.5-1 °C were reported for the centre of the Argentine Patagonia during the interval 1960-2010, with a mean of 0.4 °C for the whole region (CIMA, 2015). According to the RCP4.5 scenario models predict increments of 2.5-3 °C for the centre of the Santa Cruz Province with less increments towards de Cordillera (west) and the Atlantic coast (CIMA, 2015). RCP4.5 is a conservative scenario that assumes intermediate levels of greenhouse gas emissions: Mean temperatures of 1.7 °C (1.3 to 2.2) for the 2031-2050 interval would increase to 2-5 °C (1.7 to 3.3) for the 2081-2100 interval (IPCC, 2019).

Regarding precipitations, they have increased in Trelew (Arbuniés de Mac Karthy, 2004; Saurral *et al.,* 2017) and Telsen, but are slightly decreasing in Puerto Madryn, Comodoro Rivadavia, Paso de Indios, and Rio Mayo (interval 2000-2016, Colombani, 2016), and in Punta Arenas (1976-2020 interval; Fig. 1). However, significant interannual changes were recorded (Saurral *et al.*, 2017) that caused significant floods that affected Puerto Madryn in January 2016 (Bilmes *et al*., 2016) and Comodoro Rivadavia in March-April 2017 (Paredes, 2019).

This paper is an update of climatic records and several proxies applied to provide information -not available till now-, about meteorological changes at high latitudes of the Southern Hemisphere. The monthly discharges of the Patagonian rivers (Negro, Chubut, Senguerr, Deseado, Santa Cruz and Gallegos) are reported for the first time to an international audience, directly related to rain-snow precipitations, mostly in the Andes.

PATAGONIAN SETTINGS

Patagonia has different settings in regard to the configuration of the Andes Cordillera and the anti-cyclonic centres. This is caused by the orographic rains that characterise the temperate Andes (Garreaud *et al*., 2016; Arias *et al*., 2021). This orographic effect in temperate Patagonia dominated by westerly winds increased since the Miocene (Bucher *et al*., 2020). However, there were reversals in the direction of watersheds flows during the end of the Pleistocene (Isla and Cortizo, 2014; Isla *et al*., 2015). Towards the Pacific Ocean, the slopes of the Andes are steep and much of the Pacific Ocean water contribution drains towards the west. Towards the Atlantic Ocean, the watersheds are extended and evaporation dominates the hydrological cycles across the desert plains and plateaus (Fig. 1). In response to latitude, there are significant differences in the contribution of humidity coming from the Pacific Ocean (Arias *et al*., 2021).

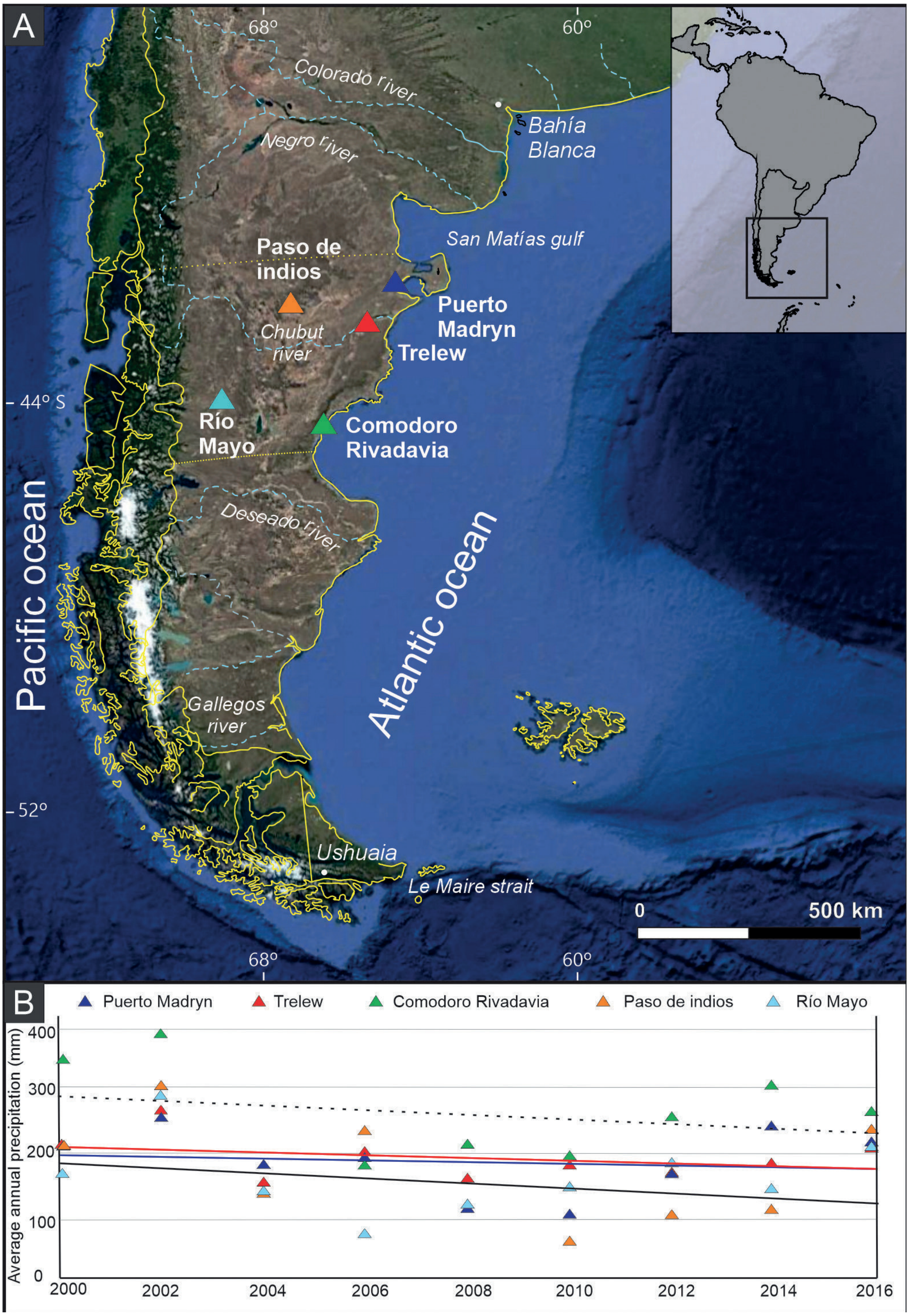

Fig. 1. A) Location of the annual runoff discharges of the major rivers of Patagonia. **B)** Average annual decreases in precipitations (mm) at some locations of the Chubut Province (2000-2016 interval; modified after Colombani, 2016).

A clear precipitation trend exists from western Tierra del Fuego to Eastern Tierra del Fuego (Coronato *et al*., 2017). Along the Beagle Channel annual precipitation rates are about 1630 mm/yr at the west (Cloue, Isla Diablo) while in Puerto Williams (to the east) are about 437 mm/yr (Santana *et al*., 2006). Using a reticulate data base, precipitation trends from W to E were estimated for the Santa Cruz Province with significant variations in latitude and longitude (Almonacid *et al*., 2021).

In Puerto Madryn, where average annual precipitations is 215 mm/yr, extreme rains of 255 mm in 4 days were recorded in 1998; an assumed recurrence of these extreme events is about 9 years (Bilmes *et al*., 2016).

METHODS

Climate data was provided by the Servicio Meteorológico Nacional of Argentina. Monthly hydrologic statistics were downloaded from the Sistema Nacional de Información Hídrica. Longer records from each river were selectively chosen. No significant rivers run across Tierra del Fuego; only the Olivia River has a very recent gauge station.

TM images and DEMs (SRTM 90 m resolution) were handled to explain fluvial captures.

Simple lineal regressions were performed to analyse trends and correlation coefficients. Statistical methods for hydrologic flow analysis are not a simple issue in regions subject to flash floods and droughts (Interagency Advisory Committee on Water Data, 1982; Chen *et al*., 2022). Historical analysis should consider intervals when dams were infilled (e.g. Negro and Chubut rivers), and with seasonal irrigation periods that can alter the natural hydrological cycle. Harmonic analysis cannot be applied to watersheds that can be completely dried (Isla and Espinosa, 2021). Autoregressive moving averages are usually applied although more complex models consider periodic or seasonal components, although in the last years climate change could have altered significantly some discharges (Khedun and Singh, 2021). Outlier tests cannot be applied when there are quasi-periodic intervals as the ENSO –triggered floods (Isla, 2018).

RESULTS

Temperature and Precipitation Trends

It is reported that temperature has increased in Patagonia while precipitations are decreasing (Masiokas *et al*., 2007; Magrin *et al*., 2014). Dealing with daily temperatures data from Ushuaia (Tierra del Fuego) maximum temperatures are reducing while minimum are increasing; on the other hand, precipitations are decreasing.

Annual Hydrologic Modules

All the rivers that drain from the Andes to the Atlantic Ocean diminished their discharges across the Patagonian desert. However, some rivers have high discharges while others have low discharges (Coronato *et al*., 2017; Fig. 2). These Atlantic watersheds are draining piedmont lakes. Some of them have captured other lakes during the Holocene (Negro, Santa Cruz). Instead, some rivers diminished their watershed areas (Chubut). The Colorado River had an extended watershed that most of it became inoperative during the Upper Pleistocene (Isla and Espinosa, 2021). The Chubut river has also lost part of the discharge area at the Andean piedmonts (Isla and Cortizo, 2014; Isla *et al*., 2015).

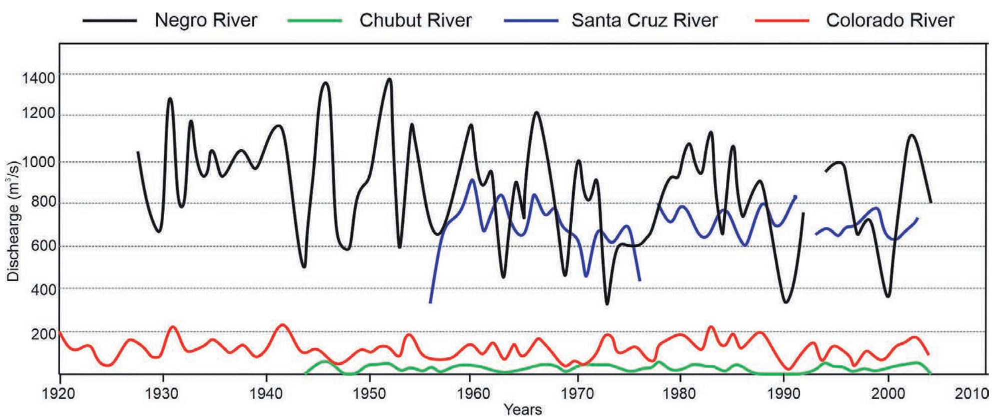

Fig. 2. Annual means of the rivers discharges. Negro (Primera Angostura station) and Santa Cruz (Charles Fuhr station) rivers have captured other watersheds while Colorado (Pichi Mahuida station) and Chubut (Los Altares station) watersheds were captured or became less operative.

Monthly Variations

As most of the rivers are draining the Andes Cordillera, they have peaks related to the melting of the snow accumulated during Southern Hemisphere winter (June to September). Interannual differences were mostly assigned to strong ENSO years (Araya Ojeda and Isla, 2016; Isla and Espinosa, 2021). The discharge data from three proven allochthonous rivers (Chubut, Deseado and Santa Cruz) is reported spanning from latitudes of 43 to 51°S.

The Negro River watershed at Primera Angostura (40°27′22″S – 63°47′10″W)

The Negro river receives water from the Andes via the Limay and Neuquén rivers. 3000 years ago this watershed increased its area when it captured the lakes Aluminé and Moquehue (Isla *et al*., 2019). The Primera Angostura gauge (Guardia Mitre) is at the lower watershed and has a discharge record since 1927. The upper watershed is very productive of apples, pears and peaches. The river was subject to floods until the middle of the XX century when several dams succeeded to lower the peaks of the floods (Fig. 3; Isla *et al*., 2010).

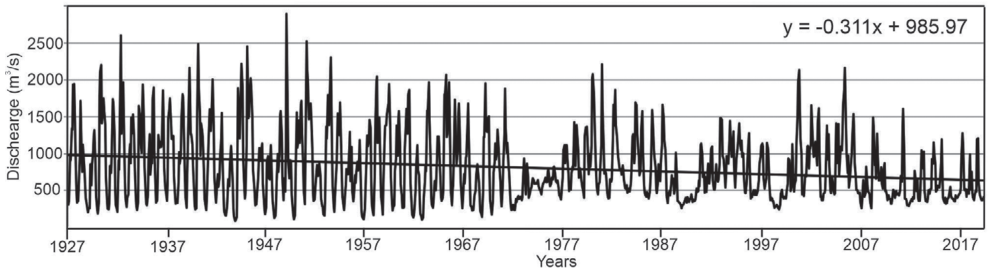

Fig. 3. Discharge (m^3/s) of the Negro River at Primera Angostura (1927-2021). Floods were reduced since the dams' constructions during the seventies.

The Chubut watershed at Los Altares (43°53'S – 68°24'65"W)

The Chubut River diminished its discharge in the last years (Fig. 4). Since the last glaciation, the watershed has become restricted as most of the recharge areas were today draining to the west (Isla and Cortizo, 2014; Isla *et al*., 2015). Maximum discharges were recorded during the winter months of 1961 and 1962 (Fig. 4A).

The Chubut watershed at Ameghino Dam (43°41'55"S – 66°28'39"W)

The Ameghino Dam became closed between 1965 and 1971 (Fig. 4B)

The Seguerr River watershed (46°00'42"S – 69°30'54"W)

The Senguerr river is draining two piedmont lakes: La Plata and Fontana. It flows to the south and ends at the Musters Lake that discharges to the Colhue Huapi Lake via the Falso Senguerr River. Significant changes occurred at this watershed due to the deflation that caused reversals of the regional relief (Simeoni, 2008). During the Holocene, both lakes comprised a single one named Sarmiento (González Diaz and Di Tommaso, 2014). It was assumed that both lakes drained to the Atlantic Ocean (via the Chubut River) before becoming an endorheic watershed (Montes *et al*., 2017). Both lakes summed 889 km^2 but the original Sarmiento Lake occupied 4300 km^2. Today, the Musters Lake keeps 447 km^2 but the Colhue Huapi Lake became almost dried completely due to channels performed to supply the cities of Comodoro Rivadavia and Caleta Olivia, and the petroleum industry. The Musters Lake extends at the 273 m above mean sea level while

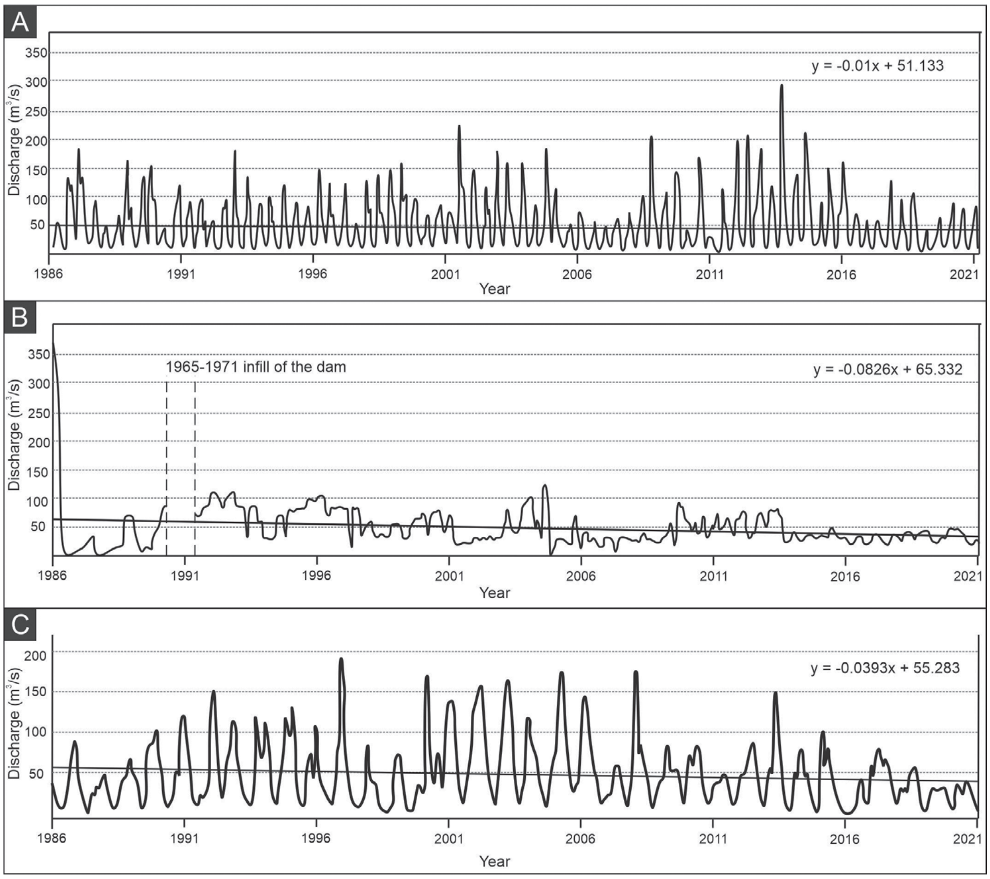

Fig. 4. A) Monthly discharge (m³/s) diminution of the Chubut River measured at Los Altares station (interval 1943-2021). **B)** Discharges of the Chubut River (m³/s) at the Ameghino Dam (interval 1961-2019). **C)** Monthly discharges of the Seguerr River (m³/s) at Los Molinos station (1986-2021 interval).

Colhue Huapi lake level is 20 m below. The first lake has depths of 20 m while the second has only 2-5 m (Gonzalez Diaz and Di Tommaso, 2014). In the past, these lakes discharged to the north towards the Chubut River. Monthly records from the Senguerr River at Los Molinos station indicate a linear trend diminishing the discharge with peaks during strong ENSOs (1997 and 2015; Fig. 4C).

The Deseado River watershed (46°43′36″S – 69°35′37″W)

The Deseado River used to drain the Buenos Aires-General Carrera Lake, and also the Cochrane-Pueyrredon-Posadas lacustrine system, towards the Atlantic Ocean. Both, the Pinturas and the Deseado rivers, carved deeply their valleys into volcanic rocks. About 11,000 years ago, both piedmont lakes systems were captured by the Barker River (Fig. 5). The Deseado and Pinturas rivers therefore diminished drastically their discharges (Isla *et al*., 2015) and it was still diminishing in the last years.

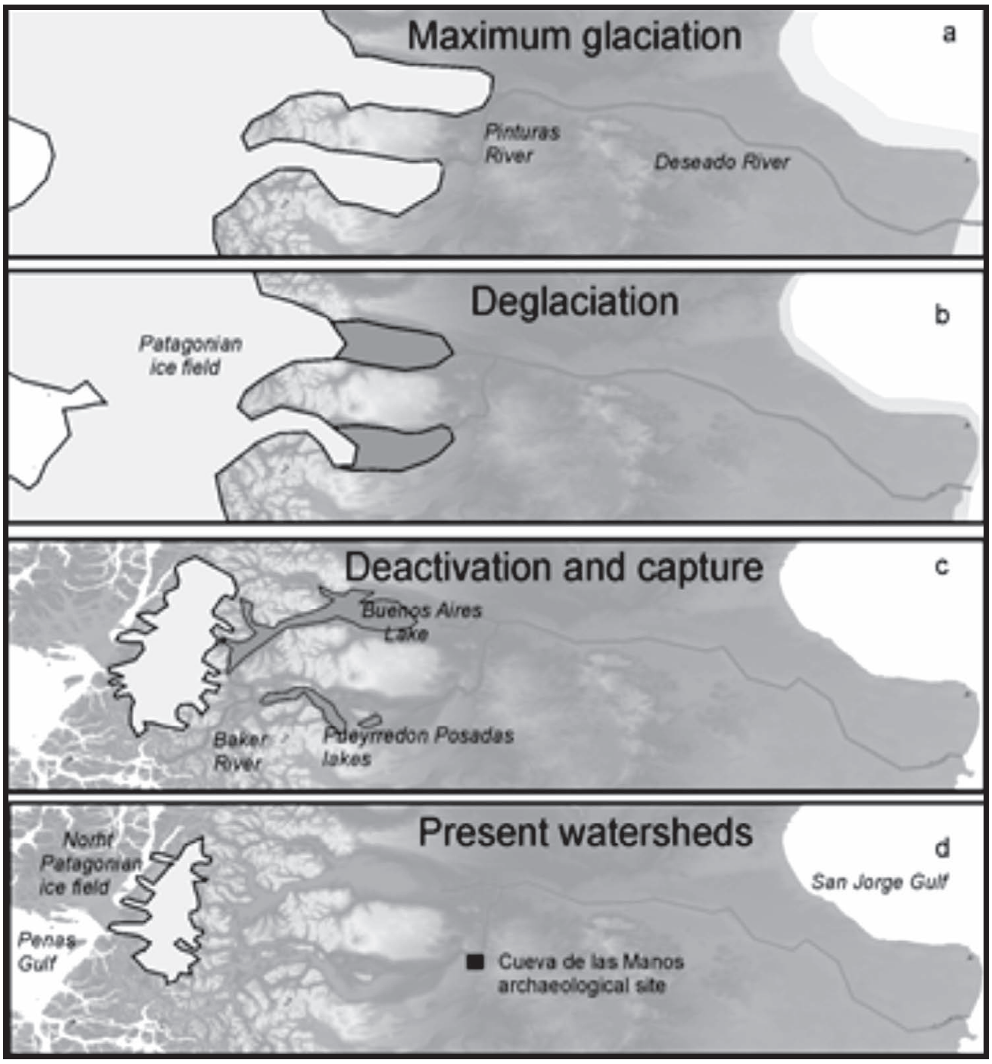

Fig. 5. Variations of the Deseado River watershed (modified after Isla and Espinosa, 2021).

At the eastern most station the discharge is very low and diminishing significantly (Fig. 6). Seasonal peaks occurred every October during the sprig season.

The Santa Cruz River watershed

The Santa Cruz River has a complex watershed draining four large piedmont lakes: Belgrano, San Martin, Viedma, Argentino, with captured and deactivated watersheds (Fig. 7). Two large dams were planned to be constructed at the middle valley of the Santa Cruz River watershed: Nestor Kirchner (former called Condor Cliff) and Jorge Cepernic (formerly La Barrancosa).

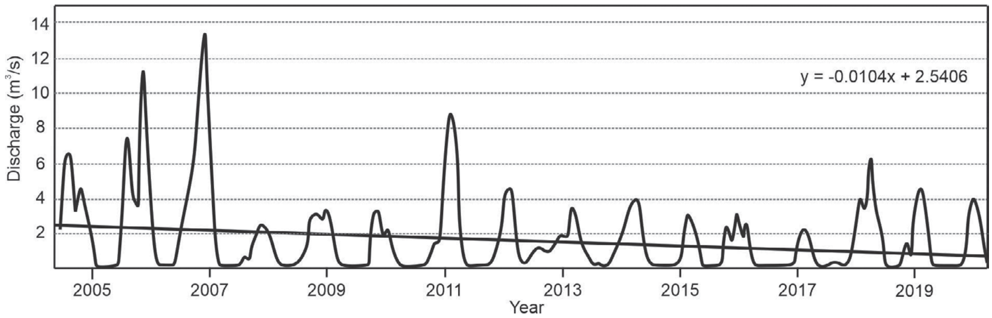

Fig. 6. Annualdis charge of the Deseado River (m³/s) at Route 39 (interval 2004-2019).

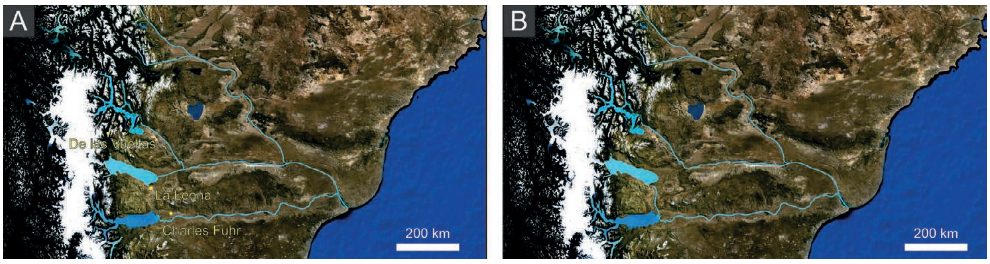

Fig. 7. The Santa Cruz River watershed had significant changes when the La Leona River began to flow towards the Argentino Lake.

Las Vueltas River at National Park Los Glaciares (49°19′40″S – 72°52′57″W)

The Viedma Glacier has receded only 500 m between 1986 and 1994, although an ice-damned lake outburst in 1994 (Lliboutry, 1998). The smaller Torre Glacier receded 350 m between 1968 and 2022 (Schmidt *et al*., 2023). The Río de las Vueltas flows across the El Chaltén village. It had two significant peaks in 2008 and 2011. It had also two low-discharge intervals in 2007 and 2016 (Fig. 8A).

La Leona River (49°48′27″S – 72°03′09″W)

This river connects the Viedma Lake to the Argentino Lake. It has therefore regular peaks in its discharges, although low-water discharges were recorded during the beginning of the seventies (1970-1974; Fig. 8B).

Santa Cruz River at Charles Fuhr station (50°16′03″S – 71°53′12″W)

The Santa Cruz River has an increasing discharge in the last years (Fig. 8C). This behaviour has different explanations, concerned specifically to the Perito Moreno Glacier:

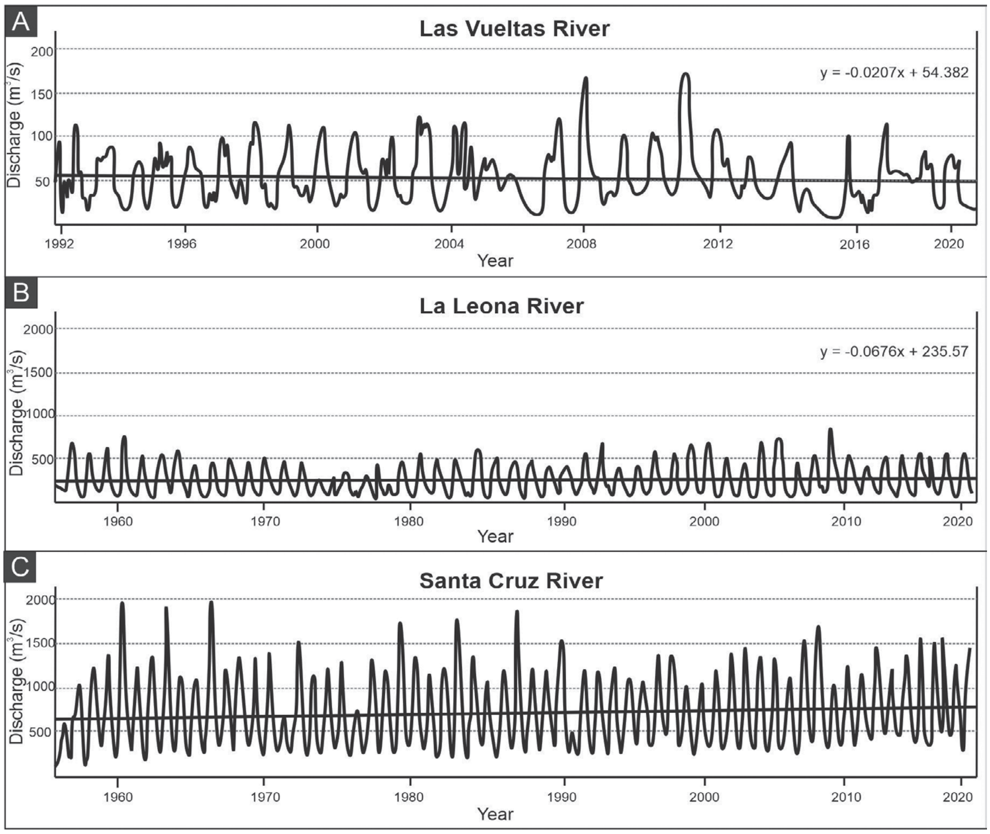

Fig. 8. A) Las Vueltas River station (interval 1991-2020). **B)** La Leona (interval 1956-2020). **C)** Santa Cruz River discharges (m^3/s) at Charles Fuhr gauge station (interval 1955-2020).

– The watershed captured the upper watershed of the Frías Glacier.
– There is seismic activity below the glacier,
– The recharge areas are protected from the solar insolation, and
– The water flow below the ice has caused periodic advances (Malagnino, 2008).

Two dams were planned to be constructed at this river, to the east of the piedmont lakes: Cóndor Cliff and La Barrancosa, renamed as Nestor Kirchner and Jorge Cepernic projects.

The Gallegos River at Puente Blanco station (51°53’40”S – 71°35’50”W)

The Gallegos River is monitored in Puente Blanco (close to the Andes piedmont) during the interval 1993-2021. Maximum discharge (185 m^3/s) was recorded in October 1995. The trend is diminishing its discharge (Fig. 9).

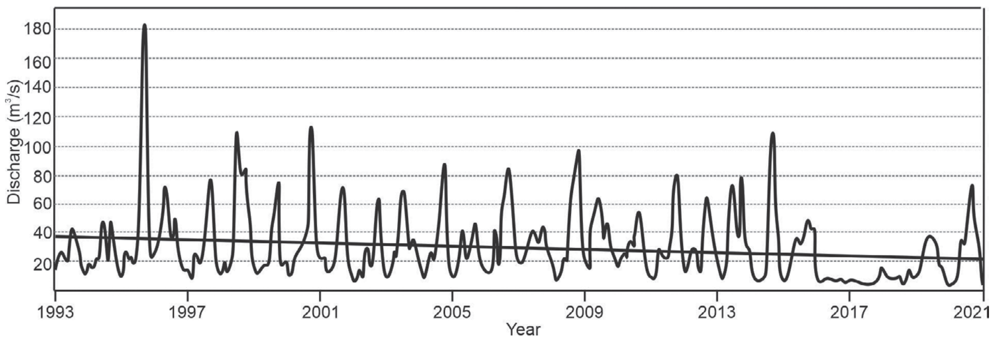

Fig. 9. The Gallegos River discharge (m^3/s) at Puente Blanco (1993-2021 interval).

DISCUSSION

The analyses of these hydrologic records imply that Patagonian larger rivers are diminishing their discharges from Andes piedmont lakes towards the Atlantic Ocean. In this sense, some have changed their watersheds due to competition with rivers draining to the west (Pacific Ocean). Some of them lost their connection to these lakes during the Upper Pleistocene-Early Holocene (Chubut and Deseado rivers). Others have increased their watersheds during more recent times (Negro, Santa Cruz).

The Westerly bias

Since the first images of the Seasat radar in 1995, it is clearly stated that the strongest winds of the planet are concentrated in the Southern Hemisphere. In Southern Patagonia, westerly winds velocity over 10 m/s dominate during the whole year (Recalde, 2010; Zular *et al.*, 2013). At Chubut Province, the migration of dunes was estimated between 30 and 70 m/yr during the interval 2003-2013 (Montes *et al.*, 2015). Same processes occurred in northeastern Tierra del Fuego (Arche and Vilas, 1987), and at the shallow lakes close to the Rio Grande city (Perdomo *et al.*, 2021).

Precipitation over Patagonia is mostly produced by disturbances embedded in the westerly flow from the Pacific Ocean (Mayr *et al.*, 2007a, b) and strongly topographically-altered by the Southern Andes (Garreaud *et al.*, 2013). Rains dominate to the west of the Andes while the eastern region is conditioned by the evaporation rates.

Climate models from the Southern Hemisphere are simulating a strengthening, a poleward shift and a narrowing of the Antarctic Circumpolar Current (Fyfe and Saenko, 2006). When westerly winds and the Subtropical Front move south, moist air stops flowing over Patagonia, and warm waters enter the mid-latitude oceans; this favours glacier retreats. When the westerly winds and Subtropical Front expand to the north, strong winds carry precipitation to Patagonia, and cold Southern Ocean waters cool the mid-latitude oceans; this favours glacier advance (Antarctic glacier.org, 2021). However, there are certain doubts about the oceanic response to the modern poleward shift of the westerlies (Russell *et al*., 2006). Models run for this poleward shift have also indicated significant seasonal and regional variations (Goyal *et al*., 2021).

Westerly winds and the seasonal amplitude of latitudinal shifts of the Pacific and Atlantic are also responsible for vegetation changes (Mancini *et al*., 2005). Pollen studies in some piedmont lakes from the Patagonian Andes indicate significant variations of the westerly winds that led to drier intervals and increments of their strength between 11,200 and 4,500 years BP suggesting a broadening of the wind belt (Van Daele *et al*., 2016).

The glacier record

According to a glacier inventory of the Southern Patagonia Icefield performed with remote sensing images, only two glaciers (Frías and Bravo) are not calving in the last years (Aniya *et al*., 1996). The Perito Moreno Glacier had several readvances during the Holocene (Strelin *et al*., 2014). Based on photographs from glaciers and runoff records during the XX century (period 1912-2002) drier and warmer trends were suggested for northwestern Patagonia (Masiokas *et al*., 2007).

Applying microwave images (Nimbus 7 and DMSP satellites) from 1979 to 2006 no significant trend was recognized in the snow cover and snow mass of the Southern Andes (Foster *et al*., 2009). However, two peaks (1982-1983, and 1997-2000) should be related to strong ENSO events.

The pollen record

Based on pollen records, the arid-semiarid region shifted towards the east while the western limit remains fixed as the present-day 300 mm isohyet (Mancini *et al*., 2005). While in northwestern Patagonia changes were caused by the westerlies influence (Schäbitz and Liebricht, 1998), to the east there were more seasonal effects on the water availability (Mancini *et al*., 2005). Vegetation changes can be applied to approach former paleohydrologic records. Pollen records were used as proxies for a Palaeohydric Balance Index (PBI), based on the water requirements of the main plant taxa represented by the pollen types recognised (Echeverría *et al*., 2017).

CONCLUSIONS

Significant changes in the watersheds were inherited from the Pleistocene. River captures between the Pacific and Atlantic watersheds affected the allochthonous fluvial discharges. The increase in arid conditions in Western Patagonia is particularly affecting the rivers flowing to the Atlantic.

Westerly winds play a significant role delivering rains to the west of the Andes, and increasing evaporation to the east.

Precipitations are diminishing across the plateaus of Eastern Patagonia, although interannual variations were recorded. These interannual variations are common in South America derived from the variations of the Pacific Ocean influence.

Except the Santa Cruz River where glacier and fluvial captures occurred, most of Patagonian rivers are diminishing their discharges.

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