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The Manso Glacier drainage system in the northern Patagonian Andes: an overview of its main hydrological characteristics

Andrea I. Pasquini,* Karina L. Lecomte and Pedro J. Depetris

Centro de Investigaciones en Ciencias de la Tierra (CICTERRA, http://www.cicterra-conicet.gov.ar/), CONICET-UNC, Avenida Vélez Sarsfield 1611, X5016GCA Córdoba, Argentina

Abstract:

The Manso Glacier (~41°S, 72°W), in the northern Patagonian Andes of Argentina, is a regenerated glacier that, like many other glaciers in the region and elsewhere, has been showing a significant retreat. Glacial melt water feeds the Manso Superior River, which, before crossing the Andes to reach a Pacific outfall, flows through the Mascardi (a deep, oligotrophic and monomictic lake) and significantly smaller Hess and Steffen lakes. Harmonic analysis of Mascardi's lake level series suggests that the El Niño-Southern Oscillation signal has been strong during the 1985–1995 decade but has grown weaker during the initial decade of the 21st century. Hydrological trend analyses applied in data recorded in the uppermost reaches show a monthly and annual decreasing trend in the Manso Superior River discharge series and Mascardi's lake level, which are connected with both, decreasing melt water discharge and (austral) wintertime atmospheric precipitation. Downstream, the decreasing signal initially looses statistical significance and then, when flowing through Steffen Lake, reverses the lake level trend that becomes significantly positive. This suggests that, on its way to the Pacific Ocean, the Manso River receives abundant Andean snow melt water and atmospheric precipitation, which are sufficient to obliterate the negative trend recorded in the uppermost reaches. The reason for this local phenomenon is that the Manso is an antecedent river (aka superposed stream), and hence, the valley crossing the Andes allows the incursion of Pacific humidity that modifies the hydrological regime several hundred kilometres inland.

KEY WORDS hydrological time series; trend analysis; ENSO; climate change; glacial retreat

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INTRODUCTION

Because of progressive melting, glacial retreat is a process that is being documented worldwide. In Andean Patagonia, the ~54-km-long Upsala Glacier (the apparent misspelling comes from the old spelling with one p of Uppsala University, which sponsored the initial glaciological work in the area) in Argentina's Los Glaciares National Park has shown significant retreat during the last decades (Skvarca *et al*., 2003). In other parts of the world, glacial receding is apparent in some instances since the 19th century or even earlier, such as in the Gangotri Glacier, in the Himalayas, which has been receding since the late 18th century (e.g. Singh, 2004). Current glacier retreat is mainly associated with global warming because there seems to be an increasing glacial melting rate (allegedly since the second half of the 20th century). There are, however, some exceptions where, because of what appear to be singular circumstances, glaciers may be stable (e.g. Pasquini and Depetris, 2011, and references therein) or are even advancing, as it happened in recent years in the Pio XI Glacier (aka Brüggen Glacier) in the Chilean Andes (e.g. Rivera and Casassa, 1999).

*Correspondence to: Andrea I. Pasquini, Centro de Investigaciones en Ciencias de la Tierra (CICTERRA, http://www.cicterra-conicet.gov.ar/), CONICET-UNC, Avenida Vélez Sarsfield 1611, X5016GCA Córdoba, Argentina.
E-mail: apasquini@com.uncor.edu

If glaciers do not calve on fjords and, instead, are located on a continental seaboard (i.e. as in Argentina's Patagonian Andes), glacial melt water usually feeds streams, rivers, groundwater and/or glacial lakes. Increasing or decreasing melt water discharge triggers modifications, which may be of varied nature in the hydrological system that is usually associated with receding glaciers.

Focusing on different aspects, many contributions have looked into the Manso Glacier, Mascardi Lake and Manso River area (e.g. Chillrud *et al*., 1994; Markert *et al*., 1997; Masiokas *et al*., 2008, 2010; Pasquini *et al*., 2008a; Pedrozo *et al*., 1993; Pedrozo and Chillrud, 1998; Rabassa *et al*., 1978, 1984; Rogora *et al*., 2008; Román-Ross *et al*., 2002). In this input, such glacial–riverine–lacustrine system in Argentina's Northern Andean Patagonia is considered (Figure 1), bringing forward aspects of hydrological nature, which may be related, directly or indirectly, to changes allocated to global climate change. Clearly, during the initial receding stages, glaciers supply more melt water to downslope valleys. But, undoubtedly, the process of continued glacier retreat reaches a point when a significantly reduced ice mass starts altering the melt water discharge rate, which may progressively decrease (e.g. Bradley *et al*., 2006).

An abridged regional view of the hydrological highlights prevailing on the Atlantic seaboard of southern South American was presented by Depetris and Pasquini

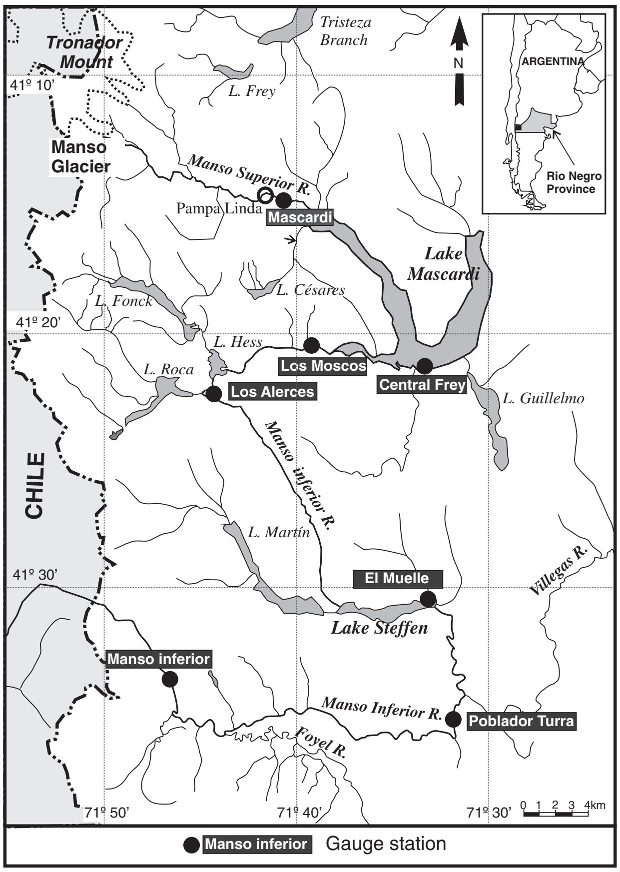

Figure 1. Manso Glacier–Lake Mascardi–Manso River system showing its main hydrographical features and the location of the gauging stations

(2008). In this paper, expanded information is sought on the hydrological response of a system that includes a receding glacier, lakes (i.e. relicts of Pleistocene glaciations) and mountainous rivers. In the process, we probed into the often enigmatic role of El Niño-Southern Oscillation (ENSO), whose effect is superimposed on the usual seasonal variation that sometimes exhibits opposing trends and discontinuities.

THE SYSTEM'S BACKGROUND INFORMATION

The glacial and lacustrine area and the enclosing drainage basin (~6050 km^2) considered here is located in Argentina's Río Negro and Chubut provinces, in Patagonia's northern Andes (Figure 1). The area is an integral part of the Nahuel Huapi National Park, the oldest (established in 1934) natural park and reserve in Argentina. Like many other similar areas in the Andean Patagonian region, the area was heavily glaciated during the Pleistocene; lakes and drainage nets were largely brought about by glacial erosion, moraines and other forms of glacial and post-glacial sediment accumulation. The region's highest peak is Mount Tronador (~41°S, ~3500 m a.s.l.; it rises more than 1000 m above nearby mountains in the Andean cordillera), which hosts the Manso (Spanish for 'tame') Glacier (aka Ventisquero Negro, Spanish for 'black snowdrift'). The mountain's name (Tronador, Spanish for 'thunderer') conveys the loud noise of ice and rock avalanches, and falling seracs that feed the glacier's lower level. Therefore, the receding Manso Glacier (Figure 1) is of the regenerated kind (i.e. a glacier that develops from ice-avalanche material beneath a rock cliff); several other glaciers, such as Alerce, Casa Pangue, Castaño Overo, Río Blanco, Frías and Peulla, are also hosted by Mount Tronador. The glacier's upper portion is composed of 'clean ice' (i.e. devoid of rock debris), which feeds the lower level several hundred metres below. Abundant rock debris in the glacier's lower level conveys a dark aspect to the ice, giving birth to the name Ventisquero Negro. According to existing evidence, glacier advances or stalling occurred in 1870, 1890, 1900, 1920, 1950 and by mid-1970 (e.g. Masiokas *et al*., 2010). During the last decades, the glacier experienced a considerable thinning of its snout and a significant retreat, which can be confirmed through the existing geologic and photographic evidence. Moreover, the Casa Pangue Glacier, on the northwest side of Tronador, underwent a marked thinning, retreating 52 m year^{-1} between 1981 and 1998. The retreat and thinning is attributed to a decrease in precipitations and to the ongoing global warming (http://www.glaciares.org.ar/paginas/index/rio-manso). Figure 2 shows the recent evolution of the glacier's snout, demonstrating the ice loss through melting of several hundred metres at the glacier's receding front. Masiokas *et al*. (2010) completed an articulate analysis of the Manso Glacier's dynamics since the Little Ice Age.

There is an elevation difference of ~170 m between the glacier's terminus (i.e. the system's upper catchments) and the Manso Superior River mouth (i.e. where it flows into Mascardi Lake), delivering its discharge (mean

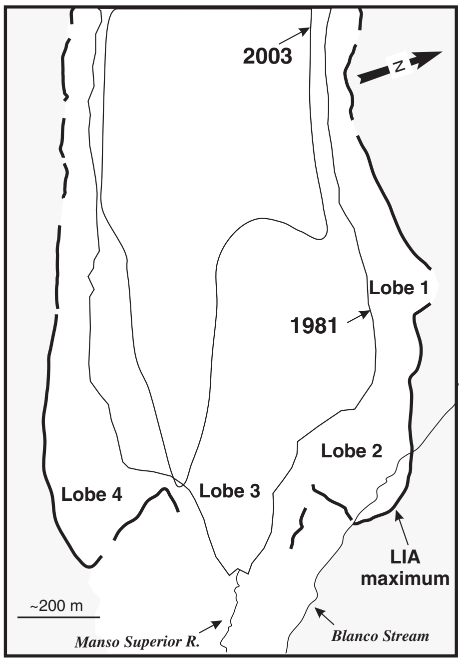

Figure 2. Schematic map of the lower portion of the Manso Glacier showing the evolution of the glacier's snout and the location of the moraine systems during the Little Ice Age (LIA). Modified from Masiokas *et al*. (2010)

annual discharge of ~11 $m^3 s^{-1}$) mainly supplied by the glacier's melt water (in spring and summer) and abundant wintertime precipitation.

The river originating at the lake's outfall is known as Manso Inferior River (Figure 1). It flows through Lake Hess (~1.5 km^2, Figure 1), and then its course swerves towards the southeast and receives some tributaries before reaching Lake Steffen (~5.2 km^2, Figure 1). The Manso Inferior River mean discharge increases significantly after leaving Lake Steffen (~67 $m^3 s^{-1}$), and then its course turns westward. Before crossing the Andes, it is joined by the Villegas and Foyel rivers and, bearing the Puelo River name, delivers its total discharge to the Pacific Ocean, at Chile's Reloncaví Bay. Therefore, the Manso is an antecedent river (http://en.wikipedia.org/wiki/Antecedent_drainage_stream); hence, although the drainage basin is almost fully developed on the eastern side of the Andes, it belongs to the Pacific seaboard.

The mountainous climate in the region is temperate cold and humid, with a mean annual temperature of ~7 °C (in the Mascardi Lake area, about 12 °C is the annual mean for the entire drainage basin). Mean temperatures of 17.4 °C and 3.8 °C have been recorded for January and July, respectively. It has abundant snowfall (mostly between May and August) and rainfall during the austral winter (Figure 3a) that, incidentally, is subjected to a marked west to east decreasing gradient; at the Chile–Argentina border, the annual precipitation is 2500–3000 mm; along Bariloche–El Bolsón is ~1000 mm and in the drainage basin's eastern limit is 500 mm (Masiokas *et al*., 2008; Masiokas *et al*., 2010, and references therein).

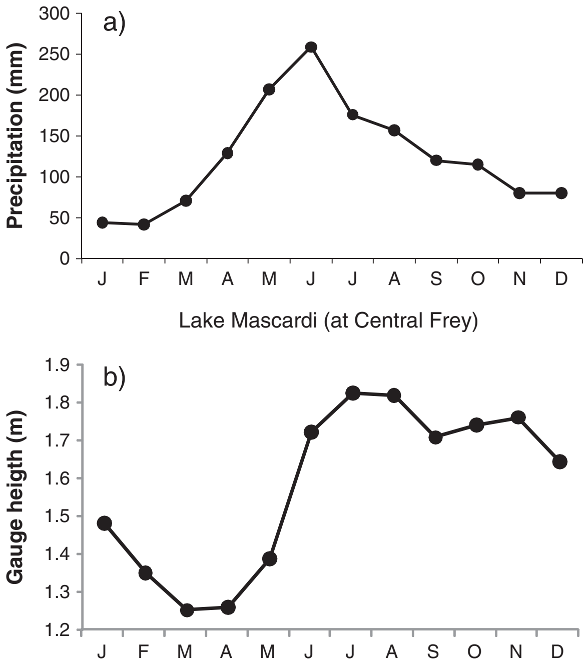

Figure 3. (a) Mean pluviograph for the Mascardi Lake area (Central Frey station) for the period 1970–2010. Note that maximum precipitation occurs during the austral winter; (b) mean hydrograph of Mascardi Lake water level for the same period

Reflecting the variability of climate in the region, Nahuel Huapi's western half is covered profusely with temperate rain forests, whereas xerophytic Patagonian flora is dominant on the eastern half of the park. The dominant tree species in the park are *Nothofagus dombeyi* (cohiue), *Nothofagus pumilio* (lenga) and *Nothofagus antartica* (ñire). Also present is *Fitzroya cupressoides* or Patagonian cypress, a slow-growing conifer. Other floras include *Luma apiculata* (arrayán), *Austrocedrus chilensis* (Chilean cedar), and so on. (http://www.parquesnacionales.gov.ar).

The geology of the region (e.g. Dalla Salda *et al*., 1991; Gonzalez Bonorino, 1979) involves two main types of country rocks: metaluminous granitoids (Late Paleozoic–Tertiary) and a thick Lower Tertiary volcanic sequence (Eocene–Oligocene). Varves, tephras and glacial–glaciofluvial deposits are widely disseminated throughout the region. Mount Tronador is a Miocene stratovolcano consisting of basaltic and basaltic andesite lavas and pyroclastic rocks.

Prevailing cold mountainous weather and Andean active tectonics determine that the Manso River drainage basin is controlled by the so-called weathering-limited regime (e.g. Stallard and Edmond, 1983). Therefore, solid phases or dissolved products of rock disintegration show a close geochemical similarity with parental lithology (e.g. Miocene basalts of the Tronador Formation and other volcanic byproducts). Román-Ross *et al*. (2002) revealed that mineral hydrolysis in the region supplies a relatively reduced amount of dissolved material: Mascardi's bottom sediments exhibit a low chemical index of alteration (CIA) of ~55 (i.e. close to Upper Continental Crust's CIA). The modelling of the europium fractionation indicates little reworking of sediments, with a total loss of less than 30% as soluble or weathered particulate material (Román-Ross *et al*., 2002).

The restricted intensity of weathering reactions results in the system's diluted waters. Bonetto *et al*. (1971) studied the main chemical aspects of the Manso Superior River. The waters were of the bicarbonate-calcium type; the relative abundance of anions was $HCO_3^- > SO_4^{2-} \geq Cl^-$, whereas the sequence for the main cations was $Ca^{2+} > Mg^{2+} > Na^+ > K^+$. Specific conductance varied between 24.1 and 40.9 $\mu S\,cm^{-1}$, with highest values during the ice/snow melt season. Moreover, pH was close to neutral (7.0–7.5), and free CO_2 fluctuated in the 1 to 2 $mg\,L^{-1}$ range. SiO_2 reached 18 $mg\,L^{-1}$ during the snow melt season and decreased to ~8 $mg\,L^{-1}$ during low waters.

The oligotrophic lake (~790 m a.s.l.), named after Nicolás Mascardi, a 17th century Jesuit who first visited the area, has a surface area (A) of 39.2 km^2 (Figure 1); it is 23 km long and about 4 km wide, and its maximum measured depth is ~218 m (Pasquini *et al*., 2008a, 2008b, and references therein). The lake's perimeter or 'coastline length', l, is ~54 km (Bonetto *et al*., 1971); therefore, the ratio $l : A \cong 1.4\ km^{-1}$, which corresponds to a low-sinuosity coastline, with little influence of littoral processes.

The most significant hydrochemical characteristics of Lake Mascardi were also described by Bonetto *et al.* (1971). At the time of their study, the total dissolved solids content in the lake waters was low, which is similar to the Manso Superior River. Bonetto *et al.* (1971) also explored other limnological characteristics in the lake: water temperature was always above 4 °C during the survey, with winter circulation and summer stratification; the well-defined summer thermocline was always located between 10 and 30 m depth. The Mascardi is a typical warm monomictic lake (i.e. a holomictic lake that mix from top to bottom during one mixing period each year).

DATA AND METHODS

Argentina's Secretaría de Recursos Hídricos supplied hydrological and climate records for the studied rivers and lakes (Figure 1, Table I), which were examined by means of statistical techniques, such as trend and harmonic analysis. Original daily gauge-height or discharge readings were used as basic data, which were converted to monthly means prior to processing. The rainfall data series of San Carlos de Bariloche (~35 km northeast of Lake Mascardi) was obtained from the European Climate Assessment and Database (http://climexp.knmi.nl). In this opportunity, we have used data from more stations (downstream of Lake Steffen) and longer data series than those used in Pasquini *et al.* (2008b). In the case of the Manso Superior River (at Mascardi station), the added data spanned from 1991 until 2010; this series was reconstructed correlating gauge height with discharge measurement recorded at Pampa Linda (near Mascardi, Figure 1).

To assess the significance of river discharge and water level trends, we made use of the seasonal Kendall test (Hirsch *et al.*, 1982), which was utilized to examine monthly trends, and the Mann–Kendall test, known as Kendall's tau (Mann, 1945; Kendall, 1975), to test trends on mean annual climate data (i.e. precipitation series at San Carlos de Bariloche). Both tests are nonparametric tools that detect monotone trends in time series (e.g. Burn and Hag Elnur, 2002; Yue *et al.*, 2002). The seasonal Kendall test has been recognized as one of the most robust techniques available to disclose and estimate linear trends in environmental data (Hess *et al.*, 2001).

Continuous wavelet transform (CWT) was the method used, in some instances, to examine periodicities in data series. CWT examines time series using mother wavelets that are stretched and translated with a resolution in both time and frequency. This useful tool to study time series offers advantages in comparison with traditional Fourier analysis because it provides a time-scale localization of a signal. The literature submits numerous reviews on the theoretical aspects of CWT and Fourier analysis (e.g. Lau and Weng, 1995; Torrence and Compo, 1998; Labat, 2005).

RESULTS AND DISCUSSION

Hydrological aspects of the Mascardi and Steffen lakes

Lake Mascardi's mean water level variability (Figure 3b) shows the influence of austral wintertime atmospheric precipitation (June, July and August) and also a discernible melt water contribution during the austral springtime. Masiokas *et al.* (2008) have already pointed to the historical decrease trend of precipitation in the area. For example, the Mann–Kendall analysis of historical rainfall at nearby San Carlos de Bariloche (Figure 4) shows a significant Sen's negative slope ($p < 0.05$) that substantiates the decreasing precipitation trend (Pasquini *et al.*, 2008b, and references therein).

Pasquini *et al.* (2008b) studied the historical water level variability of seven Patagonian lakes. According to their findings, the Mascardi appears to be, among the studied lakes, the only one that exhibits a significant decreasing trend in the water level time series. The seasonal Kendall trend analysis of deseasonalized gauge readings ($N = 420$, for the period 1970–2005) showed negative, highly significant coefficients ($p < 0.001$) in January, February and March (i.e. dry summer) and also, with lower significance, in November and December (i.e. melt water months), thus showing that summer lake water levels have a tendency to decrease (i.e. summers have been progressively drier) and that the melt water contribution has been also decreasing (Pasquini *et al.*, 2008b).

Table I. Name, location and record period of studied gauge stations in the Manso Glacier drainage system

River/lake	Gauge station name	Latitude (S)	Longitude (W)	Height (m a.s.l.)	Q_{mm}/H_{mm} record period
Manso Superior R.	Mascardi[†]	41°15′03.0″	71°39′58.0″	800	1969–2009[a]
Lake Mascardi	Central Frey	41°21′28.6″	71°33′46.0″	728	1970–2010[b]
Manso Inferior R.	Los Moscos	41°20′51.7″	71°38′28.9″	795	1946–2010[a]
Manso Inferior R.	Los Alerces	41°22′25.4″	71°45′45.4″	700	1951–2009[a]
Lake Steffen	El Muelle	41°30′22.2″	71°32′31.3″	310	1976–2010[b]
Manso Inferior R.	Poblador Turra	41°35′36.7″	71°31′15.2″	499	1974–2010[b]
Manso Inferior R.	Manso Inferior	41°33′21.6″	71°46′49.5″	300	1963–2010[b]

[a] Q_{mm}, monthly mean discharge.
[b] H_{mm}, monthly mean gauge height.
[†] Reconstructed series by correlation between gauge height and discharge.

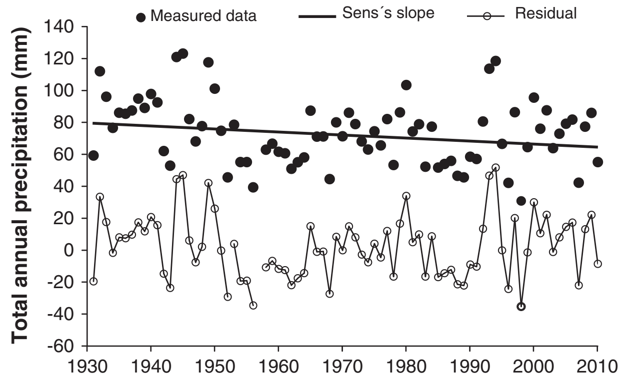

Figure 4. Mann–Kendall trend test for mean annual rainfall series at the city of San Carlos de Bariloche (~35 km northeast of Mascardi Lake; period 1930–2010). Decreasing trend is statistically significant at $p < 0.05$

Now, with the comparison of earlier results with the new extended deseasonalized water level series (1970–2010, $N = 477$), the seasonal Kendall test adds months with significant decreasing trend: May, August and October. The analysis also shows high significance ($p < 0.001$) for the negative τ coefficient of March and lesser significance ($p < 0.01$) for the months of January and February. November and December, with negative τ coefficients, show still lesser significance ($p < 0.05$), as well as May, August and October (Table II). Like in the previous analysis, Lake Mascardi shows a decreasing trend during the dry summer months and even during the rainy season. Interestingly, the decreasing trend is also evident during the months when ice melt/snowmelt peaks (i.e. October, November and December; Figure 3).

Lake Steffen (Figure 1, Table I), downstream from Lake Mascardi, shows the opposite trend in its deseasonalized water level (Table II). Results already reported (Pasquini *et al.*, 2008b) for the seasonal Kendall test applied to the 1976–2005 ($N = 341$) lake level series showed only one significant ($p < 0.05$) positive τ coefficient in March. The extended series (1976–2009, $N = 402$) now shows an apparent change (Table II): during the dry season (i.e. January and February), τ coefficients are positive and statistically significant ($p < 0.05$), thus implying that the lake's water levels tend to increase, in opposition to what the seasonal Kendall test shows for the uppermost part of the drainage basin. Furthermore, the τ coefficient for the extended data set (all months combined, Table II) is now positive and statistically significant ($p < 0.05$), whereas it lacked such condition in the 1976–2005 data set.

There is no available data on the water contribution from Lake Martín and associated tributaries (Figure 1), but it is deemed as the decisive factor in the lake level change. The trend modification (i.e. from negative to positive coefficients), as it will be shown in the following paragraphs, is also noticeable in the Manso Inferior River discharge trend analysis.

Pasquini *et al.*, 2008a employed CWT to analyse the time-scale localization of the periodical signal in maximum water level time series (period 1970–2005) from Lake Mascardi. The time-frequency spectrum showed significant signals with interannual (~2.5 and

Table II. Seasonal Kendall test results for Manso drainage basin (streams and lakes) monthly mean hydrological time series

River/lake	Station name	N	τ coefficients												
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
Manso Superior R.	Mascardi†	467	−1.94*	−1.66*	0.97	0.74	−1.11	−0.48	−0.33	−0.23	−0.19	−0.02	−1.12	−1.54	−1.23
Lake Mascardi	Central Frey	477	−2.93**	−4.46**	−4.53***	−0.70	−1.71*	−1.53	−0.65	−1.94*	−1.01	−1.89*	−1.40*	−2.15*	−3.42**
Manso R.	Los Moscos	759	−2.74**	−2.43**	−1.59	−0.71	−2.28*	0.23	1.24	−0.87	0.15	0.35	−1.95*	−0.65*	−2.09*
Manso R.	Los Alerces	696	−2.29*	−2.62**	−1.13	−0.05	−1.98*	0.12	0.19	−1.23	0.29	0.31	−1.54	−1.44	−1.79*
Lake Steffen	Muelle	402	1.75*	1.75*	1.59	1.30	0.14	−0.32	1.04	0.32	0.81	1.20	.62	1.13	1.79*
Manso Inferior R.	Poblador Turra	379	0.15	−0.73	−1.27	−0.03	−0.64	−0.96	1.09	0.88	0.77	0.66	1.16	−0.28	0.1
Manso Inferior R.	Manso Inferior	490	2.85**	3.57***	3.28***	3.14***	2.30*	2.80**	3.03**	2.68**	3.99***	3.84**	2.36**	1.93*	4.63***

N, number of months.
*$p < 0.05$, **$p < 0.01$ and ***$p < 0.001$.
† Reconstructed series by correlation between gauge height and discharge.

~6 years) and nearly decadal periodicity, which were close to ENSO recurrence. Fourier analysis reconfirmed such findings (Pasquini *et al*., 2008b) and also showed significant periodicities for Lake Mascardi by using mean, maximum and minimum water level series. All were coherent with ENSO occurrences in the equatorial Pacific through a comparison with the Southern Oscillation Index.

Figure 5(a and b) shows the CWT spectra for the Mascardi's processed extended data series. In this opportunity, the deseasonalized (i.e. anomalous values) mean water level readings for the period 1970–2010 were employed to assess periodicities. The upper figure (Figure 5a) shows the CWT spectra with interannual periodical signals. One of them is discernible for the period 1975–1990 with a periodicity of ~28 months. The second interannual signal is stronger than the first one and has a period of ~70 months; this signal is evident for the period that spans from the 1980s until the 1990s. Finally, there is a quasi-decadal signal that spans almost all the analysed period, although it shows maximum power in 1990–1994.

Figure 5(b) shows the 'critical limits' for the same CWT. Differing from confidence levels, CWT 'critical limits' should be considered approximate because the spectral peak heights (contour magnitudes) can be impacted by the variable smearing in the time-frequency domain arising from multiresolution analysis. The highest critical limits for the Mascardi's CWT are identifiable, for the ~70-month period, during the 1985–1995 decade. Noticeably, the signal in the lower periodicity range (25 to 45 months) became fainter and disappeared toward the late 1990s. This also suggests that the interannual ENSO signature became fainter in the region after that period.

Hydrology of the Manso River

As described previously, the Manso Superior River has upper catchments at or near the Manso Glacier, reaching a mean annual discharge of ~11 $m^3 s^{-1}$ close to its outfall into Lake Mascardi. The upper basin surface area (i.e. including Lake Mascardi, 41°10′, 41°25′S and 71°52′, 71°25′W) reaches 580 km^2, and its specific water yield is over 60 $l s^{-1} km^{-2}$. After leaving the lake (mean annual discharge ~35 $m^3 s^{-1}$), the river flows through other lakes (i.e. Hess and Steffen, Figure 1) and progressively increases its mean discharge until it traverses the Argentina–Chile border with a mean flow of ~80 $m^3 s^{-1}$, discharge that includes the Foyel River contribution (Figure 1). Pasquini *et al.* (2008b) also applied the seasonal Kendall trend test to Manso River deseasonalized discharges and found significant ($p < 0.01$) decreasing trends – as in Lake Mascardi – for the summer months of November, December, January and February (i.e. the dry season). The statistical analysis showed that, as the river flowed downstream, the τ negative coefficients progressively lost statistical significance until the river reached Lake Steffen, where only one of all the τ coefficients (March) was positive and significant ($p < 0.05$) (Pasquini *et al*., 2008b).

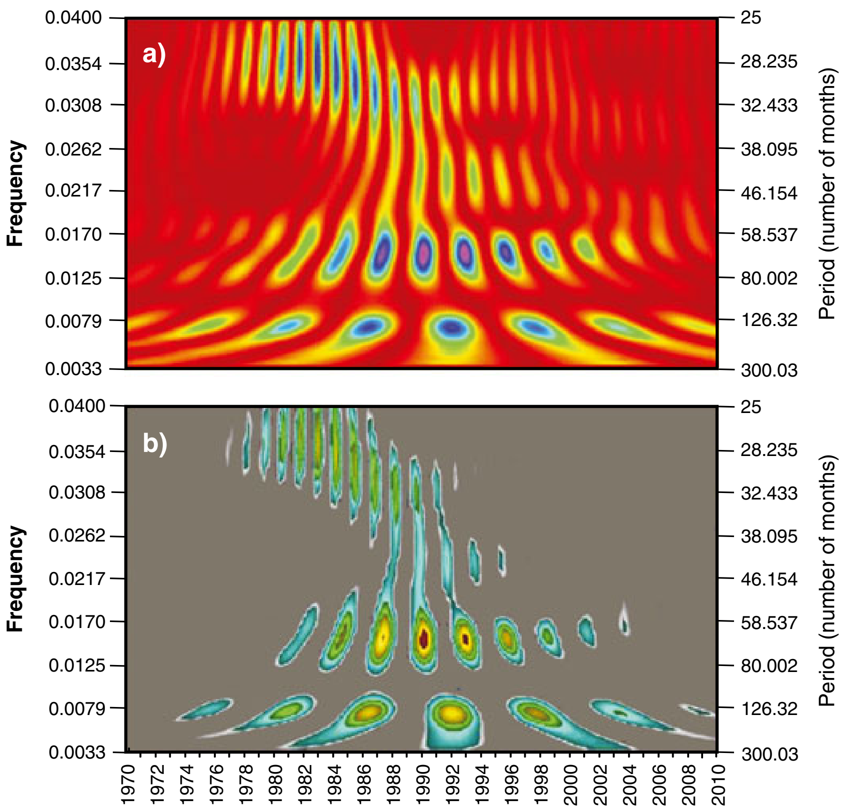

Figure 5. (a) Real part of the continuous Morlet wavelet power spectrum of Lake Mascardi deseasonalized monthly mean water level (at Central Frey station); (b) critical limits for the same wavelet spectrum. The critical limit gradients are the following: eight-level cyanscale from 50% to 90%, eight-level greenscale from 90% to 95%, eight-level yellowscale from 95% to 99% and eight-level redscale from 99% to 99.9%

It is interesting to point out that the addition of data to the original set (Table II) brought about some changes to the earlier hydrological image: (1) in the Manso Superior River (at Mascardi gauging station with reconstructed data), new negative τ coefficients (for January and February) are lower and less significant than previous ones; November and December lost their statistical significance entirely; (2) in the Manso Inferior River (at Los Moscos), the comparison between the previous analysis (Pasquini *et al.*, 2008b) and the current data set shows that the decreasing trend in March and April lost significance; melt water months maintain their negative significant trend; (3) the Manso Inferior River at Los Alerces station remained invariant.

The analysis now turns towards new downstream stations, which were not previously considered. The seasonal Kendall test applied to data recorded at Poblador Turra station (Figure 1) does not show any significant trend throughout the year. In contrast, at the Manso Inferior, in a gauge station close to the Argentina–Chile border, the analysis shows significant positive τ coefficients for the whole year, particularly for February, March, April and September ($p < 0.001$). This means that, in that particular region, there has been a tendency to flow increase during the recent past (i.e. 20–30 years) in total opposition to what was shown for the upper drainage basin (Table II). This becomes clear in Figure 6, where there appears to be a discontinuous increase in discharge (even in the deseasonalized mode, Figure 6b) that is discernible since the early 1990s.

CONCLUDING COMMENTS

The receding Manso Glacier and a declining atmospheric precipitations regime result in the system's statistically significant decreasing water yield, which, in the system's upper reaches, can be verified through trend analysis. It must be recalled here that such a negative trend was observed in the Negro River (its upper catchments are very close to Manso's upper catchments), that most Patagonian rivers do not show a significant trend in their respective deseasonalized discharge series and that they also show a verifiable remote connection with Pacific's ENSO and/or the Antarctic Oscillation (Pasquini and Depetris, 2007; Depetris and Pasquini, 2008).

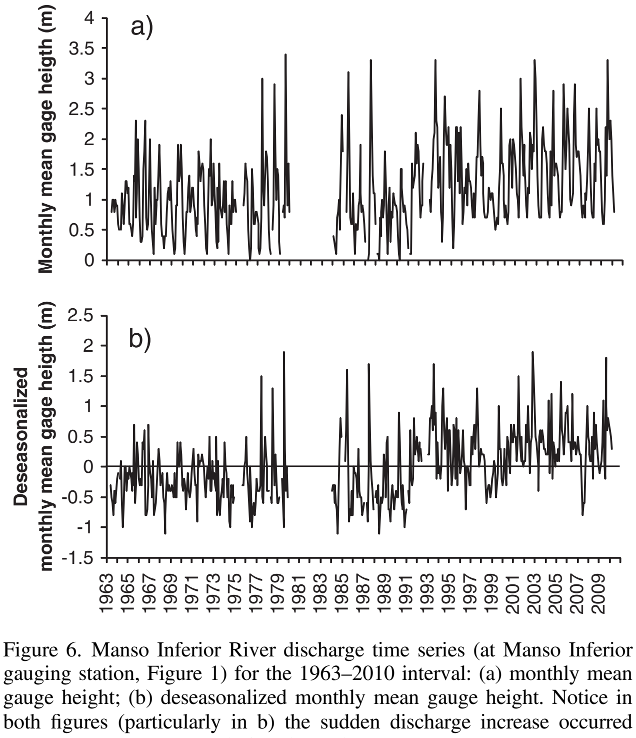

Figure 6. Manso Inferior River discharge time series (at Manso Inferior gauging station, Figure 1) for the 1963–2010 interval: (a) monthly mean gauge height; (b) deseasonalized monthly mean gauge height. Notice in both figures (particularly in b) the sudden discharge increase occurred during the early 1990s

The seasonal Kendall trend test has shown significant negative coefficients for the months of January and February at the Manso Superior River (i.e. the dry season is becoming drier). When the river reaches Lake Mascardi, the trend test – applied to deseasonalized water level data – increases the number of months with negative τ coefficients and expands its statistical significance. Not only the seasonal dry season (i.e. austral summer) becomes more evident (i.e. through larger and more significant τ coefficients), but also the negative coefficients are transmitted to the rainy season (i.e. May and August) and to the months when snowmelt/ice melt peaks (October–December). We interpret this process not only as the direct impact of decreasing rainfall/snowfall but also as the result of a diminishing glacier mass providing melt water.

Continuous wavelet transform's highest critical limits for Lake Mascardi are recognized through the 1985–1995 decade, for the ~70-month period. The signal in the lower periodicity range (25 to 45 months)was distinctly fainter and vanished toward the late 1990s. This also hints that the interannual ENSO signature became fainter in the region after that period (i.e. 1985–1995).

Negative coefficients are maintained for January and February further downstream, at Los Moscos and Los Alerces; negative τ coefficients in May (i.e. decreasing precipitation in fall) and November and December (at Los Moscos) convey the image that the signal of decreasing snowmelt/ice melt contribution persists downstream.

In an earlier study (Pasquini *et al.*, 2008b), Lake Steffen did not show a significant water level trend. Surprisingly, the negative signature of the incoming Manso Inferior River is lost at Lake Steffen, and τ coefficients for deseasonalized water level data become significantly positive ($p < 0.05$) for the dry months (i.e. January and February). After the Manso Inferior River leaves Lake Steffen, its seasonal Kendall coefficients initially loose significance (i.e. at Poblador Turra, probably because the number of observations is not sufficiently large), and then, before the river crosses the Andes and reaches its outfall in the Pacific Ocean as Puelo River, the Kendall analysis exhibits markedly positive, statistically significant τ coefficients, meaning that in this region, the system acquired wetter dry seasons during the austral summer and wetter wintertime rainfall/snowfall seasons, as well as larger contributions from snowmelt/ice melt.

How is it possible that a hydrological system that is showing decreasing trends in rainfall/snowfall as well as the impact of a dying glacier in the upper reaches drastically changes the negative trend and exhibits excess water throughout the year when it approaches the outfall? Our hypothesis rests on the peculiar geographical characteristics of the Manso River system (i.e. it is an antecedent river, with upper catchments on the eastern side of the Andes and a Pacific outfall on the western side): the valley that crosses the Andes is a gateway to Pacific humidity that breaks through and apparently affects the system's hydrology, all the way upstream to Lake Steffen.

Lastly, there is a distinct discontinuity in the early 1990s in the Manso Inferior discharge series: is it related to a change in the dynamics of the ENSO remote connection? or is it determined by some local shift in atmospheric circulation? Moreover, how is the hydrology of this natural system going to evolve if the current decreasing flow trend continues at such a measurable pace? How would the system readjust to the disappearance of the Manso Glacier and other glaciers in the region?

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