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Short Communication

Are southern South American Rivers linked to the solar variability?

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ABSTRACT: This article explores the Sun's influence on the hydrological cycle in southern South America (SSA) at the range of interannual-to-multidecadal scales from the early 1900s to 2011. The solar variability is described by the sunspot number (SSN) index. The hydrological cycle is examined by using annual mean discharges of the Paraná River (PAR) and the Atuel River (ATU) that represents the behaviour of the subtropical Argentinean Andean hydrological system. Wavelet-based methods are used in order to describe relationships in the entire time-frequency domain. The SSN–PAR connection is statistically weak in oscillations with period about 11 years (the Schwabe's solar cycle). Therefore, the solar forcing at this scale must be considered with great caution. The periodicity about 30 years is highly significant throughout the analysed period. Two potential physical mechanisms affecting the Paraná discharge could be involved: one is the solar irradiance influence on the Inter Tropical Convergence Zone (ITCZ), and the other is the solar influence on the Pacific long-term variability. The SSN–ATU connection shows by far the most striking, robust and convincing result for the Schwabe cycle. A large amplitude and statistically significant cycle with a period about 11 years is observed not only in the Morlet-based global and local wavelet spectra of the Atuel discharges and SSN but also in the global and local spectra of Cross and Coherent wavelets in most of the analysed period. High (low) discharges occur following maxima (minima) of the Schwabe cycles with time lags of up to ~2 years. Previous studies have shown a close relationship between the subtropical Argentinean Andean Rivers and the El Niño/Southern Oscillation (ENSO), as well as a solar influence on the ENSO variability. We suggest that El Niño events occurring a few years after solar maxima could explain the connection. Periodicities longer than 30 years are suggested.

Additional Supporting information may be found in the online version of this article.

KEY WORDS Paraná River discharge; Atuel River discharge; subtropical Argentinean Andean Rivers; 11-year solar cycle; sunspot numbers; wavelets transform; southern South America; hydrological cycle

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1. Introduction

The influence of solar activity on global and regional climate variability is currently debated. Some mechanisms involved in the interaction of solar irradiance and galactic cosmic rays with sea surface temperature, atmospheric circulation and cloud cover affecting regional climates are explained by Perry (2007), among others. Moreover, Gray *et al.* (2010) provide a summary of the current knowledge about solar variability, solar–terrestrial interactions and mechanisms determining the response of the Earth's climate system to the solar activity. The hypotheses described by these authors to explain the climatic response to solar variations can be grouped into two categories: (1) changes associated with variations in solar irradiance; (2) effects of energetic particles, including solar particles and galactic cosmic rays, on the cloud formation.

River discharges are valuable climatic indicators because, in the absence of anthropogenic forcing (e.g. modifications in the land use due to urbanization and agricultural practices), their variability is mainly associated to changes in the precipitation and temperature over the corresponding basin. Hence several authors have investigated the solar signal on rivers for different regions in the world. Some examples of studies reporting evidence of significant solar influence on the variability of river discharges can be found in Tomasino and Dalla Valle (2000)

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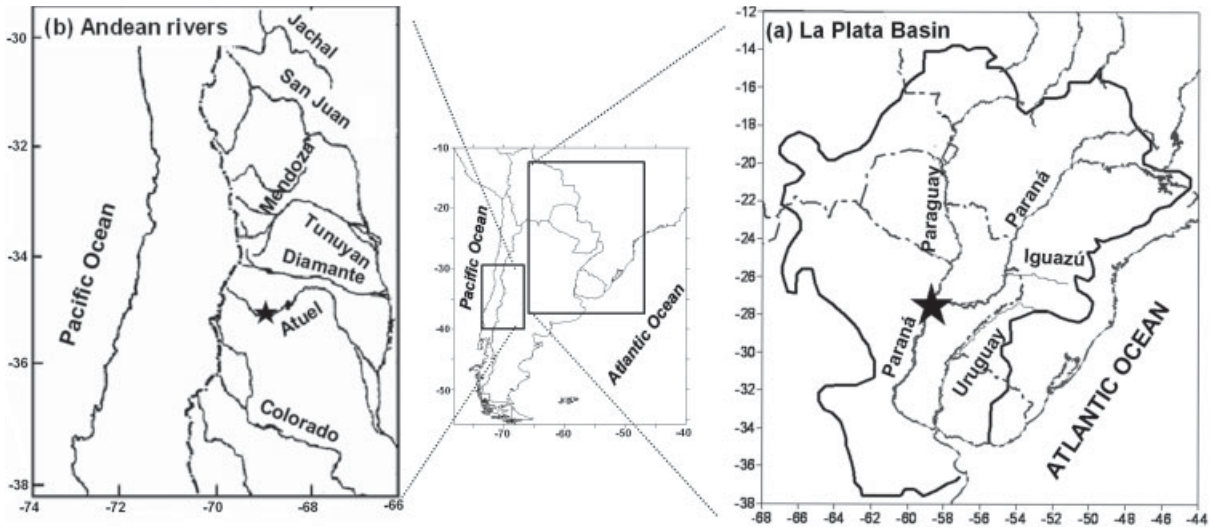

Figure 1. Rivers and the two gauging stations considered in this study. Corrientes in the PAR (right) and La Angostura in the ATU (left) are indicated by the black stars.

and Landscheidt (2000) for the Po River, in Perry (2006) for the upper Mississippi River Basin, in Ruzmaikin *et al.* (2006) for the Nile River and in Vita-Finzi (2008) for the Mediterranean basin.

Recent studies have suggested that the solar signal could be detected on rivers located to the east of the Andes in South America between 10°S and 40°S (SSA. Figure 1). Mauas *et al.* (2008), after the elimination of secular trends and cycles with periods equal or smaller than 11 years in the time series of the sunspot numbers (SSNs) and the Paraná River (PAR) discharges at Corrientes gauging station (Figure 1), obtained strong positive correlations at interdecadal scales. Furthermore, Mauas *et al.* (2011) have shown similar results for San Juan, Atuel and Colorado subtropical Andean rivers. The authors propose that at multidecadal scales '*higher solar activity corresponds to larger precipitation, both in summer and in wintertime, not only in the large basin of the Paraná, but also in the Andean region north of the limit with Patagonia*'. Likewise Antico and Kröhling (2011), using multitaper power spectral method and correlation analysis, have shown that the 7–9 years oscillation of the Paraná annual discharge is linked to the absolute value of solar angular momentum. On the other hand, Labat (2008) analysed southern South America (SSA) river discharges using global wavelet spectra that yield similar results to the conventional Fourier analysis. He determined a 4–6 year oscillation in the Andean rivers that could be directly related to ENSO events. He also found a distinct near-decadal 11–13-year oscillation—being the main variability of the SSA Rivers—and a 27–30-year interdecadal oscillation for the Paraná—which can be considered as a major disturbance because the signal also appears in watersheds of the Orinoco and the Amazon—without reference to any forcing to either signals.

The above results suggest a possible Sun–Rivers relationship in SSA, which motivates the current research. To our best knowledge, no one has investigated yet such a relationship within all possible frequencies ranging from interannual-to-multidecadal scales during the instrumental period. Therefore, the aim of this paper is to thoroughly analyse the link between the solar signal and discharge of the main SSA Rivers (Figure 1) through the Paraná and the Atuel that represents subtropical Argentinean Andean Rivers according to Compagnucci and Araneo (2007). Note that the Schwabe solar cycle of 11 year, that accounts for the greatest variance of solar variability, is actually a band of periodicities ranging from 10 to 12 years (Richards *et al.*, 2009). The wavelet-based methods can handle time series that contain quasi-cycles and it constitutes and advantageous with respect to other methods (Veerstegh, 2005). Hence we apply the global and power wavelet analyses to examine individual time series together with cross, coherent and other derived wavelet analysis to describe relationships over the entire time-frequency domain. In this sense, this research is the first attempt of using a wavelet approach for searching possible Sun-climate links in SSA throughout the last 100 years. This is an original contribution to the study of climate variability in SSA.

The article is organized as follows. Section 2 presents the characteristics and processes involved in the streamflow variability of the Paraná and the Atuel as well as possible physical mechanisms connecting the river response to the solar forcing. Section 3 depicts the data and methodology and Section 4 describes the main results. Discussion and concluding remarks are given in Section 5.

2. Physical mechanisms underlying possible river responses to solar forcing

The PAR is one of the largest rivers in the world extending throughout the La Plata basin over southern

Brazil, Paraguay and eastern Argentina. The behaviour of this river is dominated by the liquid precipitation on the basin, having a short delay in the relationship between precipitation and runoff. It has a well-defined annual cycle with phases that can be traced primarily to the physiography and precipitation regime in the basin (Berbery and Barros, 2002). At the Corrientes gauging station, the river has a drainage basin of about 1,950,000 km^2 ('Sub-Secretaria de Recursos Hídricos' hereinafter SSRH, 2004). On the other hand, the Atuel River (ATU) at the La Angostura gauging station has a notable smaller drainage basin of only 3800 km^2 (SSRH, 2004). However, the ATU behaviour reflects hydro-climatic processes of all the subtropical Argentinean Andean Rivers (Figure 1), almost from the northernmost Jachal River at 30°S to the southernmost Colorado River at 37°S (Compagnucci and Araneo, 2007). All these drainage basins encompass an area about 260,000 km^2 (SSRH, 2004). The effect of liquid precipitation in these Andean Rivers is unimportant because their discharges mainly depend on the spring-summer melting of snow accumulated during winter in the high Andes ranges.

Moreover, the El Niño/Southern Oscillation (ENSO) affect the Paraná by modulating tropical precipitation in its drainage basin (e.g. Robertson and Mechoso, 1998; Camilloni and Barros, 2003) and the subtropical Andean Rivers by regulating the winter snowfalls in their headwaters (e.g. Compagnucci *et al.*, 2000; Araneo and Compagnucci, 2008). In addition, evidence of the connection between solar activity and the sea surface temperature in the equatorial Pacific has been introduced by different authors (e.g. Mann *et al.*, 2005; Velasco and Mendoza, 2008), as well as the role of the ENSO events as a mediator of the solar influence on the climate (e.g. Emile-Geay *et al.*, 2007). Consequently, the mean oceanic-atmospheric conditions in tropical Pacific basin could be the connector in the potential relationship between solar activity and SSA hydro-climate variability.

3. Data and methodology

Annual mean discharges of the PAR measured at Corrientes (27.28°S, 58.50°W) in the period 1904–2011 and of the ATU measured at La Angostura (35.06°S, 68.52°W) in the period 1906–2011, comprise two of the longest and without gaps records of SSA (Figure 1). Data were provided by the SSRH of Argentina (http://www.hidricosargentina.gov.ar/acceso_bd.php).
The solar variability is measured by the annual SSN index, taken from the National Geophysical Data Center (http://www.ngdc.noaa.gov).

In order to analyse local variations of power in time series with multiple periodicities, wavelet-based analysis is applied to the discharge and SSN time series. The most frequently used wavelet functions are the Mexican hat and Morlet wavelet transforms. The Mexican hat wavelet (derivatives of a Gaussian; DOG, $m = 2$) is a real valued whereas the Morlet wavelet is a complex function. The most noticeable difference between them is that the Mexican hat gives a better resolution in time whereas the Morlet wavelet resolves the frequency with more accuracy (Torrence and Compo, 1998).

Considering that the focus under analysis is narrow oscillation bands or quasi-cycles, e.g. around 11-year solar cycle, we chose to show and discuss the Morlet Wavelet because it returns information about both amplitude and phase and it is better adapted for capturing oscillatory behaviours. The Morlet Wavelet consists of a complex exponential function $e^{i\omega_0 t/s}\ e^{-t^2/(2s)^2}$, where t is the time, s is the wavelet scale and ω_0 is a non-dimensional frequency considered as $\omega_0 = 6$ to satisfy the admissibility condition (Farge, 1992). Torrence and Compo (1998) defined the wavelet power $\left|W_n^X(s)\right|^2$, where $W_n^X(s)$ is the wavelet transform of a time series X and n is the time index. The significance refers to the power of the red noise at 95% confidence level (Grinsted *et al.*, 2004).

Common periodicities in the time series are investigated with the Cross-Wavelet (XWT) analysis (Hudgins *et al.*, 1993; Grinsted *et al.*, 2004) that exposes the relative phase in the frequencies where two time series have high common power. The time lags separating the two time series are also determined by the phase of the XWT. Although this methodology is useful for non-stationary time series, it can displays misleading significant peaks of common variability just because the wavelet power spectrum of one of the considered time series has strong peaks in those frequencies (e.g. Maraun and Kurths, 2004). Such misleading peaks vanish in the Wavelet Coherency (WTC) analysis (e.g. Grinsted *et al.*, 2004) that highlights the frequencies and the corresponding relative phase where two time series covary even though both have low power at such specific frequencies. The option considered in this study to calculate the coherence of the system is through the relation signal/noise $WTC_{s/n}$ defined by Velasco Herrera *et al.* (2010): $WTC_{s/n} = [WTC/(1-WTC)]$. The statistical significance is estimated using Monte Carlo methods with red noise to determine the 95% significant level and the corresponding cone of influence (COI), where edge effects could be important (Torrence and Compo, 1998), is shown by paled colours in the Wavelet, XWT and $WTC_{s/n}$. Arrows in both XWT and $WTC_{s/n}$ spectra show the phase relation between the time series. Horizontal arrows pointing to the right (left) indicate that both series are in-phase (anti-phase) and nonhorizontal arrows describe out-of-phase relationships. In the graphics of the next section, arrows pointing downward (upward) indicate that SSN cycle leads (follows) the corresponding river discharge cycle.

The time lags between PAR and SSN, and between ATU and SSN for a determined oscillation band are calculated by $\Delta\tau = \frac{1}{2\pi}\Delta\varphi\,\Delta T$; where $\Delta\tau$ is the delay, $\Delta\varphi$ is the phase and ΔT is the period. The wavelet-filtered reconstructions of a determined oscillation band are obtained from a time-scale filter (Leal-Silva and Velasco Herrera, 2012). Time-scale filter is defined as

$X_n = \frac{\delta_j \delta_t^{1/2}}{C_\delta \psi_o(0)} \sum_{j=0}^{J} \frac{\mathrm{Re}\{W_n(s_j)\}}{s_j^{1/2}}$; where δ_j is the factor for scale averaging, C_δ is a constant ($\delta_j = 0.6$ and $C_\delta = 0.776$ for Morlet wavelet) and ψ_o removes the energy scaling (Torrence and Compo, 1998).

Complementary, we apply the Mexican hat wavelet (in supporting information) to evaluate the robustness of the Morlet wavelet results, particularly for the low frequencies where edge effects could be important for the Morlet transform. A practical step-by-step guide to wavelet analysis together with the strengths, limitations and advantage of the Morlet and Mexican hat wavelet functions can be found in Torrence and Compo (1998). Details of the Morlet function are in Velasco Herrera *et al.* (2010) and references cited therein. The XWT as well as the WTC analysis have been used in hydrologic research by other authors (Labat *et al.*, 2005; Adamowski, 2008; Labat, 2010; Zhang *et al.*, 2012).

4. Results

4.1. Individual power wavelet spectra

Several authors have examined different characteristics of time series representing the solar variability. In particular, the analysis of the annual Total Solar Irradiance since 1600 performed by Velasco and Mendoza (2008) reveals that the widely described 11-year solar cycle periodicity disappeared during part of the Maunder minimum period (about 1500–700 AD) and was weak during the Dalton minimum period (about 1750–1850 AD), but it became stationary with high significant power since the beginning of the 20th century. Figure 2(a)–(c) shows the power wavelet analysis of SSN for the 20th century evidencing the solar-cycle stationary state previously documented. The global wavelet further shows strong significant power in the periodicity band about 8–12 years (significant at the 95%). At the beginning and end of the record, the 11-year signal seems to weaken, coinciding with the small amplitude of the solar cycle 14 in the early 20th century and the recent deep and prolonged solar minimum at the end of solar cycle 23.

The discharge time series of the Paraná (Figure 2(d)) exhibits a variability change in the 1970s when magnitudes became higher than $1.5 \times 10^4\,\mathrm{m^3\,s^{-1}}$ as was described by Amsler *et al.* (2005) and Krepper *et al.* (2008), among others. The global wavelet spectrum (Figure 2(e)) shows that oscillations around 3.5, 9 and 30 years are significant. The 3.5-year periodicity is associated with the influence of ENSO events on this river (e.g. Robertson and Mechoso, 1998; Berbery and Barros, 2002) whereas the near-decadal 9-year oscillation has been connected with oceanic forcing by Robertson and Mechoso (1998) and also with the solar motion by Antico and Kröhling (2011). Note that the 11-year solar cycle is not a significant signal in the wavelet power spectrum (Figure 2(e)). The power wavelet spectrum shows that the variability associated with these significant oscillations are non-stationary throughout the century (Figure 2(f)). In fact, the 3.5-year variability is important before 1915 and during the 1960s–1970s, the 9-year oscillations are particularly intense in 1910s–1930s and 1960s–1980s. Otherwise, oscillations around 30 years have a significant global spectrum and high power throughout the entire century, albeit this interdecadal variation lays within the COI region effects.

The discharge time series of the Atuel also show a change in the 1970s when the magnitudes became higher than $30\,\mathrm{m^3\,s^{-1}}$ in almost all years (Figure 2(g)). This characteristic is observed in all rivers of the eastern subtropical Andean region and is attributed to the change in the Pacific Decadal Oscillation (PDO) phase (Waylen *et al.*, 2000). The global spectra (Figure 2(h)) describe significant oscillations with peaks around 4–5, 7, 11 and 22 years. The oscillations around 4–5 years are associated with the ENSO influence on the Andean river flows (Compagnucci *et al.*, 2000) whereas the 11- and 22-year periodicities are also typical of the solar variability (Schwabe and Hale cycles, respectively). The local power spectrum (Figure 2(i)) detects that variability of 4–5 years is particularly intense in 1900s–1920s, oscillations around 7 years are important in 1930s–1970s and oscillations around the Schwabe and Hale cycles are significant in 1930s–1950s and after the 1960s, respectively.

4.2. Covariability between the Sun and the rivers

As was mentioned before, the power wavelet analysis shows that the time series of SSN and PAR have significant oscillations in a band around 11 and 9 years, respectively (Figure 2(a)–(f)). The common power of PAR-SSN is displayed by the XWT (Figures 3(b) and (c)) in which both global and local spectrum suggest significant link for the band near 11 years over almost all the century. From these results, we could speculate that there is a physical connection between SSN and PAR in the band of 8–12 years. However, the presence of changes in the orientation of the phase arrows in the XWT (Figure 3(c)) describes changes in the corresponding time lag among the series. For the around 11-year band, the time lag series (Figure 3(d)) demonstrates the instability in the SSN–PAR relationship, shown by the changes in the amplitude and sign of the phase through time. The wavelet-filtered reconstruction at about the 11-year cycle (7-to-14 year band) of PAR and SSN (Figure 3(e)) shows the same problem. In fact, a maximum (minimum) in the Schwabe solar cycle is followed by a maximum (minimum) in the discharge values, with same delay of around 2 years from the early 1900s to the middle 1940s. Afterwards, the relationship becomes the inverse: the peak in the Schwabe cycle is coincident with low discharges, or delayed in 1 or 2 years. From the early 1970s to the middle 1990s the lagged direct relationships are re-established, but during the 2000s the relationship seems to be the inverse again. Although the global $\mathrm{WTC_{s/n}}$ (Figure 3(f)) shows a significant peak at ~11 years, the local power spectrum (Figure 3(g)) displays a lack of significant links in most of the analysed period. The $\mathrm{WTC_{s/n}}$

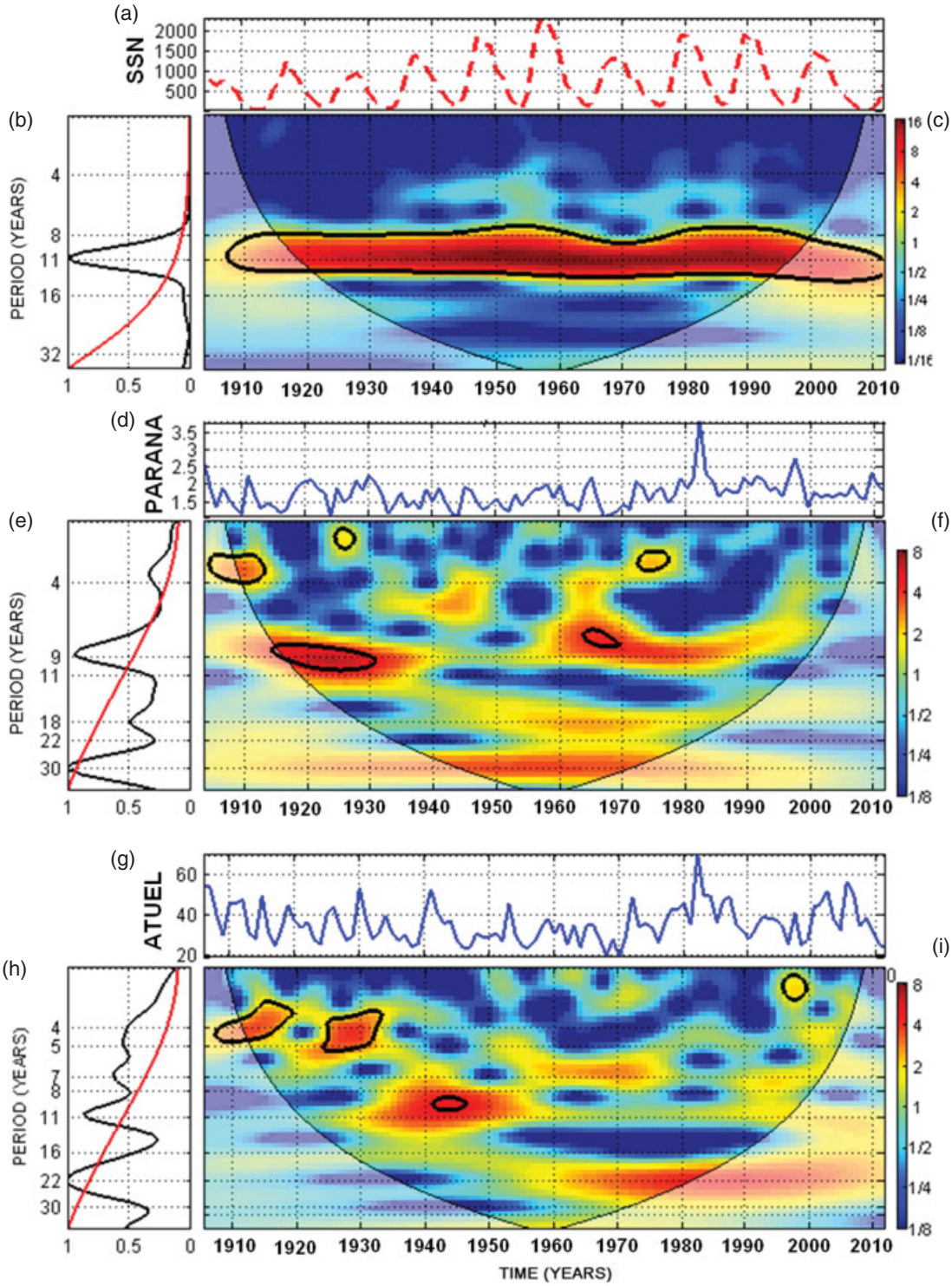

Figure 2. (a) Time series of SSN, (b) global and (c) local wavelet power spectrum using Morlet transform. The same for Paraná (d–f) and Atuel (g–i). The red lines in (b), (e) and (h) indicate the 95% confidence level and paled colours in (c) (f) and (i) indicate the COI. Discharges units: the Paraná in 10^3 m^3 s^{-1} and the Atuel in m^3 s^{-1}.

results, for oscillations periods near 11 years, suggest significant coherency with phase arrows indicating that SSN leads PAR (vectors pointing downward) during the three first decades. However, two uncorrelated time series may lead to significant linear correlations over short-time periods just by chance that could be the case of the apparent PAR–SSN connection observed during the first decades of the PAR record. It means that most of the links described by the XWT might arise because of the strong variability in one of the time series as was mentioned in Section 3. In other words, the strong variability around 11 years, detected in SSN (Figures 2(a)–(c)), can produce misleading peaks in the XWT. The $WTC_{s/n}$ also displays close relationships throughout the entire century

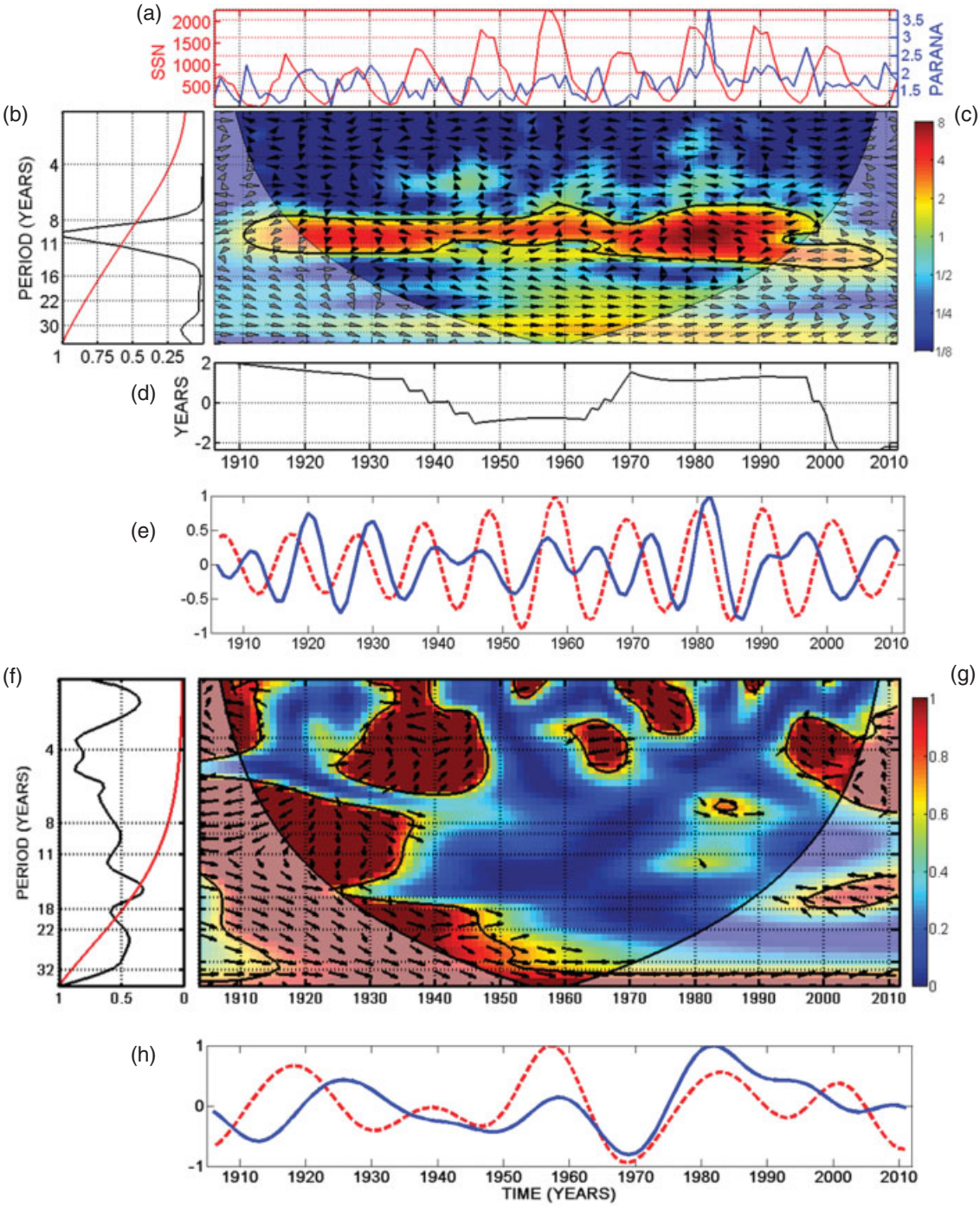

Figure 3. (a) Time series of SSN (red) and Paraná (blue), (b) global and (c) local power cross-wavelet spectrum using Morlet transform, (d) time lag in years for ~11-year cycle, (e) wavelet-filtered reconstruction of the 11-year cycle of SSN (red dashed) and Paraná (blue), (f) global and (g) local power spectrum of the coherence-wavelet using Morlet transform, (h) wavelet-filtered reconstruction of the ~30-year cycle of SSN (red dashed) and Paraná (blue). The red lines in the global spectrum indicate the 95% confidence level and the paled colours in the local spectrum indicate the COI (see the text for more details).

around oscillations of 30 years that are typical of the Sun-modulated cosmic rays activity (Pérez-Peraza *et al.*, 2012). Although the ~30-year periodicity (oscillations from 25 to 35 years) extends almost entirely within the COI region, the wavelet-filtered reconstruction for PAR and SSN are in phase with good agreement almost from the 1940s to 1980s (Figure 3(h)). Furthermore, the Mexican hat wavelet (Figure S1, Supporting Information) shows a significant peak in the band centered at ~30 years in the WTC global spectrum, and a direct link with significant values since the second half of the 20th century located outside the COI in the WTC local spectrum. Therefore, while the SSN-PAR link at 11-year cycle must be considered with great caution, the ~30-year cycle link, suggested by the $WTC_{s/n}$ Morlet wavelet, becomes more robust considering the Mexican hat wavelet results.

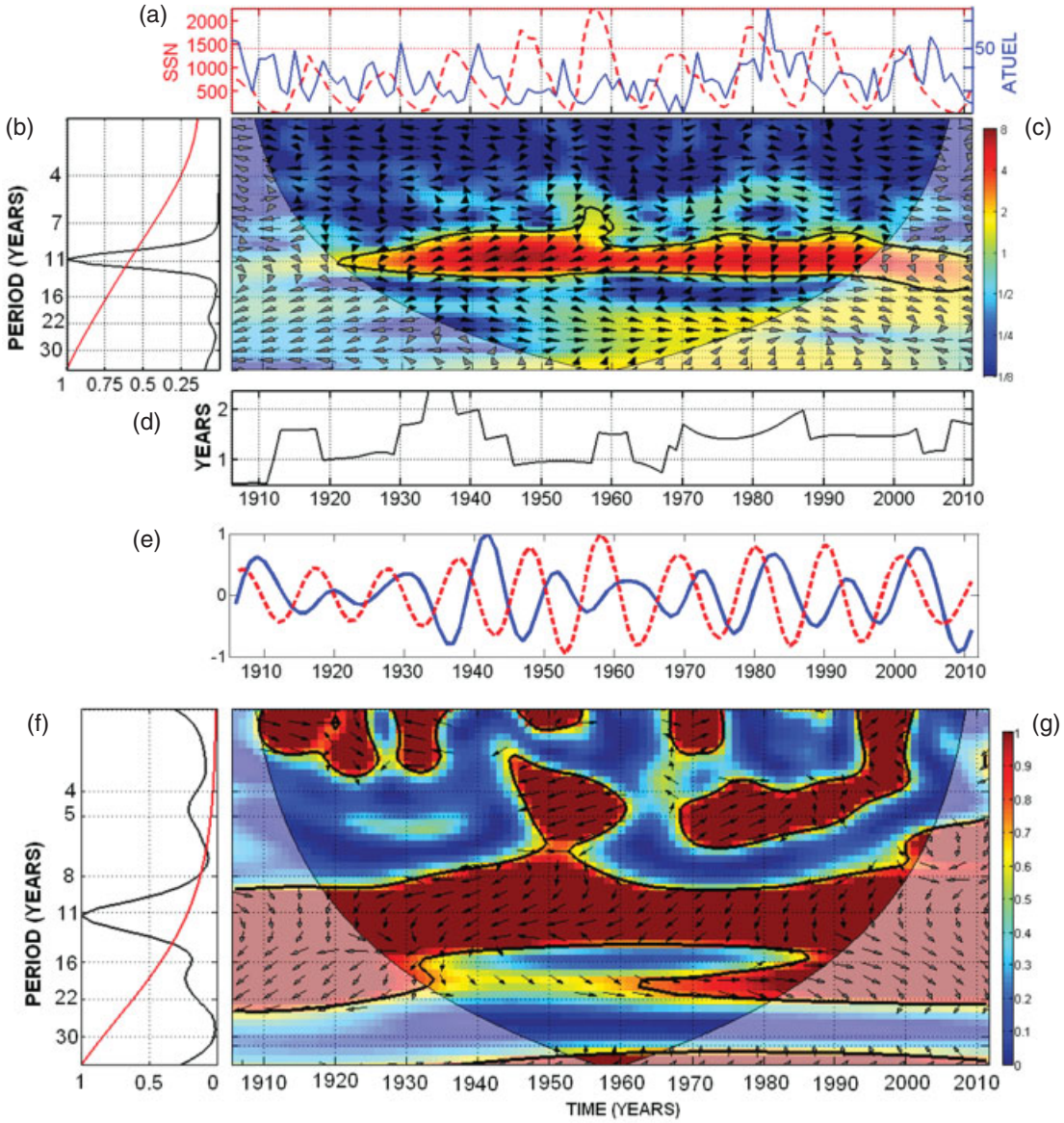

Figure 4. (a) Time series of SSN (red) and Atuel (blue), (b) global and (c) local power cross-wavelet spectrum using Morlet transform, (d) time lag in years for ~11-year cycle, (e) wavelet-filtered reconstruction of the 11-year cycle of SSN (red dashed) and Atuel (blue), (f) global and (g) local power spectrum of the coherence-wavelet using Morlet transform. The red lines in the global spectrum indicate the 95% confidence level and the paled colours in the local spectrum indicate the COI (see the text for more details).

The characteristics of the relationship between the SSN and ATU are different from those detected in SSN-PAR. As was previously described, large amplitude and statistically significant cycles around 11 years are observed not only in the local and global wavelet spectra of SSN and ATU (Figure 2(a)–(c) and (g)–(i)) but also in the global and local spectra of XWT (Figures 4(b) and (c)). These results suggest that the relationship SSN–ATU is significant over almost all the century for Schwabe cycles when the solar activity leads the Atuel discharge (Figure 4(c)). In spite of the changes in the lags, the relationship remains with the same sign all through the analysed period. For the ~11-year periodicity, the phase sign in the series of time lags (Figure 4(d)) remain positive throughout the analysed period. Furthermore, the wavelet-filtered reconstruction (Figure 4(e)) shows that a maximum (minimum) in the Schwabe solar cycle is followed by a maximum (minimum) in the river discharge values, with lags ranging from 0 to 2 years, being the relationship always direct. This connection between SSN and ATU in oscillations around 11 years is remarkably significant in the $WTC_{s/n}$ analysis during the entire 1906–2011 period (Figures 4(f) and (g)). The $WTC_{s/n}$ also describes significant time lagged relationship in oscillations around 22 years (Hale solar magnetic cycle) before the 1930s and after the 1960s and in oscillations longer than 30 years. These significant links are located inside the COI and can thus be affected by edge effects. However, the Mexican hat wavelet analysis (Figure S2) suggests a significant ATU-SSN link for oscillations longer than 30 years in both global and local spectra of the cross-wavelets.

5. Discussion and concluding remarks

This study shows a new description of the solar influence on climate in SSA for an observational period of 100 years, from the early 1900s to 2011. Specifically, the possible links between the SSNs and the annual discharges of the Paraná and the subtropical Andean Rivers through the Atuel are examined analysing their covariability in the entire time-frequency space.

Previous studies, using global wavelet analysis, showed important variability in oscillations around 11 years in the discharges of SSA Rivers (e.g. Labat, 2008). Furthermore, studies based on filtering the secular trend and periodicities shorter than 11 years suggest that the SSN are highly correlated at multidecadal scales with SSA Rivers postulating that higher solar activity corresponds to larger precipitation in summer and winter over the Paraná basin and the Andean region (Mauas *et al.*, 2008; Mauas *et al.*, 2011). Antico and Kröhling (2011) have further demonstrated that the variability of the PAR annual discharge is linked to the solar motion represented by the absolute value of solar angular momentum, which is dominated by cycles of about 7–9 years. To our best knowledge, this is the first attempt to elucidate the full interannual-to-multidecadal range of covariability in time and frequency between the solar variability and SSA River discharge variability using wavelet-based methods.

The XWT suggests a close connection between the SSN and PAR around the typical 11-year solar cycle. However, the $WTC_{s/n}$ indicates that the covariability is only present in the first three decades of the analysed period. Furthermore, the ~11-year wavelet-filtered time series and the time series of time lags for the Paraná–Sun relationship show alternated direct-and-inverse relationships, that is to say, changes in the phase and sign together with changes in the time lags. Such changes in lag and sign of the covariability can arise if one variable has an oscillation with close but distinct frequency that the other, even in the absence of significant physical relationship between them. According to the previous results of Antico and Kröhling (2011) and our wavelet results, the PAR time series oscillates with ~9-year cycle that is shorter than the Schwabe cycle though close to it. Therefore, the relationship for this 11-year band is a poor assumption that must be taking with caution, especially when one wants to use it to predict the Paraná flow from the solar cycle forecast.

Another distinct SSN–PAR connection is through the ~30-year oscillation, previously detected by Mauas *et al.* (2008) and Mauas *et al.* (2011) as a multidecadal oscillation. It seems to be significant in the Morlet $WTC_{s/n}$ local spectrum throughout the analysed period. Its significance results to be reinforced by the Mexican hat WTC analysis. Moreover, Mauas *et al.* (2008) had proposed that increased solar irradiation causes more evaporation in equatorial-subtropical regions, enhancing the net transport of moisture flux to the continent. According to Poore *et al.* (2004), changes in solar irradiance can be associated with the northward-southward shift of the Inter Tropical Convergence Zone (ITCZ), which can affect precipitation over the PAR drainage basin. Multidecadal relationship between the solar variability and the PDO (Velasco and Mendoza, 2008) together with the connection between the PDO or ENSO-like variability with the Paraná discharges (Genta *et al.*, 1998; Boulanger *et al.*, 2005) can give us another potential physical mechanism. Nevertheless, note that only three complete cycles of 30 years are present in flow records whose length are near 105 years. Hence, further research is needed in order to support the suggested understanding of Sun–PAR connection and other possible mechanisms at multidecadal scales.

Contrarily to the results for the PAR, the relationship between the Sun and the ATU at the ~11-year cycle is much more robust and convincing. Their XWT and $WTC_{s/n}$ Morlet wavelets result to be statistically significant in almost all the analysed period. The ~11-year solar cycle is not an intermittent feature for the Atuel and, therefore, for all the remaining subtropical Argentinean Andean Rivers. High (low) discharges occur following maxima (minima) of the Schwabe cycle with time lags that can be up to ~2 years, determining a positive relationship. Such a connection would be mediated through the ENSO cycles that produce changes in the atmospheric circulation forcing the variability of these rivers. Thus, high (low) annual discharges are associated with El Niño (La Niña) events which produce excess (deficit) of snow accumulation during the winter previous to the snow-melting season (Compagnucci and Araneo, 2007; Araneo and Compagnucci, 2008). In turn, Meehl and Arblaster (2009), using modelling and observational data, have shown that the Sun modulates the El Niño events, through wind-forced ocean Rossby waves near 5°N and 5°S, a few years after solar maxima. Note that the Atuel discharge also follows the SSN with a time lag of a few years. Furthermore, an association between SSN–ATU with periodicities longer than 30 years is suggested by both the Morlet XWT and $WTC_{s/n}$. The Mexican hat XWT (Figure S2) further displays significant oscillations longer than 30 years. Such an evidence of long-term links between the solar variability and the subtropical Argentinean Andean Rivers needs to be tested by further investigations using longer time series provided by proxy data available in the area. This also allows us to speculate that other climatic elements and the atmospheric circulation at the South Hemisphere may be also involved in these responses to the solar variability.

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