
International Journal of River Basin Management
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/trbm20

# Multi-annual variability of streamflow in La Plata Basin. Part II: simulations for the twenty-first century

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Accepted author version posted online: 10 Jan 2014.Published online: 28 Feb 2014.

To cite this article: Alvaro Díaz, Fernanda Maciel & Ramiro Saurral (2013) Multi-annual variability of streamflow in La Plata Basin. Part II: simulations for the twenty-first century, International Journal of River Basin Management, 11:4, 361-371, DOI: 10.1080/15715124.2014.880708

To link to this article: http://dx.doi.org/10.1080/15715124.2014.880708

*Intl. J. River Basin Management* Vol. 11, No. 4 (December 2013), pp. 361–371




Research paper

# Multi-annual variability of streamflow in La Plata Basin. Part II: simulations for the twenty-first century

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**ABSTRACT**
Water resources availability presents a high degree of uncertainty in the context of climate change. In this study, the multi-year variability of simulated streamflow for three rivers (Paraná, Uruguay and Negro) in the La Plata Basin (LPB) in the period 1991–2098 is analysed. Simulated streamflow for that period were produced in a two-stage process involving a regional climate model (RCM) and a distributed hydrology model (VIC (variable infiltration capacity)). Outputs from two RCMs (PROMES [Spanish acronym for mesoscale forecast] and RCA [Rossby Centre regional atmospheric climate model]) were used in order to assess the sensitivity of the results to different models. Various spectral methods (singular spectrum analysis, maximum entropy method and multi-taper method) were used in order to detect low-frequency variability modes and preferred quasi-periodicities for annual and seasonal simulated time series. Both simulations generate larger runoff for the twenty-first century than those observed for the twentieth century for the three rivers. For annual time series, the variability in timescales longer than 30 years is detected by one of the simulations for the three rivers, and only weakly for the Negro River in the other. Seasonal variations of the preferred modes of multi-annual variability are apparent. The River Paraná shows a persistent 10-year period during most of the year in the PROMES-VIC simulation. No LFV modes were found for any trimester in any river for PROMES-VIC, while for RCA-VIC simulations, these appeared in austral summer (Negro and Uruguay rivers) or early winter (Paraná River). A striking finding, both for annual and seasonal simulated time series, is the conspicuous presence of pseudo-periods in the 2.5–5 years band that had already been captured in the observed 20th streamflow time series [Maciel, F., Díaz, A., and Terra, R., 2013. Multi-annual variability of streamflow in La Plata Basin. Part I: observations and links to global climate. *International Journal of River Basin Management*, 11 (4), 345–360.]. This pattern is probably linked to the El Niño–Southern Oscillation (ENSO) phenomenon. These results imply that the well-known relationships between ENSO and precipitation and streamflow anomalies in the LPB are expected to prevail during the twenty-first century.

*Keywords:* Multi-annual streamflow variability; climate and hydrology models; spectral methods; climate change

## 1 Introduction

Energy consumption is steadily growing in the world. Consequently, the production of abundant, low-cost and renewable energy has become an issue of increasing importance. Hydropower can advantageously fulfil these requirements. However, climate change imposes new risks on the future availability of water resources. Various major hydroelectric dams are located in the La Plata Basin (LPB), the second largest basin in South America, that extends over more than 4 million square kilometres and is shared by Argentina, Brazil, Paraguay, Uruguay and Bolivia (see Figure 1).

Several studies have examined different aspects of the variability of the LPB hydrology: links to other components of the hydrologic cycle (Berbery and Barros 2002), detection of regime changes, oscillatory behaviour and trends in rivers streamflow (García and Vargas 1998, Genta *et al*. 1998, Robertson and Mechoso 1998) and connection to the El Niño–Southern Oscillation (ENSO) phenomenon (Mechoso and Pérez-Iribarren 1992, Camilloni and Barros 2000).

Received 28 February 2013. Accepted 27 December 2013.

ISSN 1571-5124 print/ISSN 1814-2060 online
http://dx.doi.org/10.1080/15715124.2014.880708
http://www.tandfonline.com

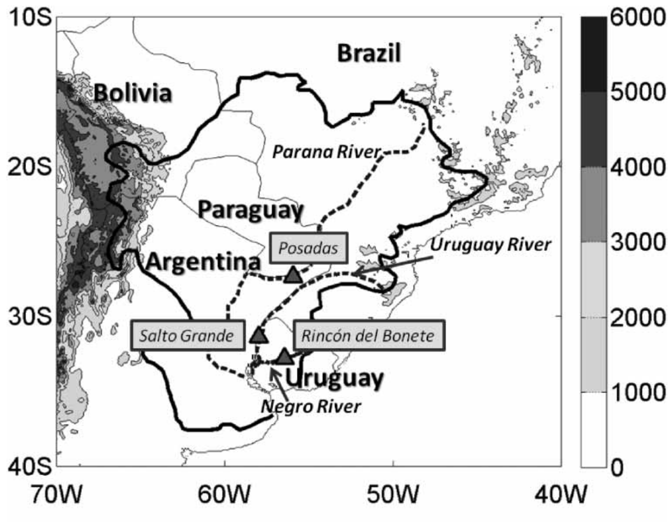


Figure 1 La Plata Basin. The three rivers and the locations of the three gauging points used in this study are indicated. Altitude is expressed in metres.

In particular, Maciel *et al*. (2013) (hereafter referred to as MDT2013), using several spectral analysis techniques, studied observed annual and seasonal streamflow time series for three rivers in the LPB: the Paraná River at Posadas (1900–1999), the Uruguay River at Salto Grande (1909–2007), and the Negro River at Rincón del Bonete (1908–2007), searching for prevailing pseudo-periodicities and low-frequency variability (LFV) modes. These features are relevant because pseudo-periodicities imply a certain degree of predictability (Robertson *et al*. 2001) and LFV modes are usually associated with monotonic trends. Given these implications, the question arises as to whether these modes of variability will persist in the future, especially in the context of climate change. In this work, developed during the CLARIS project (http://www.claris-eu.org), our aim is to address this issue by determining preferred modes of multi-year variability of long-term simulated streamflow time series for the twenty-first century in the same gauge points, and comparing them with those obtained in MDT2013.

The methodology followed to obtain the streamflow simulations and to detect predominant modes of variability is included in Section 2. Results are presented in Section 3. The conclusions of the paper are reported in Section 4.

## 2 Methodology

The procedures used to accomplish the goals of this paper include the steps given below.

Firstly, daily temperature and precipitation time series for the 1991–2098 period were obtained for the three gauge points from regional climate models (RCMs) simulations accomplished in the CLARIS Work Package 5 (WP5), using two RCMs that are presented in Section 2.1.1.

Secondly, these simulated time series were unbiased and then used as inputs to the variable infiltration capacity (VIC) distributed hydrology model, whose outputs are daily streamflow. These streamflow simulations were integrated to produce monthly time series. The VIC model will be introduced in Section 2.1.2 and the unbiasing method in Section 2.1.3. Quasi-periods and LFV modes for simulated streamflow time series were obtained via spectral methods that will be described in Section 2.2.

### 2.1 *Models and streamflow simulations*

#### 2.1.1 *Regional climate models*

We used outputs from two RCMs in order to assess the sensitivity of the results to different models. The RCMs used for this purpose were: PROMES (Spanish acronym for mesoscale forecast), from Universidad de Castilla – La Mancha, Spain (PROMES – UCLM, Sánchez *et al*. 2007, Domínguez *et al*. 2010) and Rossby Centre regional atmospheric climate model (RCA) from the Swedish Meteorological and Hydrological Institute, Sweden (RCA-SMHI, Kjellström *et al*. 2005, Samuelsson *et al*. 2006). Both models assume the IPCC-A1B emissions scenario (Houghton *et al*. 2001).

#### 2.1.2 *Hydrologic model*

The VIC hydrologic model (Liang *et al*. 1994, 1996, Nijssen *et al*. 1997) is a distributed grid-based land-surface scheme capable of solving both water and energy balances on a grid mesh. It simulates the main components of the surface and sub-surface hydrologic cycle, using a mosaic-like representation of soil type and land cover along with a subgrid parameterization for infiltration.

The model requires information on soil texture, topography, and vegetation, as well as daily information on selected meteorological variables as inputs, and was shown to successfully simulate the main hydrologic features of various basins worldwide (e.g. Mattheussen *et al*. 2000, Wood *et al*. 2002, Su and Lettenmaier 2009, Saurral 2010). VIC performs best in those basins characterized by rapid responses of runoff to precipitation, while in slow-moving water rivers, the performance is usually poor.

In this study, soil data were derived from the 5-min Global Soil Data Task data set taken from the Distributed Active

Table 1 Observed and simulated annual mean streamflow for the three rivers (km$^3$/year)

| | Negro | Uruguay | Paraná |
|---|---|---|---|
| Observed | **18.9** | **148.3** | **392.7** |
| PROMES-VIC | **26.8** (+42%) | **168.2** (+13%) | **424.8** (+8%) |
| RCA-VIC | **30.7** (+62%) | **252.1** (+70%) | **527.5** (+ 34%) |

Notes: Simulated means correspond to the 1991–2098 period. The rate of increase with respect to the observed series is shown in brackets.
Bold indicates highlight the difference between streamflow (which are expressed in km$^3$/year) and the rates of increase (which are expressed in dimensionless units).

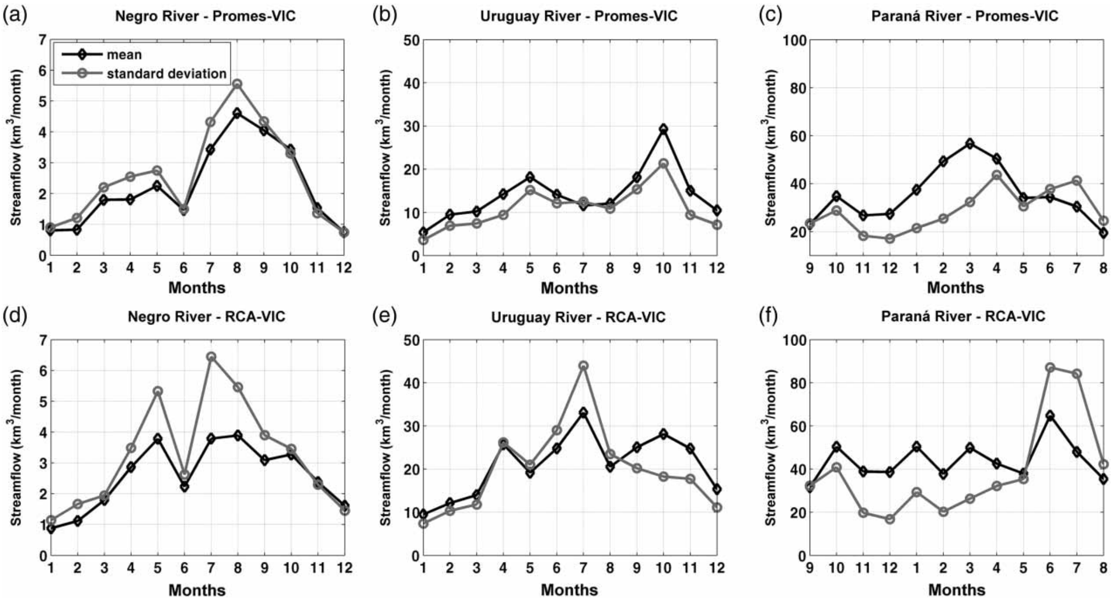


Figure 2 Mean and standard deviation annual cycles of monthly simulated streamflow for twenty-first century: (a–c) PROMES-VIC and (d–f) RCA-VIC . Note that for the River Paraná, the annual cycles begin in September.

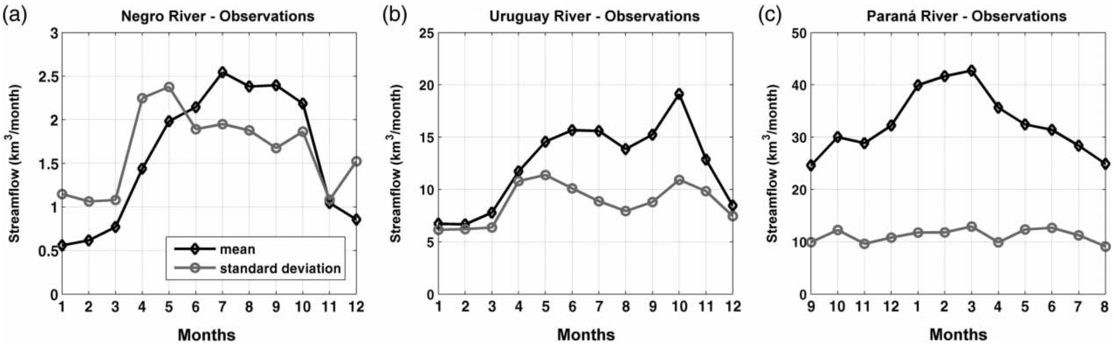


Figure 3 Mean and standard deviation annual cycles of monthly observed streamflow for twentieth century: (a) the River Negro, (b) the River Uruguay and (c) the River Paraná.



Archive Center (2000), and vegetation information were obtained from the University of Maryland's 1 km Global Land Cover product (Hansen *et al*. 2000). The meteorological information consisted of daily observed minimum and maximum temperature and daily precipitation in the period 1991–2000 as well as the same variables from the two RCMs and the period from 1991 to 2098. Spatial resolution for VIC was selected at one-eighth degree, so that all soil, land cover and meteorological information was re-gridded to that resolution before using it to force the hydrologic model.

Calibration and validation of the hydrologic model were made in previous works using meteorological data of the period 1991–2000 and tuning selected calibration parameters related to physical properties of the basin. The quality of the different simulations during the calibration stage was assessed by means of the Nash–Sutcliffe coefficient of efficiency (Nash and Sutcliffe 1970). As the three basins considered in this paper have differences in terms of climate and their responses to precipitation, calibration and validation were done separately for the Paraná, the Negro and the Uruguay rivers. More information on the calibration of the model over the LPB region can be found in Saurral (2010) and Saurral *et al*. (2013).

### 2.1.3 *Post-processing of simulations*

As is the case in most studies dealing with climate models, the RCMs used in this paper have deficiencies to simulate some aspects of the observed climate of the LPB region (see Saurral *et al*. 2013 for further details). Needless to say, these errors imply strong restrictions to the usage of the models as they are for climate variability studies or to assess potential impacts of climate change. Aiming to solve this problem, several correction schemes have been proposed in the last few years to correct the climate simulations, many of them based on statistical methods (Wood *et al*. 2002, Piani *et al*. 2010). In this paper, a statistical correction scheme is used to remove the systematic errors of

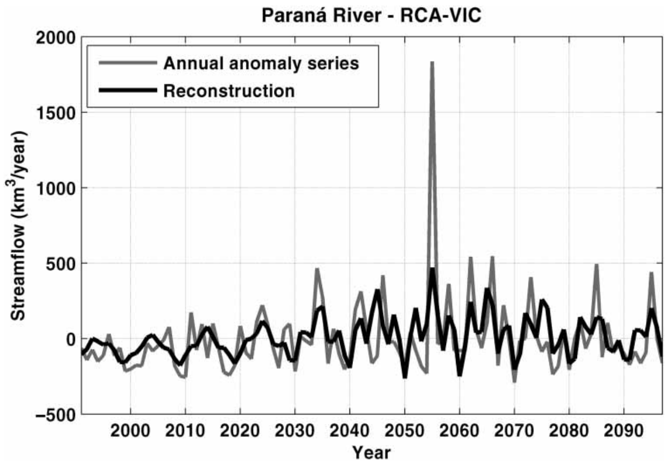


Figure 4 Simulated annual anomaly time series for River Paraná (RCA-VIC) for twenty-first century and RC associated to the five significant components obtained using SSA with a window size of $M =$ 30 years. Explained variance is 26%.



both RCMs before forcing them as input to the hydrologic model. The unbiasing scheme is based on the percentile distribution of both temperature and precipitation data for the observations and the RCMs and follows the procedure suggested by Wood *et al*. (2002). The scheme first requires the computation of the percentile distributions of monthly mean temperature and precipitation for the observations and the two RCMs in the period 1991–2000 ('present climate'). Then, the daily data of the twenty-first century are corrected by computing the monthly values of mean temperature and accumulated precipitation for all the months between January 2001 and December 2098 for each model and determining the corresponding *i*-th percentile of the distribution. The same percentile in the observations is then found, and the correction is applied, in the case of temperature, by adding to each daily data the difference between the value corresponding to that percentile in the observations and that in the RCM distribution. In the case of precipitation, RCM data are corrected by multiplying each daily data by the ratio between the corresponding percentile in the observations and the percentile in the RCM. This procedure has been already applied over the LPB to remove systematic biases in models, but for a subset of five Global Climate Models (see Saurral 2010).

Once the RCM data were unbiased, they were used to force the hydrologic model, which has as outputs daily and monthly mean discharge information on closing points that can be selected by the user. In the context of this paper, monthly mean streamflows were derived for three closing points: Posadas in the River Paraná, Salto Grande in the Uruguay River, and Rincón del Bonete in the Negro River (Figure 1). These unbiased streamflows were obtained for the period between January 1991 and December 2098 for both RCMs. All the subsequent analysis in this paper is based on this bias-free streamflow information. More information on the unbiasing procedure used in this work can be found in Saurral *et al*. (2013).

Table 2 Pseudo-periods associated to each of the five significant modes of the Paraná River simulated annual series (RCA-VIC) for twenty-first century, obtained using SSA with a window size of $M =$ 30 years

| Mode | Associated pseudo-period (years) |
|---|---|
| 1 | 3.4 |
| 2 | 3.4 |
| 3 | 10 |
| 4 | 10 |
| 5 | LFV |

### 2.2 *Spectral analysis of streamflow simulations*

The combination of each RCM output with the VIC model will be henceforth referred to as PROMES-VIC or RCA-VIC. The runoff simulations for the three gauge points for both RCMs were produced for the 1991–2098 period. These will be broadly referred to as twenty-first century simulations (hereafter 21_sim) as opposed to the twentieth-century observations (from now on 20_obs) used in MDT2013. There are no streamflow simulations available for the complete twentieth-century because the earliest starting date for the RCMs simulations was 1960.

The spectral methods used for the 21_sim runoff series are the same as those used in MDT2013 for the 20_obs time series. A very brief description is presented and more details on the methods can be found in Ghil *et al*. (2002) and Vautard *et al*. (1992).

In short, singular spectrum analysis (SSA), maximum entropy method (MEM) and multi-taper method (MTM) were used. In particular, SSA allows the extracting of information from relatively short and noisy time series, as runoff series usually are. SSA uses a time-window of length $M$ to decompose the original time series in additive series (patterns) of three types: oscillatory, LFV modes, and noise. In this way, the signal-to-noise ratio can be enhanced. All the obtained patterns are subjected to specific Monte Carlo (MC) statistical significance tests. A sinusoid is fitted to each significant oscillatory pattern in order to assign a pseudo-period to it. The sum of selected significant patterns will be called a 'reconstructed component' (RC). It is advised to use several values of $M$ within SSA and other spectral techniques, in order to correctly assess the robustness of the results.

We want to make clear that LFV modes may and will be loosely called 'trends' in the sense that they contain variability in 'long' timescales (typically longer than $M = 30$ or $M = 20$ years in this study), but this should not be confused with a monotonic behaviour.

## 3 Results

### 3.1 *Annual series*

At the first stage, we consider the main statistics of streamflow time series obtained from PROMES-VIC and RCA-VIC 21_sim and those for the 20_obs (MDT2013).

Table 3 Pseudo-periods (in years) and LFV modes associated to observed and simulated annual series

| | SSA-MC | SSA-MEM | MTM |
|---|---|---|---|
| Negro (observed; 1908–2007) | **3.6** (90%) | **3.6** | 3.6 (99%) |
| | 8.7 (90%) | **8.9** | 2.3 (95%) |
| | 9.1 (90%) | LFV | 5.6 (90%) |
| | | | 8 (90%) |
| Negro (1991–2098 PROMES-VIC) | LFV (90%) | **28** | LFV (95%) |
| | 28 (95%) | 3.9 | 3.9 (95%) |
| | | 2.5 | 2.5 (95%) |
| | | | 2.1 (90%) |
| Negro (1991–2098 RCA-VIC) | **3.4** (90%) | **3.4** | 3.4 (99%) |
| | LFV (90%) | LFV | 2.5 (95%) |
| | 16 (90%) | 16 | 4 (90%) |
| Uruguay (observed; 1909–2007) | **3.6** (90%) | **6.2** | 3.6 (99%) |
| | LFV (90%) | **LFV** | 6.4 (95%) |
| | **6.3** (90%) | **3.6** | 2 (95%) |
| | | | LFV (90%) |
| Uruguay (1991–2098 PROMES-VIC) | **4** (95%) | **4** | 4.1 (99%) |
| | 2.4 (95%) | **4.5** | 2.4 (95%) |
| | 19 (90%) | 2.4 | 19 (90%) |
| | 4.5 (90%) | 19 | |
| Uruguay (1991–2098 RCA-VIC) | LFV (90%) | LFV | 14 (95%) |
| | 14 (90%) | **14** | 4.2 (95%) |
| | 5.6 (90%) | 5.1 | LFV (90%) |
| | 3 (90%) | | |
| Paraná (observed; 1901–1999) | **LFV** (90%) | **LFV** | 3.6 (99%) |
| | **3.6** (96%) | **3.6** | 2.4 (99%) |
| | | 3.4 | 7.8 (95%) |
| | | | LFV (90%) |
| Paraná (1991–2098 PROMES-VIC) | **2.6** (90%) | **2.6** | 2.6 (95%) |
| | | 16 | 10 (90%) |
| | | 2.8 | 2.9 (90%) |
| Paraná (1991–2060 RCA-VIC) | **3.4** (90%) | **3.4** | LFV (95%) |
| | **LFV** (90%) | **LFV** | 3.4 (95%) |
| | 10 (90%) | **9.7** | 9.3 (90%) |
| | | | 2.3 (90%) |

Notes: Window sizes ($M$) of 15, 20 and 30 years were used for SSA-MC. The dominant pseudo-periods or LFV modes shown in the second column were determined adjusting a sinusoid to the corresponding empirical orthogonal function. The significance levels attained by the corresponding components according to the MC test are also shown in the second column (in brackets). Only results with at least 90% significance level are presented. Bold characters indicate that the significance level is reached for two values of $M$, and bold plus underlined characters are used when the significance level is attained by the three values of $M$. Pseudo-periods detected by MEM for significant components according to MC are shown in the third column. In the fourth column, pseudo-periods captured by MTM and the exceeded significance level (in brackets) are shown.

Table 1 shows that for all the rivers, all the 21_sim present higher long-term means than the 20_obs ones, the rate of increase ranging from 8% to 70%.

It can be noticed that, for the three rivers, RCA-VIC annual mean simulations are larger than those from PROMES-VIC. Figure 2 shows the simulated mean and standard deviation annual cycles for the three rivers. For the River Negro, both simulations produce similar timings of the annual cycles with larger values for the standard deviation than for the mean. For the River Uruguay, the peaks of both annual cycles are reached at different times of the year for each simulation. For the River Paraná, the mean annual cycles do not have the same timing while the standard deviation annual cycles are similar except for the austral autumn and winter period. It is interesting to compare these statistics with those corresponding to the observed streamflow during the twentieth century (see Figure 3). A general result is that 21_sim annual cycles of means and standard deviations for both models present overall larger values than the 20_obs ones. In addition, other main results are: for River Negro, 21_sim mean annual cycle timing is more similar (especially for PROMES-VIC) to 20_obs than that of standard

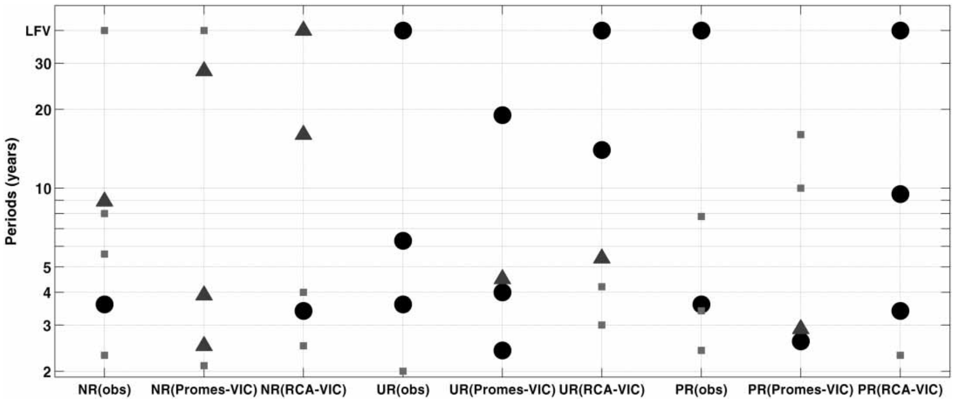


Figure 5  Pseudo-periods and LFV modes for observed (obs) and simulated (PROMES and RCA) annual series obtained by SSA-MC, SSA-MEM and MTM (see Table 3). Circles, triangles and squares indicate whether the pseudo-periods were obtained by the three, two, or only one of the spectral methods, respectively. NR, UR and PR stand for Negro, Uruguay and Paraná rivers, respectively.



deviations; for the River Uruguay, both PROMES-VIC 21_sim annual cycles are more similar to the 20_obs ones than those from the RCA-VIC; for the River Paraná, the PROMES-VIC 21_sim for means reproduces the observed summer maximum, but none of the simulations recreates the wide difference in amplitude between the mean and standard deviation annual cycles.

Figure 4 shows the annual anomaly time series for the Paraná River simulated by RCA-VIC, together with the corresponding partial reconstruction (RC) given by the sum of the five significant components arising from the SSA, for $M = 30$. Table 2 shows the pseudo-periods associated to each mode. The fraction of explained variance by this reconstruction is 0.26.

The results for the three simulated series, together with those obtained in MDT2013 for the 20_obs values, are shown in Table 3 and depicted in Figure 5. It is quite impressive that pseudo-periods in the range of 2.5–5 years appear for all the 21_sim streamflow time series. This range covers the pervasive 3.6-year quasi-period found for all the observed annual series in the past century (MDT2013), and is possibly linked to the ENSO. Isolated significant components between 9 and 28 years also occur. Besides, LFV modes appear in the RCA-VIC simulations using the three spectral methods both for the Paraná and Uruguay rivers (as it also happened for the observed corresponding time series). For the River Negro, LFV patterns are found in both model simulations – PROMES-VIC and RCA-VIC – by one and two spectral methods, respectively.

For simulated time series, the percentage of variance explained by RCs built based on significant components, using $M = 20$, is shown in Table 4. It can be seen that it ranges from 6.5% to 18.4%, and between one and three components are kept to build the RCs.

## 3.2 *Seasonal series*

Multi-annual variability during the annual cycle is analysed by applying first the SSA and then the MEM to the significant modes of PROMES-VIC and RCA-VIC simulated series of the 12 overlapping three-month periods for the three rivers.

Table 4  Percentage of explained variance of simulated annual time series by RCs associated to components with a SSA-MC significance level larger than 90%, and the components that build each RC

| Annual series | % of variance explained by the reconstructions |
|---|---|
| Negro (1991–2098 PROMES) | 11.2<br>Reconstruction associated with components: (1, 7) |
| Negro (1991–2098 RCA) | 10.8<br>(1, 4) |
| Uruguay (1991–2098 PROMES) | 18.4<br>(1, 2) |
| Uruguay (1991–2098 RCA) | 6.5<br>(1) |
| Paraná (1991–2098 PROMES) | 8.2<br>(1, 4) |
| Paraná (1991–2098 RCA) | 16.7<br>(1, 2, 3) |

Note: Windows size: $M = 20$ years.

### 3.2.1 *PROMES-VIC seasonal simulations*

It is worth noting that for the seasonal simulations produced by PROMES – VIC, no LFV modes (i.e. variability in timescales longer than 30 years) are detected along the whole year (Figures 6–8).

Most of the preferred quasi-periods detected for River Negro (Figure 6) are concentrated between two and five years, roughly resembling the corresponding results for the same river in the twentieth century (MDT2013). Quasi-periods of four to five years appear between austral spring and summer, while two- to three-year patterns appear in autumn and from late winter to early spring. Other longer periods occur in spring (10 years) and summer (13 years) and from late winter to early spring

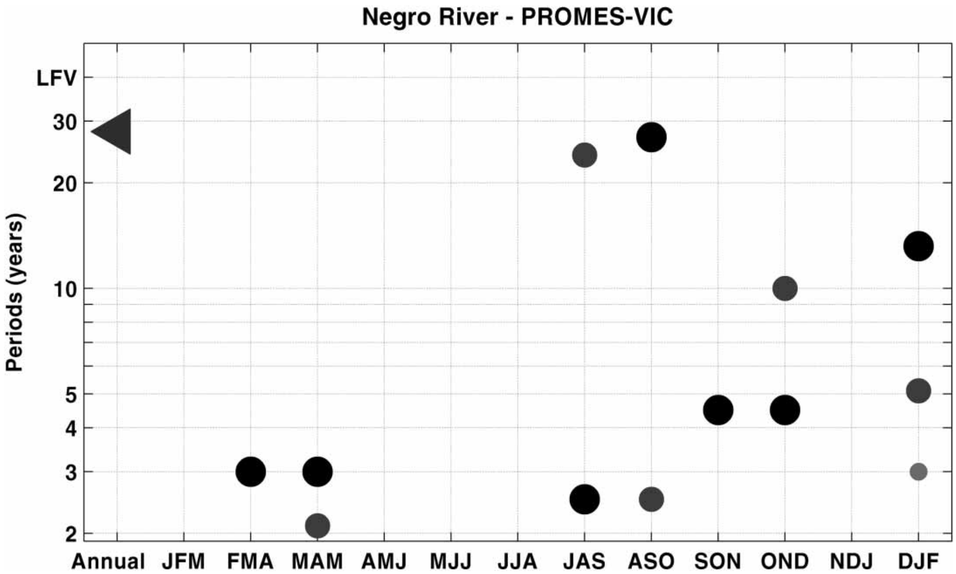


Figure 6 Pseudo-periods obtained by SSA-MEM for simulated three-month and annual series of the River Negro (PROMES-VIC). Bigger symbol sizes indicate larger spectral power of a pseudo-period than others at the same column. JFM, January–February–March; FMA, February–March–April, and so on.

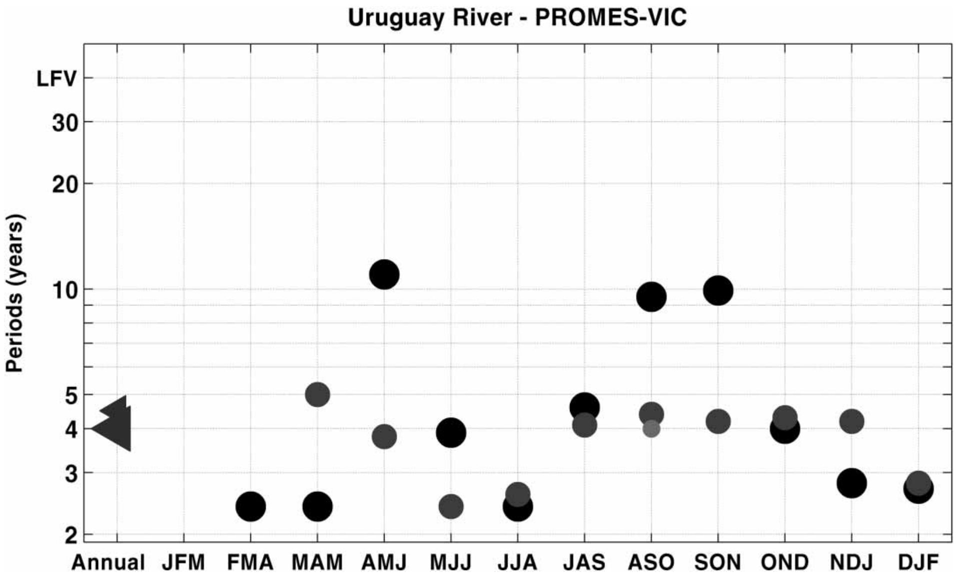


Figure 7 Same as Figure 6 except for the Uruguay River.



(around 25 years). For the case of River Uruguay (Figure 7), pseudo-periods of 2.5–5 years cover almost the whole year, except January–February–March. The rest of the pseudo-periods are quite close to 10 years, in mid-autumn and early spring. In general, there is little resemblance to the observed patterns of past century (MDT2013). For River Paraná (Figure 8), a pseudo-period of approximately 10 years is strongly present from August to June (skipping over January–February–March). Periods in the 2.5–5 years band are apparent during autumn and winter, and in spring and early summer. An isolated pseudo-period of 26 years appears in mid-summer. These 21_sim seasonal patterns do not agree with the 20_obs ones (MDT2013).

### 3.2.2 *RCA-VIC seasonal simulations*

Quasi-periods of three years prevail in autumn, winter, late spring and early summer for River Negro (Figure 9), LFV modes appear in summer and early autumn. Similarities with simulations from PROMES-VIC are scarce. Regarding the River Uruguay (Figure 10), we find that pseudo-periods from 2.5 to 5.5 years cover almost the whole year (as also detected by PROMES-VIC). Similar to the River Negro, LFV modes appear in summer and up to mid-autumn. There are also other quasi-periods around 15 years in autumn and late winter-early spring.

In the case of the River Paraná (Figure 11), preferred pseudo-periodicities are in the 2.3–4.8 years band, encompassing most

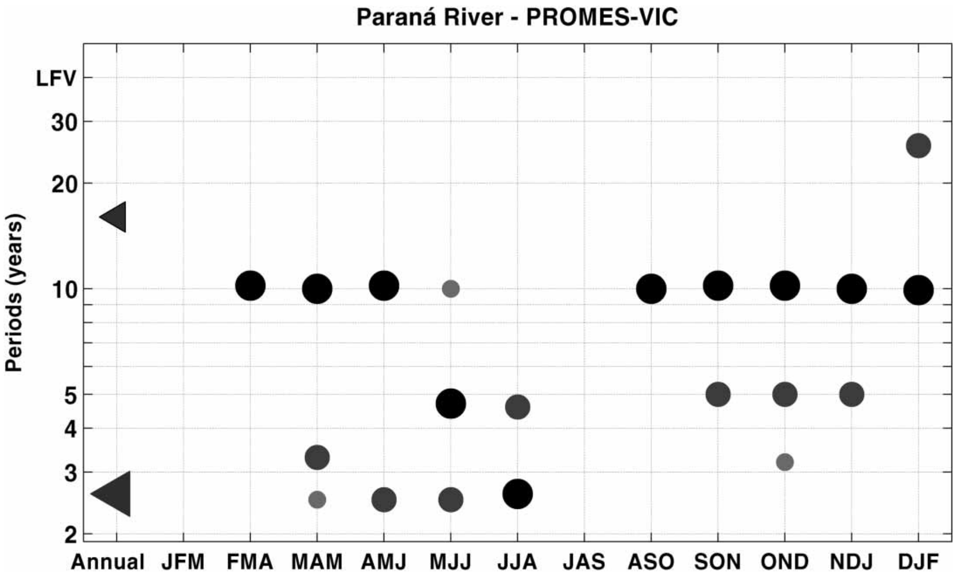


Figure 8 Same as Figure 6 except for the Paraná River.

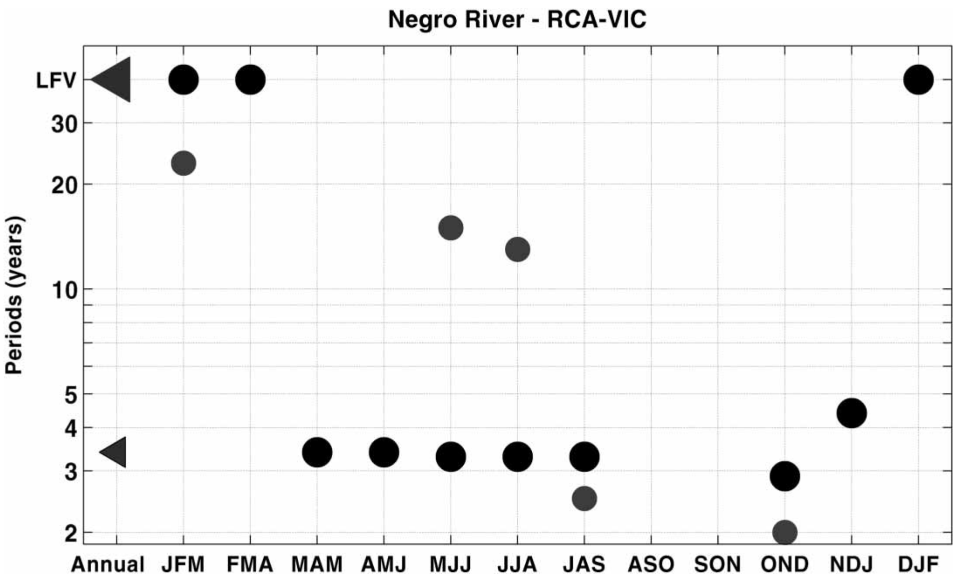


Figure 9 Same as Figure 6 except for RCA-VIC.



of the year, during summer to mid-autumn and from winter to mid-spring. LFV modes occur from mid-autumn to mid-winter. In late summer, a 15-year pseudo-period appears. There is no trace of the 10-year dominant pseudo-period detected by PROMES-VIC. The quasi-cycles in the 2.5–5.5 years range for the Uruguay and Paraná rivers occur approximately at the same time of the year as the 20_obs (MDT2013, Figures 7 and 8). The LFV modes detected for the simulated series of Negro and Uruguay rivers have similar temporal distributions along the year to those in the twentieth century (MDT2013, Figures 6 and 7).

## 4 Discussion and conclusions

The multi-year variability of simulated runoff for three rivers (Paraná, Uruguay and Negro) in the LPB in the period 1991–2098 was analysed. Two sets of simulations were obtained (PROMES-VIC and RCA-VIC). It was found that, for all the rivers, annual simulated streamflow for the twenty-first century are larger than those observed during the twentieth century. The simulated growth ranges from 8% to 42% for PROMES-VIC and from 34% to 70% for RCA-VIC. In addition, annual streamflow from RCA-VIC simulations are larger than those from PROMES-VIC simulations for the three rivers. This is consistent with the likely positive trends on precipitation expected in the LPB for the rest of the present century that were documented in previous works using different methodologies and data (e.g. Vera *et al.* 2006, Saurral 2010) and which would lead to increased runoff and river streamflow (Saurral 2010).

The timings of simulated annual cycles of means and standard deviations produced by PROMES-VIC and RCA-VIC show a

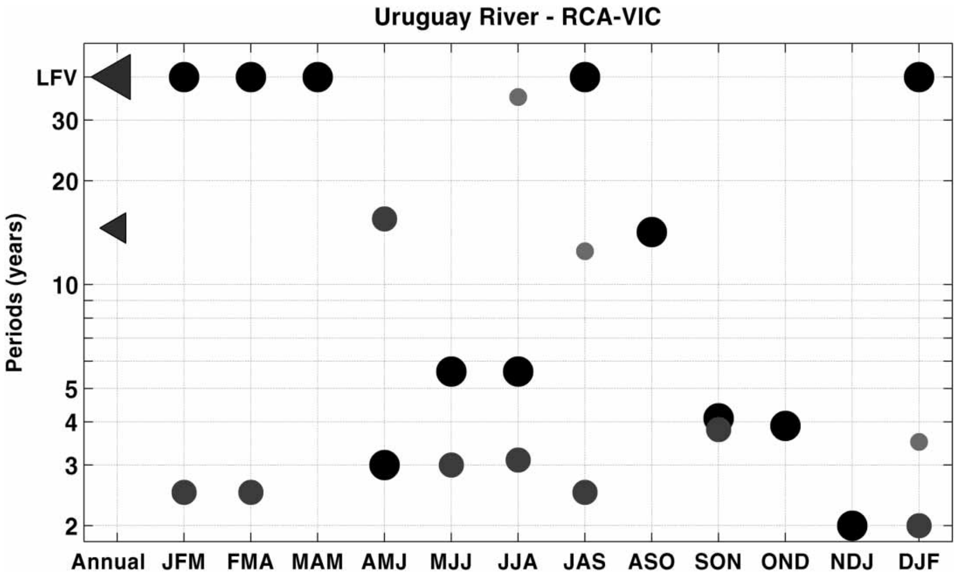


Figure 10 Same as Figure 7 except for RCA-VIC.

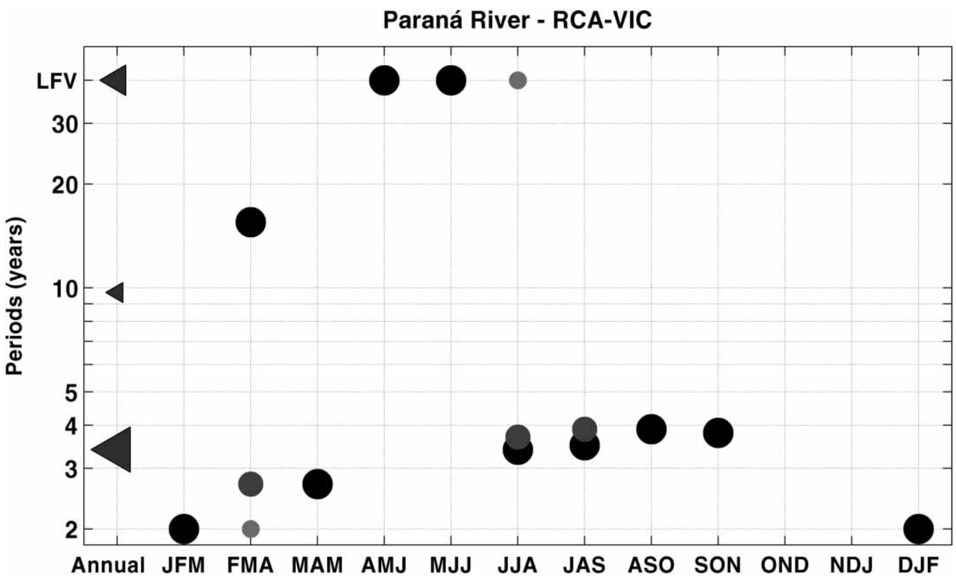


Figure 11 Same as Figure 8 except for RCA-VIC.

higher degree of similarity for River Negro than for the other two rivers. In general, the values of these simulated statistics are quite larger than those observed for the twentieth century. It was found that annual cycles produced by PROMES-VIC simulations for the twenty-first century have more resemblance to observed values than those from RCA-VIC.

Although both sets of annual simulations show differences, they share two conspicuous results: (1) for the three rivers, most of the significant detected pseudo-periods are in the 2.5–5 years band (not unlikely to those detected for the observed twentieth-century annual series) and are probably linked to ENSO; (2) LFV components are detected for the three rivers by RCA-VIC, and also by PROMES-VIC for River Negro, although this signal is not robust. We recall that for the observed annual series, the three rivers exhibited significant LFV.

Seasonal variations of the preferred modes of multi-annual variability are apparent for the simulated streamflow. For the three rivers, the 2.5–5.5 years band is dominant for both sets of simulations. The River Paraná shows a persistent 10-year period during all through the year in the PROMES-VIC simulation. It is also noticeable that no LFV modes were found for any trimester in any river for PROMES-VIC, while for RCA-VIC simulations, those appeared in austral summer (Negro and Uruguay rivers) or early winter (Paraná River).

By far, the most outstanding and robust result of this study is that, in spite of the uncertainties introduced by the use of both

RCMs, the hydrologic model and three spectral methods, pseudo-periods in the 2.5–5-year band (i.e. the ENSO timescale band) are detected in most of the twenty-first century simulations as they were in the observed twentieth-century series, both for annual and seasonal time series. This finding is especially interesting in view of the well-documented relationships between the ENSO phenomenon and precipitation and streamflow anomalies in the LPB. Many researchers (Ropelewski and Halpert 1987, 1989, Pisciottano *et al*. 1994, Camilloni and Barros 2000, Grimm *et al*. 2000, Montecinos *et al*. 2000) found that in this region there is a clear tendency to the occurrence of above (below) normal rainfall during warm, or El Niño (cold, or La Niña) events in the Pacific Ocean during particular seasons, which depend on the specific location within the LPB. Mechoso and Pérez-Iribarren (1992) analysed streamflow for the River Uruguay at Salto Grande and the Negro River at Rincón del Bonete in the period 1909–1989 for the specific seasons detected by Ropelewski and Halpert (1987) and Ropelewski and Halpert (1989) as showing significant responses in precipitation anomalies to the occurrence of ENSO episodes (i.e. November–February for El Niño years and June–December for La Niña years). They verified that streamflow followed the same tendency for both rivers in those seasons. Given the salient results found in this study concerning the simulated pseudo-periods in the 2.5–5 years' band, it is expected that these streamflow anomaly patterns in the LPB associated to ENSO will persist during the twenty-first century.

**Acknowledgements**

The authors have used the SSA-MTM Toolkit for Spectral Analysis, distributed by the SSA-MTM Group, Department of Atmospheric Sciences, University of California, Los Angeles (http://www.atmos.ucla.edu/tcd/ssa/). The authors are grateful to two anonymous reviewers, whose comments and suggestions helped to improve the quality of the manuscript.

**Funding**

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007–2013) [grant agreement no. 212492 (CLARIS LPB. A Europe–South America Network for Climate Change Assessment and Impact Studies in La Plata Basin)].

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