FP7 Collaborative Project

CLARIS LPB

A Europe-South America Network for Climate Change Assessment and Impact Studies in La Plata Basin

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D9.5: Assessment of the influence of decadal variability in hydrological scenarios and of the degree of predictability of streamflows in interdecadal timescale

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Deliverable No	**Deliverable title**	**WP**	**Lead beneficiary**	***Estimated indicative person-months (permanent staff)***	**Nature**	**Dissemination level**	**Delivery date**
D9.5	Assessment of the influence of decadal variability in hydrological scenarios and of the degree of predictability of streamflows in interdecadal timescale	WP9	P17-UR	2,50	R	PU	42

1. Introduction

In Deliverable 9.4, 2010 (hereafter referred to as D9.4) we analyzed annual and seasonal streamflow time series of Paraná River at Posadas, Uruguay River at Salto Grande, and Negro River at Rincón del Bonete, searching for preferred pseudo-periodicities and trends during periods covering essentially the 20th century. For that purpose we used several spectral analysis techniques.

In this work, our purpose is two-fold:

1) We perform similar spectral analyses to simulated streamflow time series in the same gauge points for 1991-2098 or 1991-2060, depending on the river. Those time series were produced in a two-tier process: a) daily temperature and precipitation were obtained from Regional Climate Models (RCM) runs accomplished in WP5 and, b) these were the input to the variable infiltration capacity (VIC) distributed hydrology model (Liang et al. 1994, Nijssen et al. 1997) whose outputs are daily streamflow. These were integrated to produce monthly time series that were kindly provided to us by Ramiro Saurral from WP9.

The RCM used for this purpose were: Promes, from Universidad de Castilla-La Mancha, Spain (Promes – UCLM) and RCA from Swedish Meteorological and Hydrological Institute, Sweden (RCA- SMHI) (both assuming the IPCC-A1B scenario, Houghton et al. 2001).
The combimation of each RCM with the VIC model will be henceforth referred to as Promes-VIC and RCA-VIC.

2) In order to assess the multi-annual streamflow predictability, we project to the future the reconstructed series corresponding to the pseudo-periodic and low frequency variability (LFV) modes found in D9.4 for the observed annual series, analyzing the sensitivity of results to the ending year. We also consider the possibility of including these findings in the stochastic processes that simulate streamflow in the models used to optimize operation policies in electricity systems.

2. Spectral analysis for simulated time series

The run-off simulations for the three gauge points for both RCMs were produced for 1991-2098, except for Paraná-Posadas for RCA– VIC that is available only for 1991-2060. All these will be referred to as 21st century simulations. There are no simulations available for the 20th century. The results for annual and seasonal series are presented in Section 2.1 and 2.2 respectively.

2.1. Annual series

In a first stage, we consider the main statistics of streamflow time series obtained from Promes-VIC and RCA-VIC simulations for the 21st century and those for the observed time series of 20th century.

Table 1 shows that for all the rivers, all the simulations present higher long-term means for 21st century than those observed for 20th century, the rate of increase ranging from 11% to 28%.

Table 1. Observed and simulated annual mean streamflow for the three rivers (km^3/year). Simulated means correspond to the 1991-2098 period, except for Paraná RCA-VIC (1991-2060). The rate of increase with respect to the observed series is shown in brackets.

	Bonete	**Salto Grande**	**Paraná**
Observed	**18.9**	**148.3**	**392.7**
Promes-VIC	**22.2** (+17%)	**189.1** (+28%)	**435.9** (+11 %)
RCA-VIC	**20.9** (+11%)	**187.3** (+26%)	**480.0** (+22 %)

Fig. 1 shows that although both sets of simulations give rise to roughly similar mean and standard deviation annual cycles for the three rivers, some differences are apparent. For Negro River, the standard deviation maxima are reached at different times of the year, and Promes-VIC produces a slightly higher monthly variability than RCA-VIC. Conversely, for Uruguay River, standard deviations from RCA-VIC are larger than those from Promes-VIC, while mean annual cycles are quite alike. The agreement for both mean and standard deviations for Paraná River seem to be the highest among the three rivers.

It is interesting to compare these statistics with those corresponding to the observed streamflow during the 20th century (Fig. 4 from D9.4). The main results of this exercise are: for Negro River, Promes-VIC mean values tend to be higher than the observed ones while the same holds for RCA-VIC standard deviations during autumn and early winter; for Uruguay River both simulated statistics are, in general, quite higher than those observed during the past century; and for Paraná River, there is a fair coincidence in timing of the simulated and observed maxima of mean values (occurring in late summer and early autumn) but the former are much higher than the latter; the observed monthly standard deviation is essentially constant around 10-12 km^3/month, while the 21st century simulations show a maximum in April with values very close to 50 km^3/month.

Several spectral methods were applied to both sets of simulated annual streamflow time series of the three rivers in order to detect pseudo-periodicities and LFV modes. Those methods are the same as in D9.4: singular spectrum analysis followed by a Monte Carlo test (SSA-MC), maximum entropy method (MEM) and multi-taper method (MTM).

For example, Fig. 2 shows the annual anomaly time series for Paraná River simulated by Promes-VIC, together with the corresponding partial reconstruction (RC) given by the five significant components arising from SSA, for M=20. Table 2 shows the pseudo-periods associated to each mode. The fraction of explained variance by this reconstruction is 0.344.

The results for the three simulated series, together with those obtained in D9.4 for the 20th century observed values, are shown in Table 3 and depicted in Fig. 3. It is quite noticeable that pseudo-periods of 3 to 4 years appear for all the simulated streamflow time series in the 21st century. This range covers the pervasive 3.6-year quasi-period found for all the observed annual series in the past century (D9.4), and possibly linked to El Niño-Southern Oscillation. Isolated significant components between 5 to 13 years also occur. On the other hand, it is an outstanding fact that no LFV modes are found for any of the simulated series, while these patterns appeared for the three observed 20th century streamflow time series.

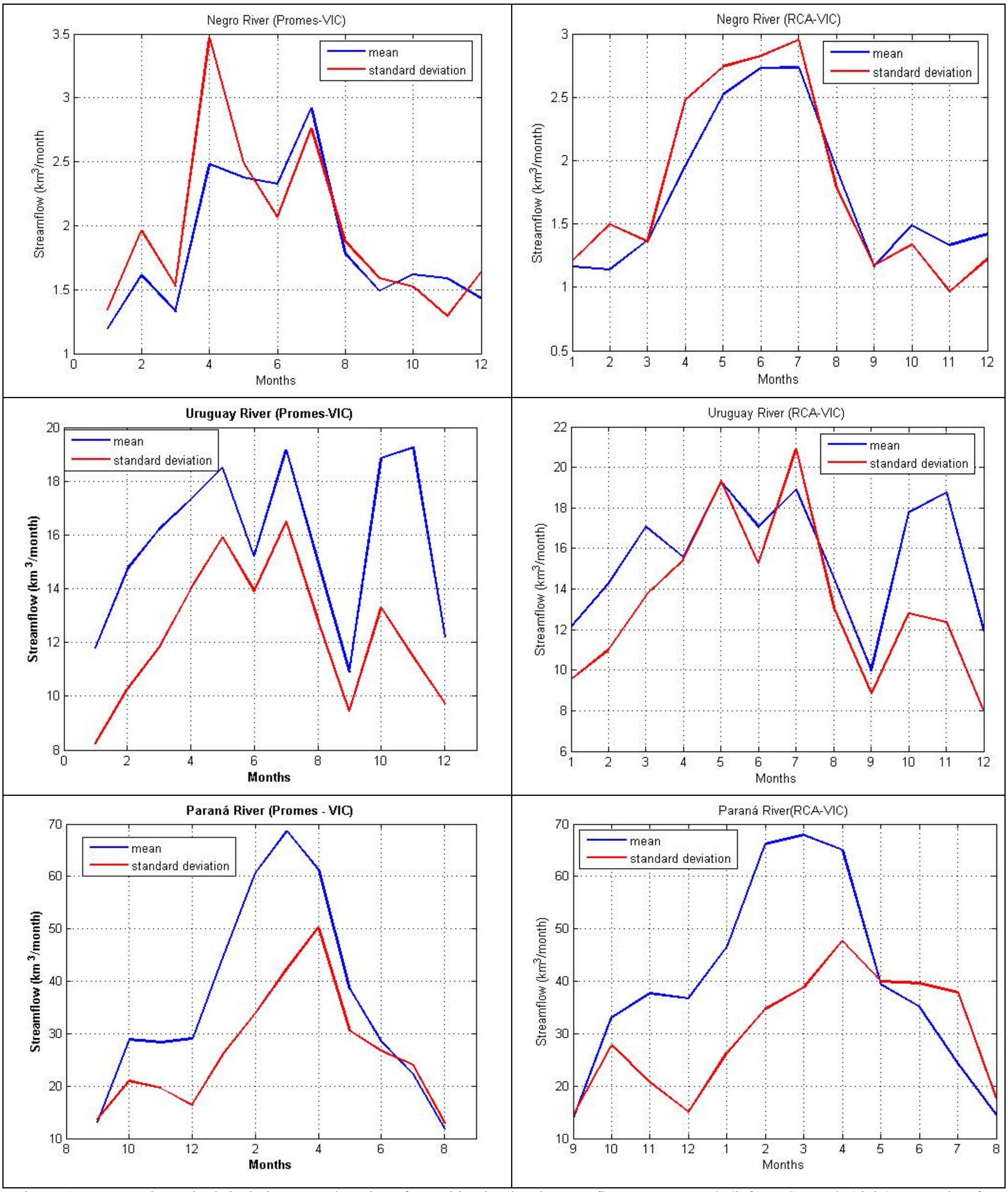

Figure 1. Mean and standard deviation annual cycles of monthly simulated streamflow: Promes-VIC (left), RCA-VIC (right). Note that for Paraná River, annual cycles begin in September.

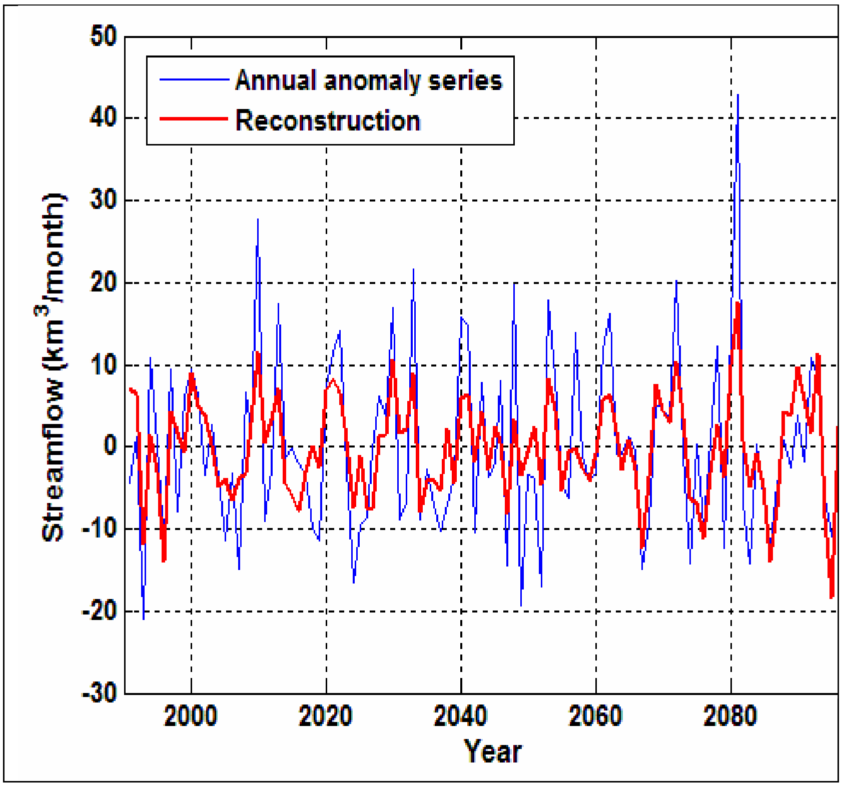

Figure 2.- Simulated annual anomaly time series for Paraná River (Promes-VIC) and RC associated to the 5 significant components obtained using SSA with a window size of M=20 years. Explained variance is 34.4%.

Table 2.- Pseudo-periods associated to each of the 5 significant modes of Paraná River simulated annual series (Promes-VIC), obtained using SSA with a window size of M=20 years.

Mode	Associated pseudo-period (years)
1	9.8
2	9.8
3	2.6
4	4
7	4

Table 3. Pseudo-periods (in years) and low frequency variability (LFV) modes associated to observed and simulated annual series. 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 EOF. 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.

	SSA-MC	SSA-MEM	MTM
Negro (observed; 1908-2007)	**3.6** (90%) 8.7 (90%) 9.1 (90%)	**3.6** **8.9** LFV	3.6 (99%) 2.3 (95%) 5.6 (90%) 8 (90%)
Negro (1991-2098 Promes)	**4** (95%) 3.1 (90%) 7.6 (90%)	**4** 3.1 10	4 (99%) 3.1 (95%) 2.1 (90%)
Negro (1991-2098 RCA)	**3.4** (95%) **5.4** (90%)	**3.3** **5.4** 4	3.3 (99%) 5.5 (95%) 4 (90%) 2.5 (90%)
Uruguay (observed; 1909-2007)	**3.6** (90%) **LVF** (90%) **6.3** (90%)	**6.2** **LFV** **3.6**	3.6 (99%) 6.4 (95%) 2 (95%) LFV (90%)
Uruguay (1991-2098 Promes)	**4** (95%) 13 (90%)	**4** 13 2.4	4 (99%) 2.3 (95%) 13 (90%)
Uruguay (1991-2098 RCA)	**3.8** (95%) **3.4** (95%)	**3.8** **3.4** **5.5**	4 (99%) 5.5 (95%) 3.4 (90%) 2.1 (90%)
Paraná (observed; 1901-1999)	**LFV** (90%) **3.6** (96%)	**LFV** **3.6** 3.4	3.6 (99%) 2.4 (99%) 7.8 (95%) LFV (90%)
Paraná (1991-2098 Promes)	**9.8** (90%) **4** (90%) **2.6** (90%) 3 (95%)	**9.8** 10.7 9.1 **2.6** **4** **3**	10 (99%) 3.8 (95%) 3 (95%) 2.6 (95%)
Paraná (1991-2060 RCA)	**3** (90%) **4.4** (90%)	**3** **4.4**	3 (95%) 4.1 (90%)

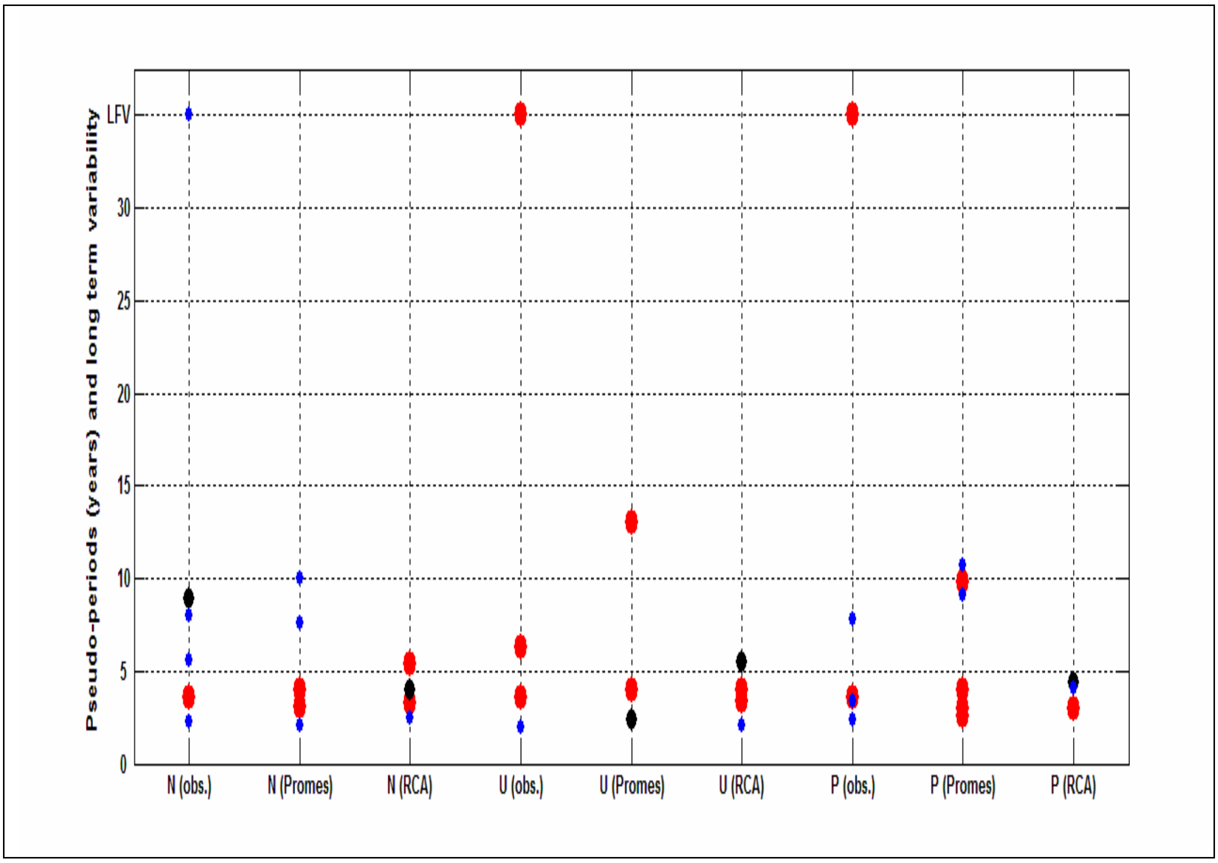

Figure 3.-Pseudo-periods and LFV modes for observed (obs) and simulated (Promes and RCA) annual series obtained by SSA-MC, SSA-MEM and MTM (see Table 3). Bullets indicate, in decreasing order of size, whether the pseudo-periods were obtained by the three, two, or only one of the methods. N, U and P stand for Negro, Uruguay and Paraná rivers respectively.

For simulated time series, the percent of variance explained by RCs built based on significant components is shown in Table 4. It can be seen that it ranges from 18% to 34%, and that between 2 and 5 components participate to build the RCs.

Table 4. Percent of explained variance of the annual time series by RCs associated to components with a SSA-MC significance level larger than 90%, and the components that build each RC. Windows size: M=20 years.

Annual series	% of variance explained by the reconstructions
Negro (1991-2098 Promes)	19.4 Reconstruction associated with components: (1, 2)
Negro (1991-2098 RCA)	31.9 (1, 2, 3, 4)
Uruguay (1991-2098 Promes)	18.4 (1, 2)
Uruguay (1991-2098 RCA)	36.4 (1, 2, 3, 4)
Paraná (1991-2098 Promes)	34.4 (1, 2, 3, 4, 7)
Paraná (1991-2060 RCA)	31.1 (1, 2, 3, 4)

2.2. Seasonal series

Multi-annual variability during the annual cycle is analyzed by applying SSA-MC and SSA-MEM to the Promes-UCLM simulated series of the 12 overlapping three-month periods for the 3 rivers. Results are shown in Figs. 4, 5, and 6, and in Table 5.

For Negro River, preferred quasi-periods are almost completely concentrated between 2 and 5 years. Quasi-periods of 4-5 years appear between early winter and mid-summer, while during autumn they are restricted to 2-3 years. A 9.5-year period appears in OND. No significant LFV components (i.e., variability longer than 20 years) are detected along the whole year. Except for this feature, the temporal pattern of pseudo-periods between winter and mid-summer is similar to that displayed for Negro River series in the 20th century (D9.4, Fig. 7).

For Uruguay River, pseudo-periods of 3.7 – 5 years appear from April to December. The rest of the periods are longer: 11.4 years (FMA), 9.5 years (SON) and 10 years (OND). No LFV components arise. In general, there is little resemblance to the patterns of past century (D9.4, Fig. 8).

For Paraná River, a pseudo-period of approximately 10 years is dominant along the year and especially strong from September to June. Periods in the 4-5 years band are apparent from June to January. Quasi-periods around 2.5 years, although weaker than the above mentioned, appear from February to August. No LFV modes are present during the year. The patterns for 20th century are similar only from July to January, although the preferred pseudo-periods are slightly lower (3-4 years).

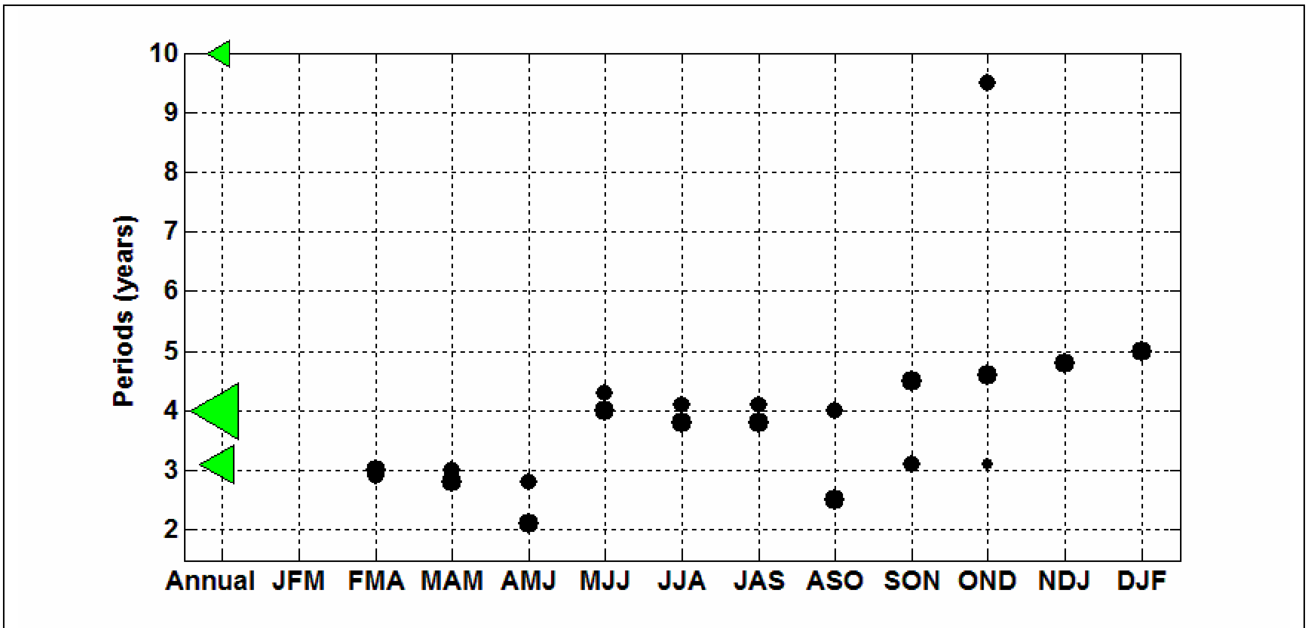

Figure 4. Pseudo-periods obtained by SSA-MEM (see Table 5) for three-month and annual series of simulated Negro River (Promes-VIC). Bigger symbol sizes indicate larger spectral power of a pseudo-period than others at the same column. (No LFV modes were detected.)

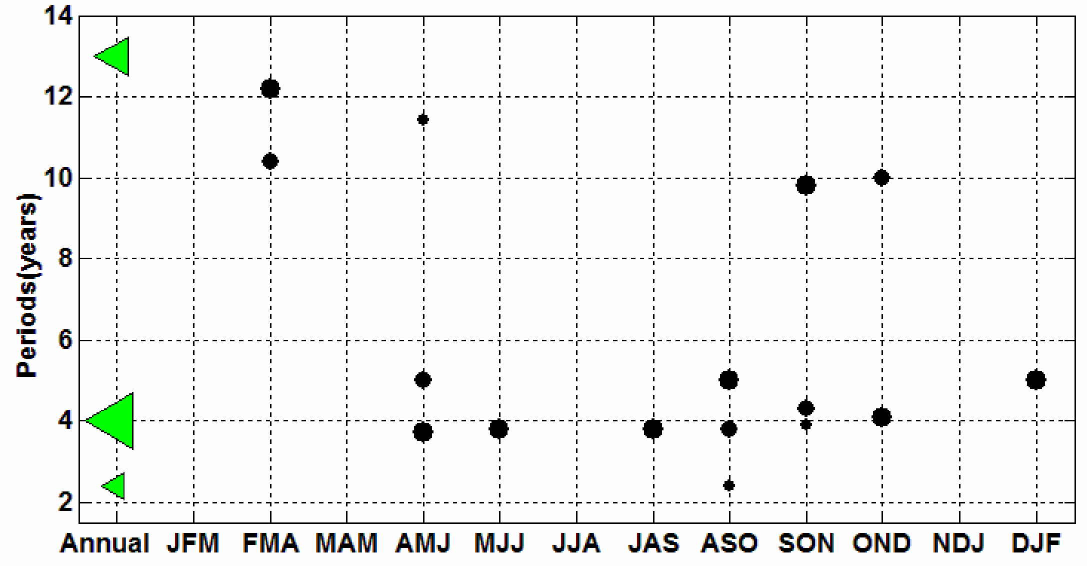

Figure 5. Same as Fig. 4 but for Uruguay River.

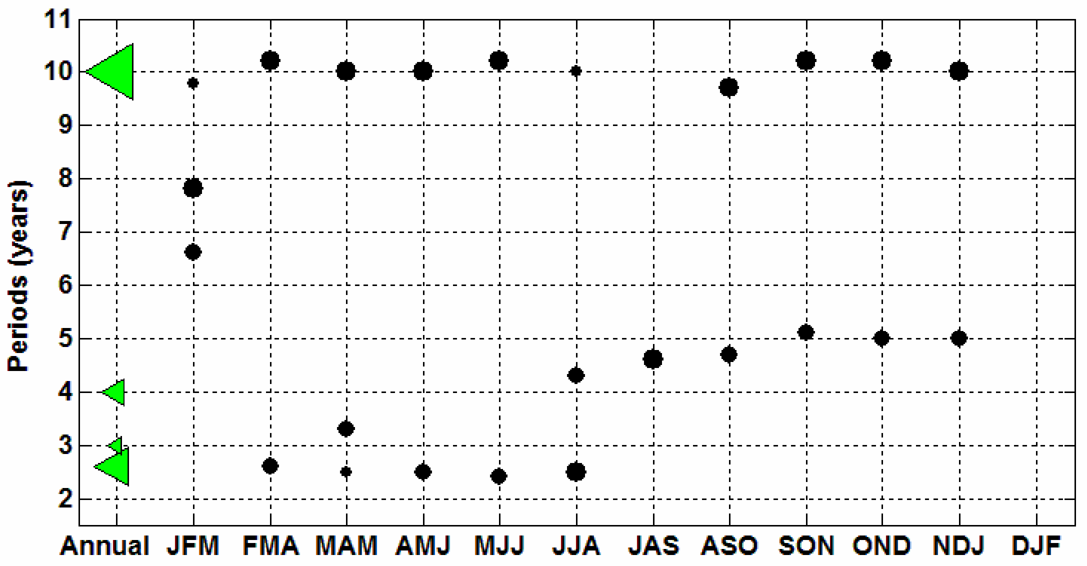

Figure 6. Same as Fig. 4 but for Paraná River.

Table 5. Pseudo-periods (in years) of three-month time series simulated by Promes-VIC for the three rivers, obtained using two methods. For each trimester, in the first column: SSA-MC was applied for M=20; only results with at least 90% significance level are presented. In the second column, pseudo-periods detected by applying MEM to MC significant components (90%) are presented; results are ordered according to decreasing spectral powers of the associated peaks.

	JFM		FMA		MAM		AMJ		MJJ		JJA		JAS		ASO		SON		OND		NDJ		DJF	
	SSA MC	SSA MEM	SSA MC	SSA MEM	SSA MC	SSA MEM	SSA MC	SSA MEM	SSA MC	SSA MEM	SSA MC	SSA MEM	SSA MC	SSA MEM	SSA MC	SSA MEM	SSA MC	SSA MEM	SSA MC	SSA MEM	SSA MC	SSA MEM	SSA MC	SSA MEM
Negro	**None**	**None**	**3**	**3 2.9**	**2.9**	**2. 8 3**	**2**	**2.1 2.8**	**4.1**	**4 4.3**	**3.9**	**3.8 4.1**	**4**	**3.8 4.1**	**2.5 4**	**2.5 4**	**4.3 3.1**	**4.5 3.1**	**4.5 3.1**	**4.6 9.5 3.1**	**4.8**	**4.8**	**5**	**5**
Uruguay	**None**	**None**	**11.4**	**12.2 10.4**	**None**	**None**	**3.7**	**3.7 5 11.4**	**3.8**	**3.8**	**None**	**None**	**3.8**	**3.8**	**5 4.1**	**5 3.8 2.4**	**9.5 4.1**	**9.8 4.3 3.9**	**4.1 10**	**4.1 10**	**None**	**None**	**5.1**	**5**
Paraná	**7.8**	**7.8 6.6 9.8**	**10 2.6**	**10.2 2.6**	**10 3.3 2.5**	**10 3.3 2.5**	**10.1 2.5**	**10 2.5**	**2.5 10.1**	**10.2 2.4**	**2.5 4.2 9.9**	**2.5 4.3 10**	**4.5**	**4.6**	**9.8 4.8**	**9.7 4.7**	**10 5.1**	**10.2 5.1**	**10.2 5.2**	**10.2 5**	**10 5.1**	**10 5**	**None**	**None**

3. Multi-annual predictability

Fig. 7 (same as Fig. 2 from D9.4) shows the anomaly time series and the partial reconstruction (by significant components 1 to 5) of Salto Grande observed annual streamflow (1909-2007). Four of the components are paired oscillatory patterns (with preferred periods of 6.3 and 3.6 years). The regularity displayed by these modes implies predictability. In order to advance in time this synthetic time series, an auto-regressive (AR) process is adjusted to it. The order of this AR-process is selected according to the Bayesian Information Criterion (BIC) (Swartz, 1978) and in this case it is found to be 6. In order to assess the sensitivity of results to the ending year of the series, this is done for the 1909-2003, 1909-2004,…1909-2007 time series. In practice, this involves: applying SSA to each series, finding the significant components, building the partial reconstruction, adjusting the AR process, and projecting it to the future up to 2015.

The obtained results are shown in Fig. 8. It can be seen that the different projections are very similar. It is also found that, if the AR adjustment is performed for each component, and they are then summed up, the results era essentially the same (not shown).

Although projections of the complete time series are not pursued in this study, these results suggest that the embedded signal can be successfully reproduced for around 10 years in advance. This enhancement of the signal-to-noise ratio followed by the projection of the partially reconstructed time series to the future could be introduced in the existing stochastic processes that simulate streamflow in the electrical system models used to optimize operation policies.

A brief description of one of these models follows. Weekly synthetic streamflow series are produced by a stochastic generator, which is used both to qualify the expected uncertainty during the optimization and also to simulate expected costs and their spread. For statistical reasons, these operations need to be performed in Gaussian space. To meet this requirement, non-linear functions and their inverse are built for each week in order to transform real space time series from and to Gaussian space. A first order AR process is built to generate the synthetic streamflow series in Gaussian space. Bearing in mind that usually several rivers are part of the electrical system, the AR process is multivariate (and normal). In this way, the synthetic streamflow for each river at time step *k* is obtained as a linear combination of the synthetic streamflows for all the rivers at time step *k-1*, plus a "noise" term that is a linear combination of normal independent random variables with zero mean and unit variance.

The incorporation of the information added by the detection of pseudo-periodic modes in river time series to such a model would be a considerable aid to decision making in the electricity sector planning.

As an example, we show in Fig. 9 the partial reconstruction obtained by applying SSA to the weekly original time series of Negro River (1909-2009), with the annual cycle removed, and to the same time series after transforming it to the Gaussian space. (If the annual cycle is not removed, the very high spectral power of the 1-year period overwhelms that of the lower frequency components of interest). It is noticeable that the obtained quasi-periods are practically the same for both time series (and are similar to those obtained for the annual series). So, the preferred quasi-periodicities are maintained when the transformation from and to the Gaussian space are performed.

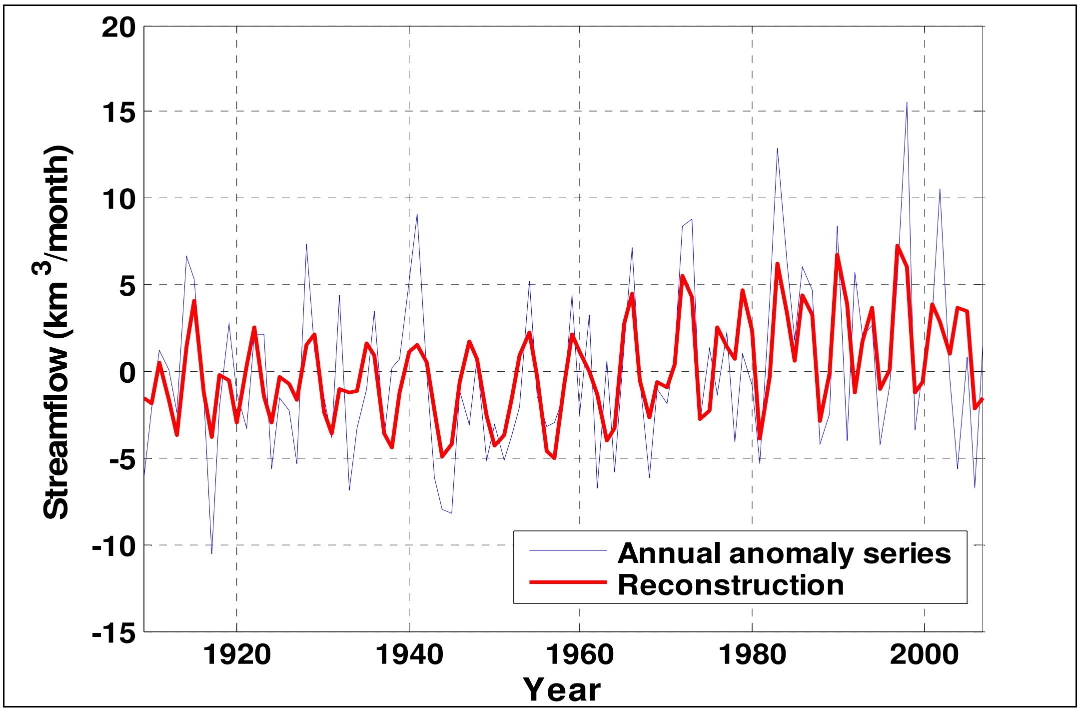

Figure 7. Annual anomaly time series for Uruguay River and RC associated to the first 5 components obtained using SSA with a window size of M=20 years.

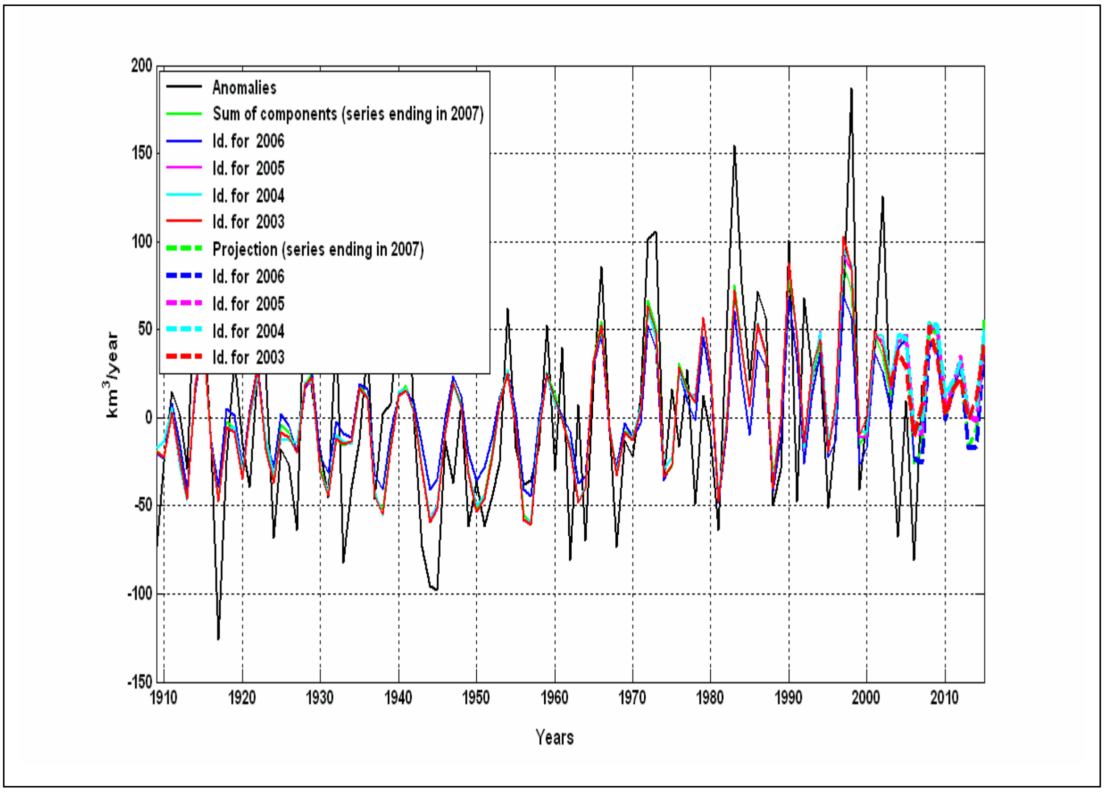

Figure 8. Sum of 5 components associated to pseudo-periods of 3.6 and 6.2 years and LFV for Uruguay River series beginning in 1909 and ending in years from 2003 to 2007 (solid), and their projections up to 2015 (dashed).

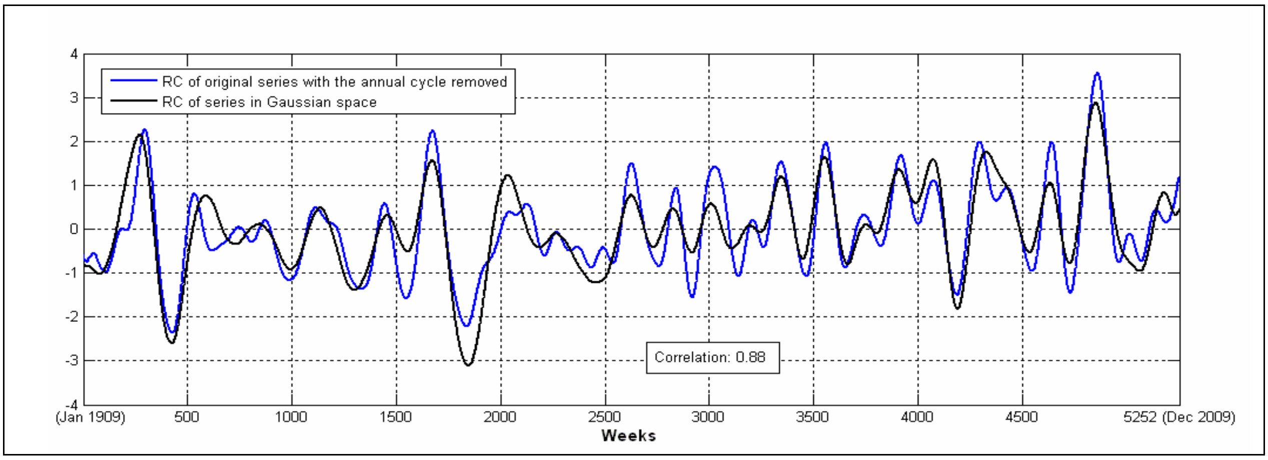

Figure 9. SSA reconstruction of weekly observed streamflow for Negro River (1909-2009): original series with the annual cycle removed (black), and original series in Gaussian space (blue). The obtained pseudo-periods are almost the same for both: 3.5, 4.8, 6.4, 9.6 years and LFV component. Correlation between both reconstructions is 0.88.

4. Conclusions

The main findings of this study are:

- Annual simulated streamflow for 1991-2098 for the 3 rivers are larger than those observed during the 20th century. Depending on the river and on the Regional Climate Model (Promes or RCA), the simulated increase ranges from 10% to almost 30%.

- The simulated annual cycles of means and standard deviations are roughly similar for both sets of simulations (Promes-VIC and RCA-VIC). In general, the values of these simulated statistics are quite larger than those observed for the 20th century, while there is a moderate agreement in timing.

- For both sets of simulated annual time series for the 3 rivers: 1) most of the pseudo-periods are in the 3-4 year band (not unlikely to the observed 20th century annual series), and 2) it is striking that no significant low frequency variability components are detected (when for the observed series, the 3 rivers showed LFV). No significant quasi-periodicities larger than 13 years were found.

- Seasonal variations of the preferred modes of multi-annual variability are apparent for the simulated streamflow. For the 3 rivers, the 4-5 year band is dominant in the second half of the year. Paraná River shows a persistent 10-year period during almost all the year. For the other two rivers these are weaker signals. No LFV modes were found for any trimester.

- SSA was applied to Uruguay River observed time series beginning in 1909 and ending in years ranging from 2003 to 2007. Then all the partially reconstructed series were projected up to 2015. Very similar results were found for all the projections, indicating that the signal captured by the dominant modes can be advanced in time realistically at least for one decade.

- The combination of the findings provided by these techniques with the electrical system models used to optimize operation policies is a potential tool that can improve the decision making process in the electricity planning sector.

Acknowledgements: To Ramiro Saurral (WP9) from UBA-CONICET (Argentina) for the VIC hydrological simulations and to modelling groups from WP5: Universidad de Castilla - La Mancha (UCLM, Spain), and Sweden's Meteorological and Hydrological Institute (SMHI, Sweden), for the Promes and RCA model runs that fed the VIC model.

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