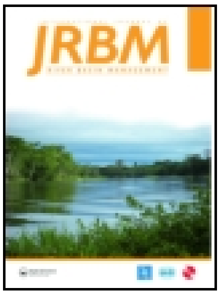

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Hydrological projections of fluvial floods in the Uruguay and Paraná basins under different climate change scenarios

Inés A. Camilloni [a], Ramiro I. Saurral [a b] & Natalia B. Montroull [c]

[a] Centro de Investigaciones del Mar y la Atmósfera (CIMA/CONICET-UBA) - UMI IFAECI/CNRS, Int. Guiraldes 2160, Ciudad Universitaria, Pabellón 2, C1428EGA, Buenos Aires, Argentina

[b] Departamento de Ciencias de la Atmósfera y los Océanos (FCEN/UBA), Buenos Aires, Argentina

[c] Centro de Investigaciones del Mar y la Atmósfera (CIMA/CONICET-UBA) - UMI IFAECI/CNRS, Int. Guiraldes 2160, Ciudad Universitaria, Pabellón 2, C1428EGA, Buenos Aires, Argentina

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Research paper

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INÉS A. CAMILLONI, *Centro de Investigaciones del Mar y la Atmósfera (CIMA/CONICET-UBA) – UMI IFAECI/CNRS, Int. Guiraldes 2160, Ciudad Universitaria, Pabellón 2, C1428EGA Buenos Aires, Argentina. Email: ines@cima.fcen.uba.ar; Departamento de Ciencias de la Atmósfera y los Océanos, Facultad de Ciencias Exactas y Naturales, Universidad de, Buenos Aires, Argentina (Author for correspondence)*

RAMIRO I. SAURRAL, *Centro de Investigaciones del Mar y la Atmósfera (CIMA/CONICET-UBA) – UMI IFAECI/CNRS, Int. Guiraldes 2160, Ciudad Universitaria, Pabellón 2, C1428EGA Buenos Aires, Argentina; Departamento de Ciencias de la Atmósfera y los Océanos (FCEN/UBA), Buenos Aires, Argentina*

NATALIA B. MONTROULL, *Centro de Investigaciones del Mar y la Atmósfera (CIMA/CONICET-UBA) – UMI IFAECI/CNRS, Int. Guiraldes 2160, Ciudad Universitaria, Pabellón 2, C1428EGA Buenos Aires, Argentina*

ABSTRACT
Hydrological modelling with climate scenario data are used to develop projections of changes in frequency and duration of flood events in the margins of the lower sections of the Paraná and Uruguay Rivers in La Plata Basin for the twenty-first century. Discharges were simulated with the Variable Infiltration Capacity hydrologic model considering the statistically bias corrected daily maximum and minimum temperatures and rainfall outputs from five regional climate models and different emission scenarios. Results show that although it is expected that compared to the current conditions the temperature would rise and precipitation would have a slight increase in La Plata Basin during the present century, more frequent and lasting fluvial flooding events in the lower Paraná and Uruguay basins could be expected. However, the range of results derived from different climate models though consistent in sign, indicate that the uncertainty is large.

Keywords: Climate change; Paraná River; Uruguay River; flooding; future scenarios

1 Introduction

Climate change as a result of the increase in the atmospheric greenhouse gases (GHG) concentration is likely responsible for the observed raise in the frequency of extreme events including severe floods and droughts as well as extreme heat around the world with profound impacts on human society and the natural environment (IPCC 2012). In particular, projected temperature and precipitation changes over the coming decades strengthen the need for regional impact studies associated with global warming to assess possible changes in magnitude, duration and/or frequency of hydrologic extremes like severe floods. A better knowledge of the future occurrence of these phenomena will help to improve the management of risks associated with climate change and will also contribute to the design of flood protection measures and water resources infrastructure.

During the last decade, the progress in climate modelling increased the confidence in the outputs required as inputs for hydrological applications promoting many climate change impact studies (Booij 2005, Xu *et al*. 2005, Andersson *et al*. 2006, Jiang *et al*. 2007, Saurral 2010, Taye *et al*. 2011, Dang Tri *et al*. 2012). However, in water resources applications, climate impact assessments require careful consideration of the sources and relative magnitude of associated uncertainties such as emission scenarios, climate and hydrology modelling and downscaling techniques (Wilby and Harris 2006, Cloke *et al*. 2010). In order to reduce the uncertainties related to climate modelling and downscaling, a statistical bias correction of the systematic errors of climate models is frequently used to produce long-term time series with a statistical distribution close to that

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of the observations to make them applicable as input for hydrology models (Hagemann *et al*. 2011, Teutschbein and Seibert 2012, Chen *et al*. 2013).

La Plata Basin is the most important area in South America in terms of population, Gross National Product and hydropower generation. During the last decades, this region has been subjected to climate trends that could be related to the increase in anthropogenic GHG. Examples of changes are increased precipitation (Haylock *et al*. 2006, Barros *et al*. 2008, Re and Barros 2009, Marengo *et al*. 2010a, Doyle *et al*. 2012) and river flows (Doyle and Barros 2011) as well as extreme temperatures (Rusticucci and Barrucand 2004, Marengo *et al*. 2010a). During the last 50 years of the twentieth century, large areas along the margins of the middle and lower sections of the Paraná and Uruguay Rivers, the main tributaries of the La Plata River in terms of discharges, were subjected to large floods caused mainly by extreme rainfall events in the upper basins that led to critical streamflow responsible for considerable damage (Camilloni and Barros 2003, Camilloni 2005).

Climate change projections for La Plata Basin indicate changes in both temperature and precipitation regimes in the future (Marengo *et al*. 2010b). The average temperature is expected to increase in all seasons throughout the basin, and the annual mean temperature will increase between 1.7°C and 3.9°C by the end of the century under the SRES A2 scenario. The average annual precipitation is also expected to increase by 5–30%, although there are large differences between seasons and regions. These changes in temperature and precipitation will probably impact the magnitude of river discharges and fluvial flood frequency/duration. Saurral (2010) and Saurral *et al*. (2013) estimated mean hydrologic scenarios for La Plata Basin considering unbiased global and regional climate model (RCM) outputs. Their results suggest a progressive increase in the main rivers' discharges during the twenty-first century under the three different emission scenarios considered (B1,

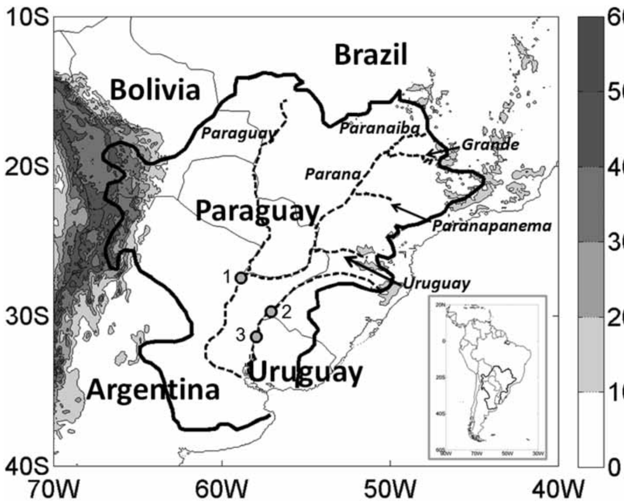

Figure 1 La Plata Basin, main rivers (– – –) and location of Corrientes (1) and Paso de los Libres (2) gauging stations and Salto Grande dam (3).

A1B and A2), indicating that although temperatures would rise, the effects of increasing precipitation would lead to increased freshwater availability over the basin.

The objective of this paper is to assess the impact of climate change on future flooding in the margins of the Paraná and Uruguay Rivers in La Plata Basin. Estimation of changes in flood frequency and duration with climate change is done considering a physically based approach that incorporates bias corrected meteorological information derived from five RCMs and a distributed hydrologic model.

The article is structured in five sections: study area and data are described in Section 2 and the methodology is presented in Section 3. Results on projected changes in flooding are shown in Section 4 while Section 5 summarizes results and conclusions.

2 Study area and data

The Uruguay and Paraná basins are both densely populated regions in La Plata Basin in Southeast South America that host important agricultural activities and hydroelectric generation plants. The Paraná River, the most important tributary of the La Plata River, has a drainage basin of 2.6×10^6 km^2 and contributes to about 80% of its streamflow. It begins at the confluence of the Grande and Paranaíba Rivers and its main tributaries are the Paranápanema, Iguazú and Paraguay Rivers (Figure 1). Upstream from the confluence with the Paraguay at Corrientes, the river is known as Upper Paraná, and from this city down to 32°S as Middle Paraná. Downstream this point, it is called Lower Paraná. The mean discharge of the Upper Paraná is approximately 16,000 m^3/s and only increases less than 1000 m^3/s downstream from Corrientes (Camilloni and Barros 2003). The Uruguay River has a mean flow of about 4500 m^3/s and it is the second tributary in importance of the La Plata River with a basin of 365,000 km^2 that includes parts of Brazil, Uruguay and Argentina. It begins near the Atlantic Ocean at a height of 1800 m above sea level and ends at the La Plata River. Upstream from Paso de los Libres, the river is known as Upper Uruguay and between this location and the Salto Grande hydropower plant, located 240 km downstream Paso de los Libres, as Middle Uruguay. From Salto Grande to its outlet, the river is known as Lower Uruguay (Figure 1).

River streamflow and water level data were obtained from the Subsecretaría de Recursos Hídricos (Undersecretary of Water Resources) of Argentina and consist of monthly mean discharges and daily maximum water levels of the Paraná River at Corrientes (27°28′S, 58°49′°W) and of the Uruguay River at Paso de los Libres (29°43′S, 57°04′°W). Daily precipitation and maximum and minimum temperature outputs for the twenty-first century from five RCMs that were run for South America were considered in the hydrologic simulations used in this study. Four of them were available through the CLARIS-LPB project (http://www.claris-eu.org): the Rossby Centre RCM version 3.5 (RCA), (Kjellström *et al*. 2005, Samuelsson *et al*.

2006), the Prognostic at the Mesoscale version 2.4 (PROMES) (Sanchez *et al*. 2007, Domínguez *et al*. 2010), the International Centre for Theoretical Physics (ICTP) RCM version 3 (Reg CM3) (Pal *et al*. 2007, da Rocha *et al*. 2009) and the *Modele de Circulation Generale du LMD* version 4 (LMDZ) (Li 1999, Hourdin *et al*. 2006). The fifth model is the Providing Regional Climates for Impacts Studies (PRECIS) modelling system (Jones *et al*. 2004) available through CPTEC/INPE. The CLARIS-LPB RCMs were run with the SRES A1B emission scenario while PRECIS outputs are available for the SRES A2 and B2 scenarios. Horizontal resolution, boundary conditions, scenarios and time slices of each RCM considered for the hydrologic simulations are presented in Table 1. Likewise, specific details on these simulations, i.e. calibration and validation results as well as on the unbiased method applied to climate outputs from RCMs, can be found in Saurral *et al*. (2013).

3 Methods

3.1 *Hydrological modelling*

The Variable Infiltration Capacity (VIC) hydrology model (Liang *et al*. 1994, 1996, Nijssen *et al*. 1997) was used to simulate the present water balance and to assess the potential impacts of future climate change on the hydrology of the Uruguay and Paraná basins. The VIC model is a spatially distributed, physically based hydrology model that balances both energy and water budgets, and has been widely implemented at scales from continental to individual watersheds (Hamlet and Lettenmaier 1999, Christensen and Lettenmaier 2007, Saurral *et al*. 2008, Zhao *et al*. 2012). The VIC model was used to simulate the hydrological cycle of the La Plata Basin with good results over most of the sub-basins (Su and Lettenmaier 2009, Saurral 2010, Saurral *et al*. 2013). In this study, we considered the discharge simulations obtained with the VIC model for the Paraná River at Corrientes at a monthly scale and the simulated daily streamflow of the Uruguay River at Paso de los Libres for the periods with available simulated daily precipitation and maximum and minimum temperature data (Table 1). The analysis is developed for the discharge series at Corrientes and Paso de los Libres as previous studies showed that the regions mostly affected by floods in the margins of the Paraná and Uruguay Rivers are downstream these stations, respectively (Camilloni and Barros 2003, Camilloni 2005). A detailed description of the hydrologic simulations can be found in Saurral *et al*. (2013) while the calibration and evaluation of the VIC model over La Plata Basin are presented in Su and Lettenmaier (2009) and Saurral (2010).

3.2 *Determination of flooding thresholds*

Fluvial flooding thresholds in the margins of the Uruguay River are defined in terms of critical water levels. However, as the VIC hydrologic model only provides estimates of river discharges, statistical relationships between flows and maximum water levels were developed. In the case of the Paraná River, there is no need to build this kind of relationship between water levels and streamflow, as the flood threshold can be set straightforward from the literature (Camilloni and Barros 2003) in terms of the river flows provided by the VIC model.

Figure 2 presents the relation between the observed monthly discharge (Q) of the Uruguay River at Paso de los Libres and the maximum daily level (H) of the river for each month at the same station for the period of 1960–1999. The figure also shows the evacuation water level (8.50 m) established by local authorities for this station.

According to the adjustment equation ($H = 2.889 \ln Q - 18.207$), the flood criterion for the Uruguay River in terms of discharges is established as those daily values above 13,200 m^3/s. Figure 2 also indicates that 35% of the days when discharges are between 5760 and 13,200 m^3/s show river levels above the evacuation threshold. Therefore, this percentage of cases in the indicated range was added to the count of flooding events with discharges above 13,200 m^3/s.

The flooding threshold for the Paraná River at Corrientes was defined considering the minimum monthly discharge observed during the two last periods with the largest floods at this station (1982–1983 and 1997–1998). Consequently, the criterion adopted in this study is that all monthly discharges above 33,000 m^3/s belonging to an at least three months spell above this value are considered as flooding events.

The difference in the time scales considered in the analysis of floods in the Uruguay (daily) and Paraná (monthly) Rivers is related to the observed features of these events during the twentieth century. The Uruguay streamflow displays a quick response to precipitation and floods usually last less than a month mainly due to the relatively large slope of the terrain (Camilloni 2005). On the contrary, the Paraná River shows a lag between rainfall in the upper basin and discharges at Corrientes of up to two months due to the geomorphology of the river that exhibits less steep terrain than the Uruguay basin. Downstream Corrientes, floods usually last longer than a month (Camilloni and Barros 2003).

4 Projected changes

4.1 *Uruguay River*

Figure 3 shows the decadal frequency of daily events with water level above the evacuation threshold at Paso de los Libres for the B2 and A2 emission scenarios according to the VIC model forced with the unbiased PRECIS climate model outputs. These hydrologic scenarios of the Uruguay River show an increase in the frequency of flooding events that by 2091–2100 almost double those of the reference period (1990–1999). Likewise, for some decades, floods are more frequent under the low emission scenario (B2) (2026–2035, 2046–2055 and 2091–2100) than for the highest one (A2).

Table 1 Horizontal resolution, boundary conditions, emission scenarios and time slices available for each RCM used in the hydrologic simulations with the VIC model.

RCM Institution	Time slices considered	Horizontal resolution	Boundary conditions	Scenario		
				B2	A2	A1B
PRECIS INPE/CPTEC (Brazil)	*1990–1999* 2016–2100	0.44 °× 0.44°	HadAM3P	✓	✓	–
PROMES Universidad de Castilla-La Mancha (Spain)	*1991–2000* 2021–2040 2071–2090	50 × 50 km	HadCM3	–	–	✓
RCA Swedish Meteorological and Hydrological Institute (Sweden)	*1991–2000* 2021–2040 2071–2090	0.5° × 0.5°	ECHAM5	–	–	✓
RegCM3 Universidade de São Paulo (Brazil)	1981–1990 2021–2040 2071–2090	50 × 50 km	HadAM3	–	–	✓
LMDZ Institut Pierre-Simon Laplace (France)	*1991–2000* 2021–2040 2071–2090	~0.48° × 0.48°	LMDZ global	–	–	✓

Notes: Reference periods of each RCM are in italics. Institutions responsible for the climate simulations with each RCM are also indicated.

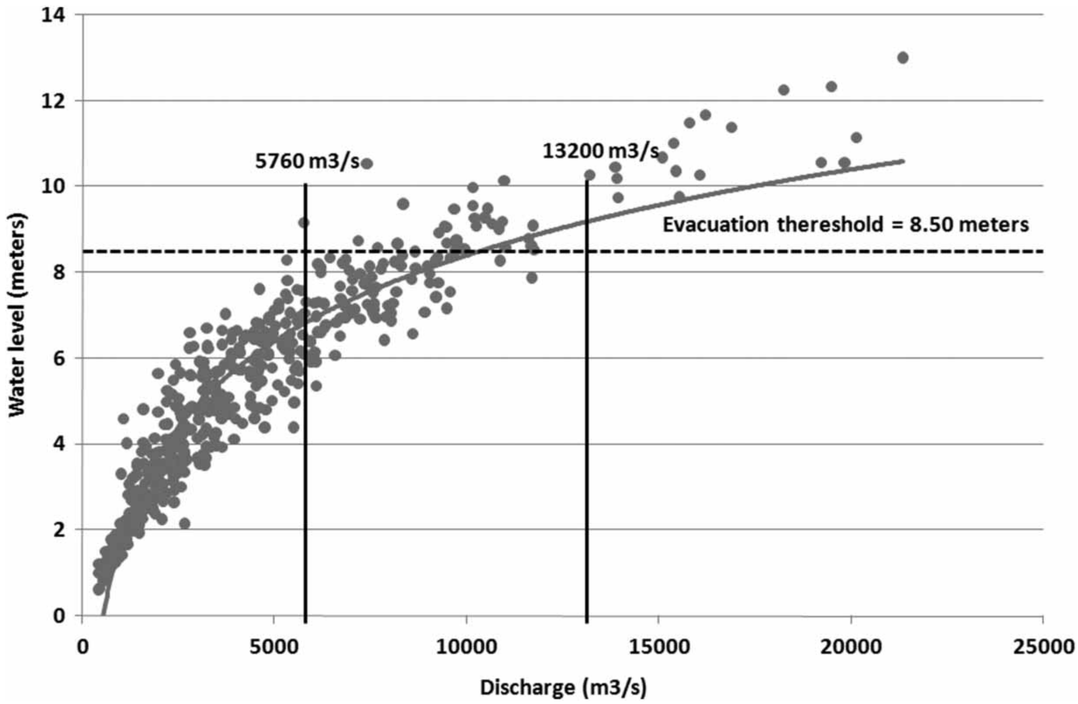

Figure 2 Relationship between the monthly discharge (Q) of the Uruguay River at Paso de los Libres and the maximum daily water level (H) for each month at the same station. Period: 1960–1999.

Figure 4 presents the changes in the frequency of days with water level above the evacuation threshold of the Uruguay River at Paso de los Libres computed considering the unbiased CLARIS-LPB climate simulations. Changes are relative to the reference period of each RCM (Table 1) and they were estimated for the near future (2011–2040) and for the end of the twenty-first century (2070–2098). Most RCMs show an increase in the frequency of flood events although the magnitude of the change is very variable. According to the ensemble of the four RCMs (Figure 4) there would be an increase in the occurrence of

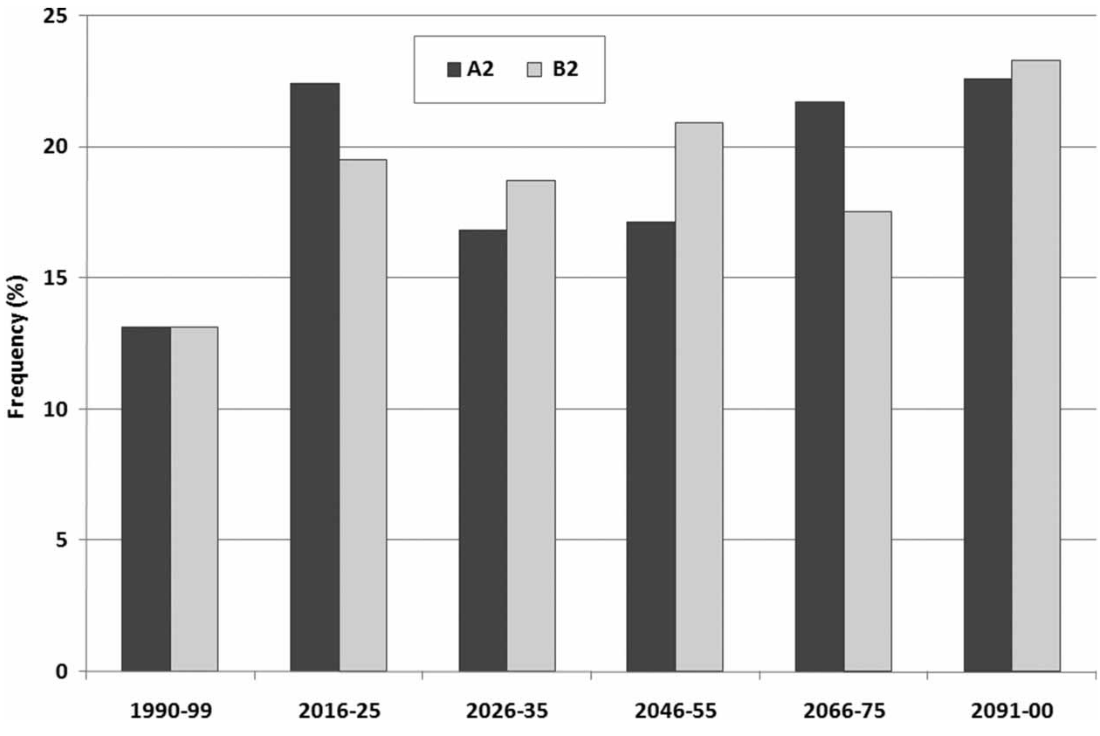

Figure 3 Decadal frequency (%) of days with water level above the evacuation threshold at Paso de los Libres (Uruguay River) for the emission scenarios B2 and A2 according to the PRECIS climate model.

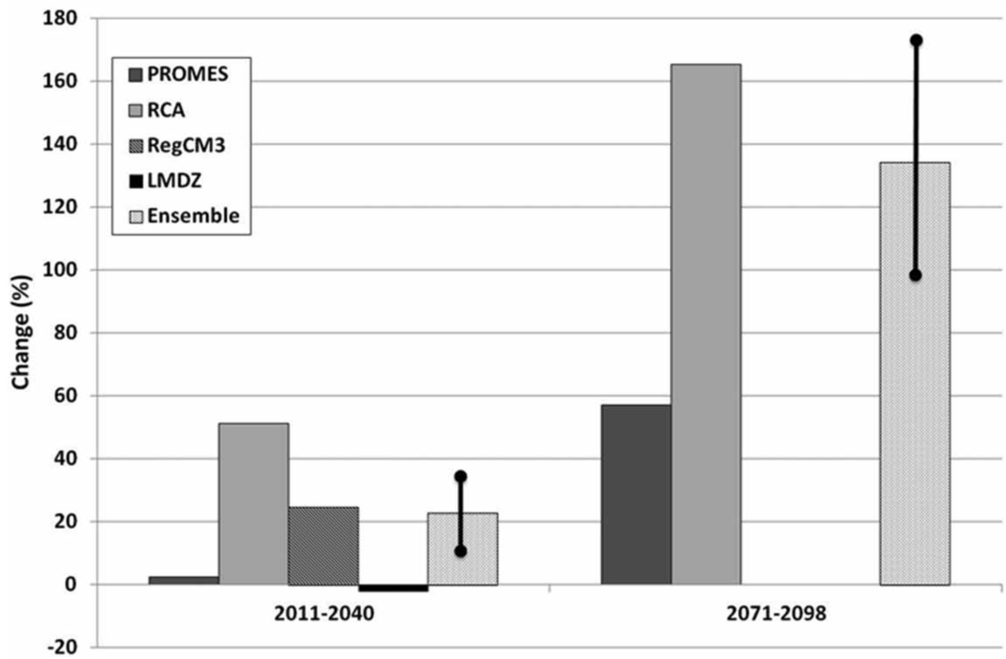

Figure 4 Percentage changes in frequency of days with water level above the evacuation threshold at Paso de los Libres (Uruguay River) for the individual CLARIS-LPB climate simulations and the ensemble mean of available models under the scenario A1B with respect to the reference period of each RCM (Table 1). Black bars represent one standard deviation among RCMs.

floods of more than 20% in the near future while flood cases will almost be twice of those estimated for the reference period at the end of the present century. These results are consistent with those derived from the PRECIS climate model (Figure 3).

Future changes in duration of flooding events in Paso de los Libres were also explored considering the VIC outputs forced with the biased corrected PRECIS (Figure 5) and CLARIS-LPB climate simulations (Figure 6). Most RCMs show a decrease in the occurrence of short-lasting floods (<6 days) and an increase in the long lasting ones (>30 days) suggesting that an increase in the negative impacts of floods could be expected.

4.2 *Paraná River*

Figures 7 and 8 show the results derived from the hydrologic simulations with the VIC model considering the RCMs'

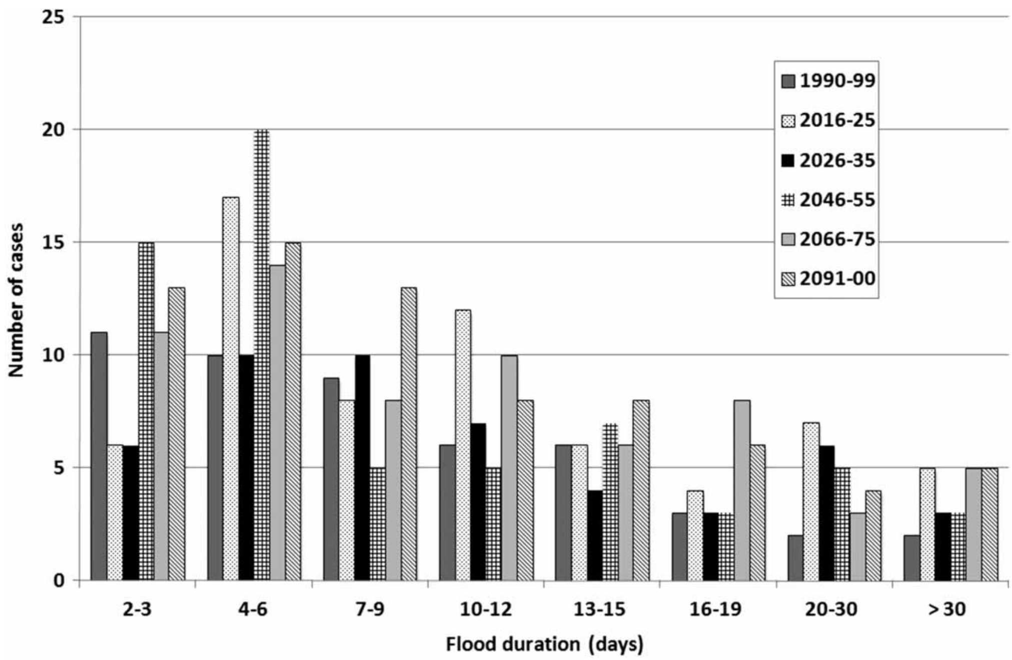

Figure 5 Decadal absolute frequency of flooding events of different durations at Paso de los Libres (Uruguay River) according to the PRECIS climate model simulations (scenario A2).

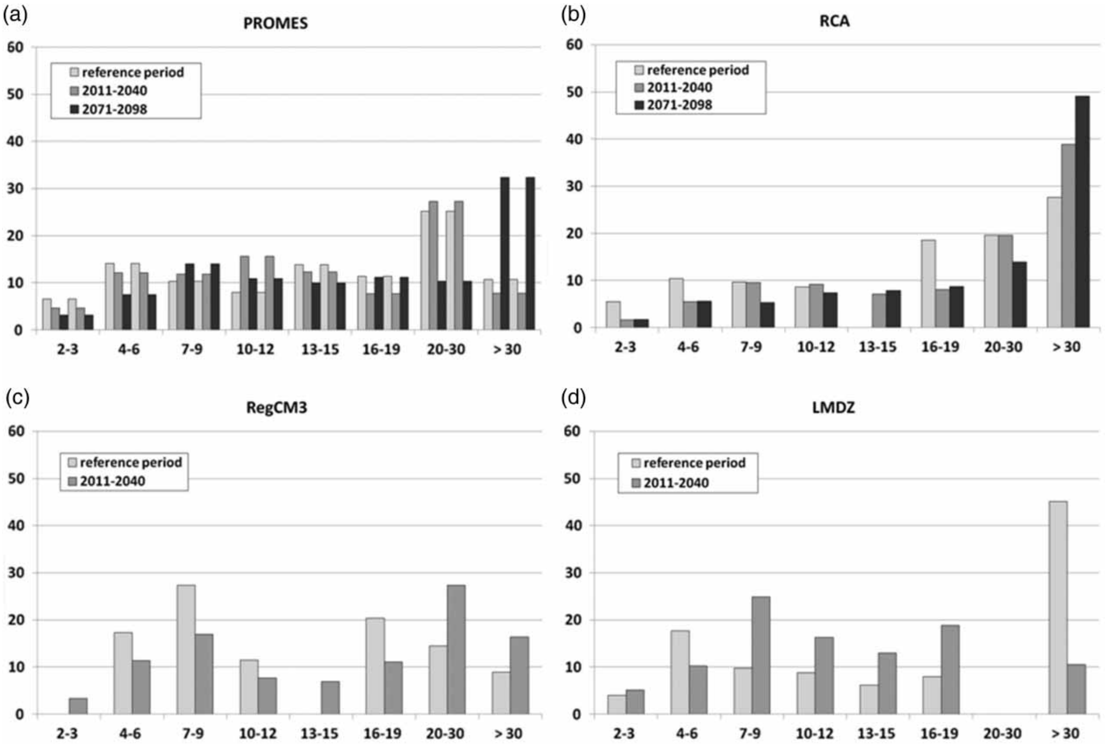

Figure 6 Frequency (%) of flooding events of different durations at Paso de los Libres (Uruguay River) according to the CLARIS-LPB climate simulations (a) PROMES, (b) RCA, (c) RegCM3 (d) LMDZ for scenario A1B.

experiments indicated in Table 1. In the case of the discharge simulations with climate data provided by the PRECIS model (Figure 7), the number of flooding events in the Paraná River by the end of the present century would be almost four times the cases of the reference period (1990–1999) with also an increase in events in the near future. Similar results are obtained when considering the CLARIS-LPB climate models and their ensemble (Figure 8) with an increase in the frequency of flooding

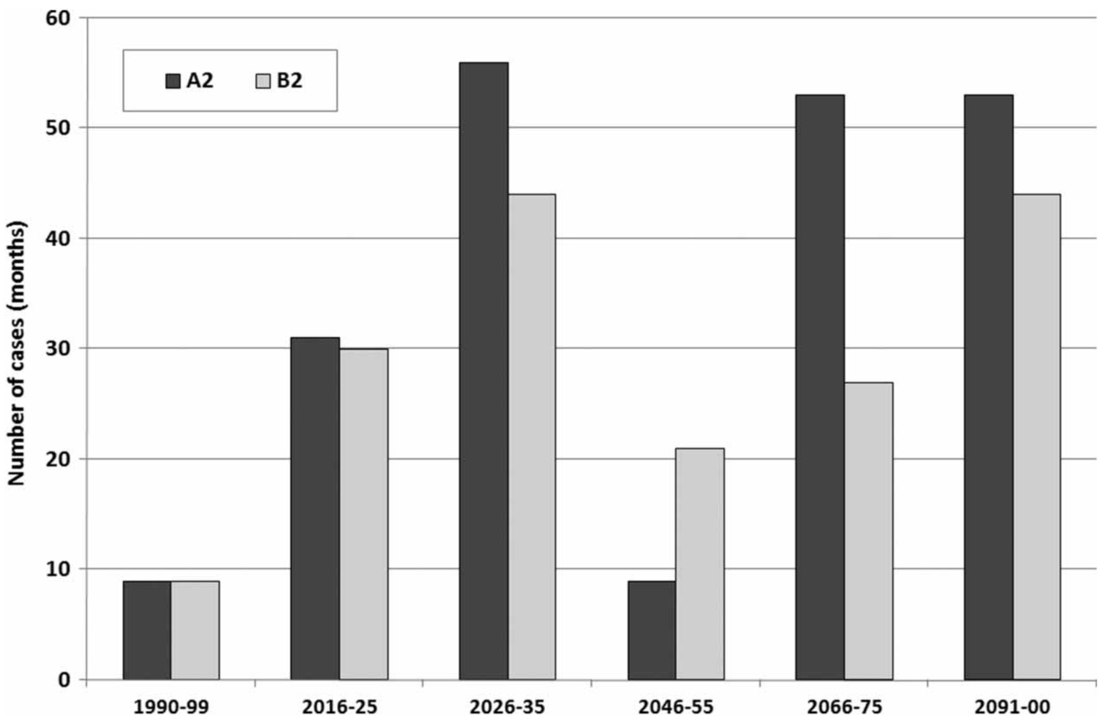

Figure 7 Number of months with discharges above the flooding threshold at Corrientes (Paraná River) according to the PRECIS climate model simulations for different decades (scenarios B2 and A2).

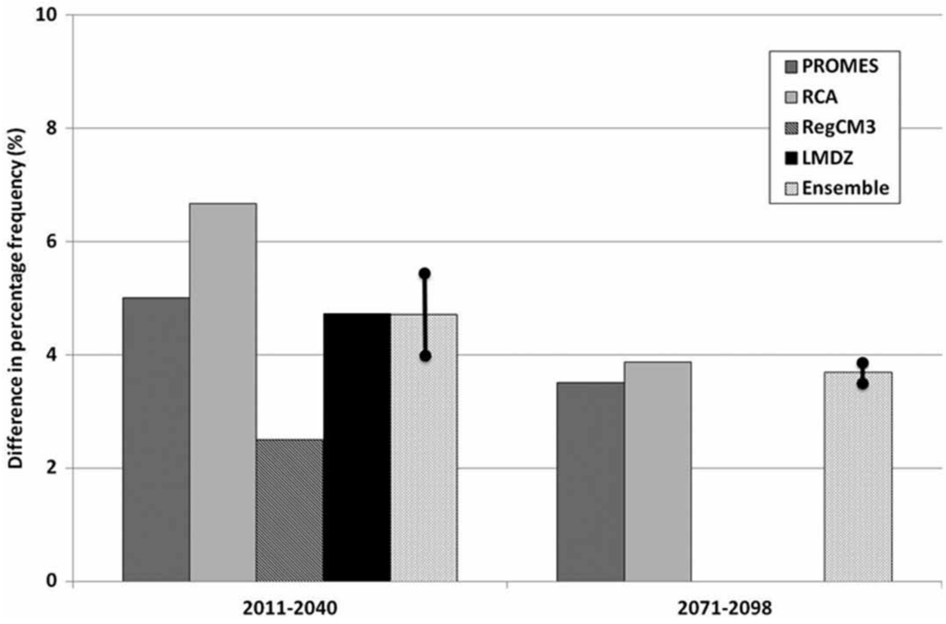

Figure 8 Differences in the percentage frequency (%) of months with river discharges above the flooding threshold at Corrientes (Paraná River) derived from the CLARIS-LPB climate simulations and for the ensemble mean under the scenario A1B with respect to the reference period of each RCM (Table 1). Black bars represent one standard deviation among RCMs.

events for both the near future and for the end of the twenty-first century. However, it is important to highlight that three RCMs (RCA, RegCM3 and LMDZ) do not exhibit floods for their respective reference periods (1981–1990 for RegCM3 and 1991–2000 for RCA and LMDZ).

Future changes in duration of flood events in Corrientes were analysed considering both the PRECIS (Figure 9) and CLARIS-LPB climate simulations (Figure 10). In all cases, only events that last more than three months were considered to avoid single episodes of one to two months of extreme flows that could not necessarily be associated with flooding at Corrientes or downstream this station. Isolated extreme flows that last equal to or less than two months usually do not propagate downstream as a flood wave (Camilloni and Barros 2003). Results

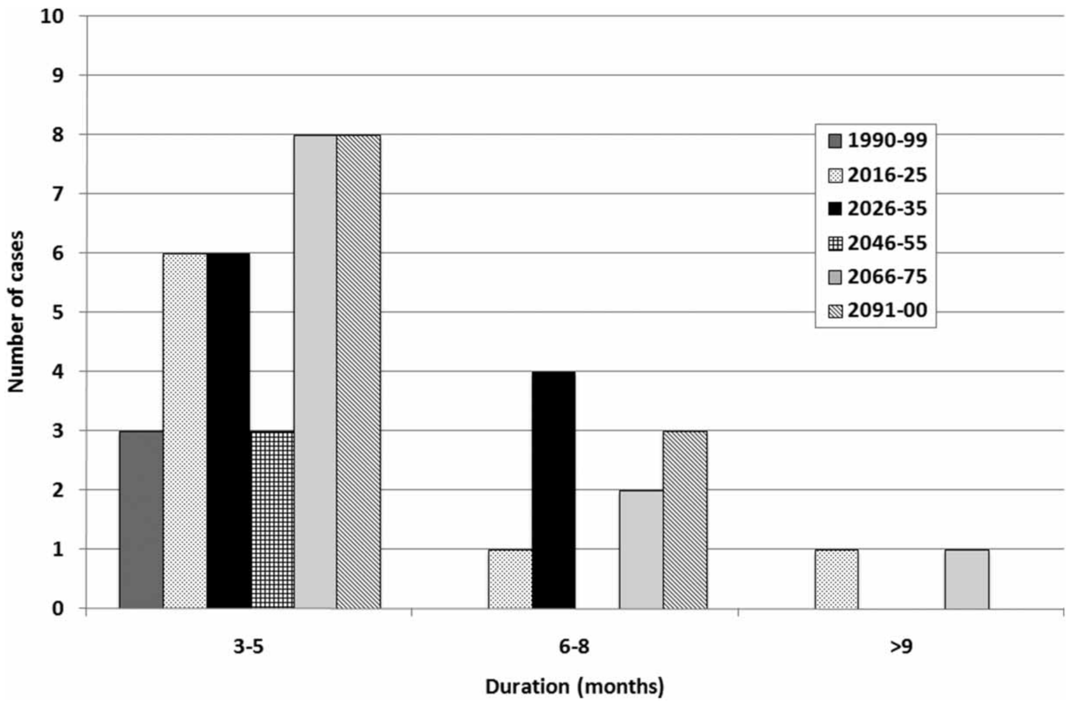

Figure 9 Absolute decadal frequency of flooding events at Corrientes (Paraná River) of different durations according to the PRECIS climate model simulations (scenario A2).

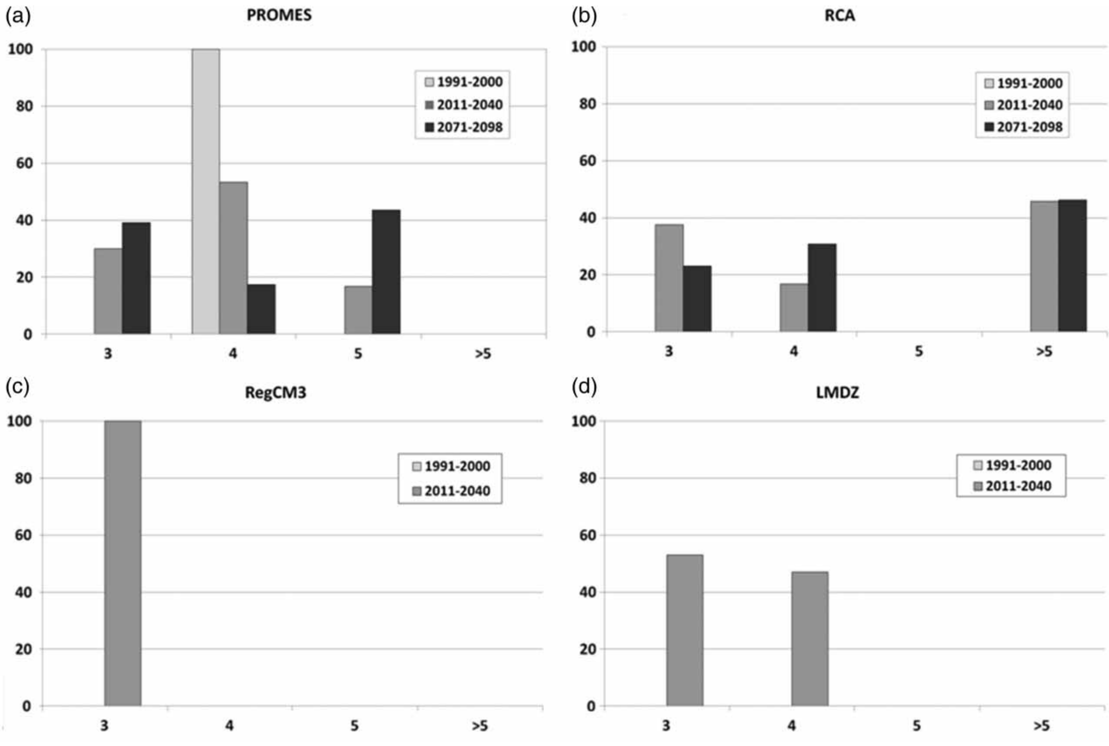

Figure 10 Distribution (%) of flooding events at Corrientes (Paraná River) according to their durations for individual CLARIS-LPB simulations (a) PROMES, (b) RCA, (c) RegCM3 (d) LMDZ for scenario A1B.

indicate increase in duration of up to nine months with respect to the reference period for the simulations with PRECIS and between three and five months for three CLARIS-LPB RCMs (PROMES, RegCM3 and LMDZ).

5 Conclusions

Climate change, as captured by a set of five different RCMs, would have a significant role in modifying some features of the flooding events in the margins of the lower sections of the Paraná and Uruguay Rivers in La Plata Basin for the twenty-first century. An increase in frequency and duration of fluvial floods was identified considering a physically based approach that incorporated unbiased meteorological outputs from RCMs with different emission scenarios to the distributed hydrology model VIC.

Saurral *et al*. (2013) found an increase not only in the mean flows but also in the largest monthly flows for the 2021–2040 (near future) and 2071–2090 (far future) periods both for the Paraná and Uruguay Rivers. Additionally, this paper reveals an increase in the frequency and duration of extreme events associated with floods considering the same climate scenarios as Saurral *et al*. (2013). Therefore, although it is expected that compared to the current conditions the temperature would rise and precipitation would have a slight increase in La Plata Basin during the present century, it could be expected that there will be an increased freshwater availability accompanied by more frequent and lasting-flood events.

However, the uncertainty bounds as depicted by results derived from different climate models are wide. Therefore, although this finding could be relevant for the adaptation of water management systems, more climate impact studies are needed to quantify the vulnerability of La Plata Basin to climate change and its dependence on changing hydroclimatic conditions.

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