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Hydrological modelling of the Iberá Wetlands in southeastern South America

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SUMMARY

The Iberá Wetlands are one of the largest inland freshwater ecosystems in the world hosting several unique flora and fauna species. They are located in northeastern Argentina, a region in southeastern South America that experienced large positive precipitation trends during the last decades. The aim of this paper is to calibrate and evaluate a hydrological model on the Iberá basin in order to quantify the hydrologic impacts of potential regional temperature and precipitation variations in the context of climate change as a result of anthropogenic greenhouse gas emissions. For this purpose, a version of the Variable Infiltration Capacity (VIC) hydrological model, accounting for the presence of lakes and Wetlands, was applied for the first time to the Iberá basin. Results show that the model can successfully simulate the main features of the system dynamics, including the daily mean streamflow of the Corriente River, the daily level of the Iberá Lake and the daily lake evaporation. Inclusion of the lake and Wetlands module improved the streamflow simulations. Sensitivity tests of the Iberá basin hydrology were performed by varying regional temperature and rainfall conditions according to the outputs of a set of climate models for three different time slices during the 21st century. These tests showed a strong dependence of the basin hydrology on the precipitation changes rather on the temperature ones.

1. Introduction

Wetlands are ecosystems covered or saturated by water during all or part of the year and represent a critical and highly productive habitat for fish and wildlife and for many unique types of plants. The hydrological conditions of these systems as well as their biological diversity can be disturbed by land use alterations and climate variability and change (Solomon et al., 2007). The knowledge of future changes in a Wetlands' hydrology associated to some or all of these forcings would help design better management practices and appropriate adaptation strategies for their conservation. The Iberá Wetlands (Esteros del Iberá in Spanish) are a marshy depression located in the province of Corrientes, in northeastern Argentina, between 27°30′ and 29 °S, and 56°25′ and 58 °W. Due to their ecological importance (Neiff, 2004), they have been included in the *Ramsar Convention on Wetlands* to guarantee their conservation in the future. They cover an area of approximately 12,000 km^2 (Neiff, 1997; Giraut et al., 2009) with a very gradual slope of 30 m along its length of 250 km and a very poorly developed drainage network that contributes to the Paraná River through the Corriente River (Fig. 1). They gain most water from precipitation, and the topographic features induce a predominantly vertical balance between precipitation, evapotranspiration and infiltration within the system. The Iberá Wetlands are part of the La Plata basin in southeastern South America (SESA). This basin hosts not only the Iberá but also the Pantanal, the largest continuous freshwater Wetlands in the world. During the last decades, SESA has been subject to hydroclimatic trends as increased precipitation (Castañeda and Barros, 1994; Giorgi, 2002; Barros et al., 2008) and river flows (García and Vargas, 1998; Barros, 2006; Camilloni, 2007; Doyle and Barros, 2011). Barros et al. (2008) showed that south of 22 °S, annual rainfall trends in SESA were positive everywhere, and mainly explained by a marked increase in the austral warm semester (October–March) with little variation during the cold period (April–September). They also found that in northeastern Argentina, southern Brazil, and Paraguay, half of the annual rainfall trend came from the El Niño phase with minor contributions from La Niña and the neutral phases. Doyle and Barros (2011) found that the two main drivers for the generalized growth of the river flows in La Plata basin were the increased precipitation and the decreased evaporation attributable to land use change, including deforestation of natural forest and crop switch from

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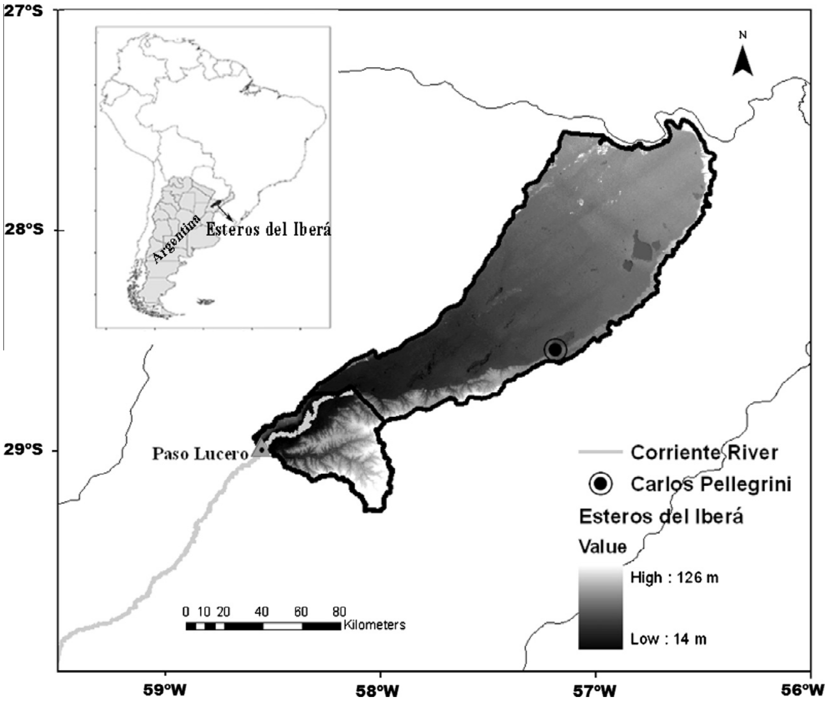

Fig. 1. Location of the Iberá Wetlands in South America showing the spatial domain considered in the hydrological modeling. The Iberá basin delimitation was taken from Giraut et al. (2009). The topography of the basin is displayed in shadings of grey, in units of meters.

sugarcane and coffee trees to soybean. However, the relative importance of these drivers is different as the rainfall increase is more relevant in the middle and lower sections of the basin. Changes in the occurrence of extreme rainfall and discharge events in SESA were also identified. Re and Barros (2009) found positive trends in the annual maximum rainfalls, as well as a remarkable increment in the frequency of heavy rainfalls over thresholds ranging from 50 mm to 150 mm and Camilloni and Barros (2003) showed that 12 out of the 16 major flooding events of the Paraná River during the 20th century occurred after 1970.

Future streamflow scenarios for the Corriente River in the Iberá Wetlands area were recently estimated by Montroull et al. (2013) using the Variable Infiltration Capacity (VIC) semi-distributed hydrologic model (Liang et al., 1994; Liang et al., 1996; Nijssen et al., 1997). They obtained larger monthly discharges for the end of the 21st century as a result of the increases in both precipitation and mean temperature projected by the regional climate model considered under a scenario of increasing atmospheric greenhouse gases concentration. However, the results of this previous study should be considered only as a first approximation for the assessment of the impacts of climate change in the Iberá Wetlands area as the VIC model version used by the authors (previous to 4.1.1) did not allow them to account for the presence of Wetlands and lakes within the basin and only discharges (not water levels) could be estimated. The main objective of the present study is to calibrate and evaluate the VIC 4.1.2 model for the Iberá Wetlands for the period 1990–2011 to assess their sensitivity to climate change in terms of alterations in some hydrological variables (streamflow, water level and evapotranspiration) to projected regional precipitation and temperature changes. This new version of the model allows the user to specify the location and soil/vegetation properties of lakes and Wetlands inside basins, which is crucial for the appropriate modeling of the Iberá region. To evaluate the impact on the quality of the VIC model simulations obtained by using the lake and Wetlands module, results without using it (no-Wetlands simulation) are also analyzed. The paper is organized as follows: Section 2 describes all datasets used in this study. Section 3 presents a description of the hydrological model and its implementation in this paper. Section 4 includes results of the calibration and evaluation processes for two different periods, while results for the no-Wetlands test and future hydrological changes are presented in Section 5. Conclusions are included in Section 6.

2. Data and methodologies

2.1. Region of study

The spatial domain of this study, from now on referred to as the Iberá region, covers approximately 14,000 km^2 and includes the Iberá Wetlands with an area of 12,000 km^2 along with the upper section of the Corriente River basin, a small upland zone of 2000 km^2 upstream Paso Lucero gauge station (Fig. 1). 80% of the runoff from these uplands drains directly into the Corriente River while the remaining 20% drains through the Wetlands (Neiff, 1997). The Iberá Lake is located in the Wetlands and has a surface area of 55 km^2. The contribution of underground water flow between the surrounding area and the Iberá region seems to be negligible (Vives et al., 2011). Thus, no underground water flow in/out of the region is considered.

2.2. Meteorological data

The meteorological data sets used to calibrate and evaluate the hydrologic model consist of daily minimum and maximum temperature, precipitation, and wind speed covering the period 1/1990–12/2011. Wind speed data was obtained from the National Weather Service of Argentina, while temperature and precipitation records were provided by the Agricultural Technology National Institute, the National Weather Service of Argentina, and the CLARIS-LPB European-South American Project Database (http://www.claris-eu.org/). Fig. 2 presents the location of the meteorological stations inside or close to the study region considered in the analysis. The number of available records for each variable is very different: 9 for wind speed, 27 for precipitation and 48 for temperature. In order to avoid possibly erroneous information, quality control analyses like the evaluation of the length of consecutive dry days and the elimination of negative precipitation values were performed before using the meteorological data to calibrate and evaluate the hydrologic model. None of the stations considered has a complete series for the whole period, although temperature records exhibit less missing data than the precipitation ones (Fig. 3). However, as the version of VIC considered in this study requires as input the spatial average of each of the meteorological variables over the domain, the lack of data in some stations and during some periods is irrelevant. The spatial mean daily precipitation data was calculated by averaging all available data using Thiessen polygons as in Zotelo et al. (2008), while the spatial means of daily temperature and wind data were calculated as simple unweighted averages. Consequently, new time series of temperature, precipitation and wind speed (representative of the regional climate) were obtained and used to calibrate and evaluate the hydrological model.

2.3. Wetlands shape, landcover and soil characteristics

Besides meteorological data, the hydrologic model also needs information regarding soil parameters and land cover within the basin. Although the VIC 4.1.2 model has the ability to represent vegetation heterogeneity through multiple vegetation tiles in each grid cell, its lakes and Wetlands module accepts only one vegetation type for Wetlands and no vegetation for the open water area. This represents a large drawback for the implementation of the VIC model in the Iberá region, which holds more than 1600 plant species (Neiff, 2004), including floating and rooted aquatic plants. Furthermore, the lake fraction of VIC does not distinguish between pelagic open water zones, water areas covered by floating vegetation or benthic zones that may in fact contain emergent Wetlands vegetation. The University of Maryland's 1 km Global Land Cover dataset (Hansen et al., 2000) was used to obtain land cover information over the Iberá region. Since only one vegetation type is allowed to be included in the Wetlands and lakes module, the woodland option was chosen as the most representative of the area. In the case of soil characteristics, while the parameters related to soil texture are fixed, others are subject to calibration. The soil parameters that are fixed in the model, were taken from the 5 min Global Soil Data Task dataset developed by the Distributed Active Archive Center (Distributed Active Archive Center, 2000) and spatially averaged within the region.

Daily pan evaporation data for the Carlos Pellegrini station were considered for comparison with the evaporation series modeled with VIC. The observed evaporation records were obtained from the Integrated Hydrological Database of Argentina (http://www.hidricosargentina.gov.ar/) for the period 2003–2009.

2.4. Hydrological datasets

Daily series of mean streamflow of the Corriente River at Paso Lucero and of the Iberá lake level at Carlos Pellegrini (Fig. 1) were used for calibration and evaluation of the VIC model. These data were taken from the Integrated Hydrological Database of Argentina for the period 1/1990–12/2011. There are few missing data (2.6%)

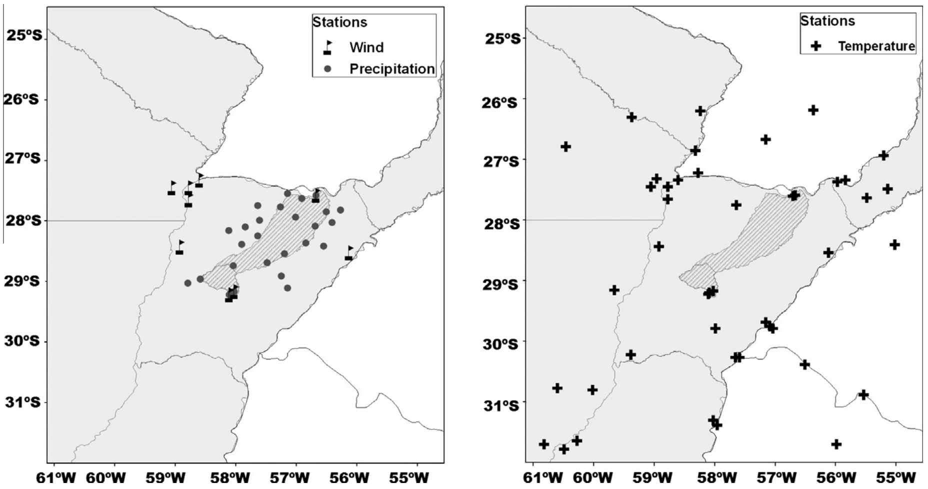

Fig. 2. Wind and precipitation stations (left; denoted by flags and dots, respectively) and temperature stations (right). The area shaded in darker grey indicates the spatial domain.

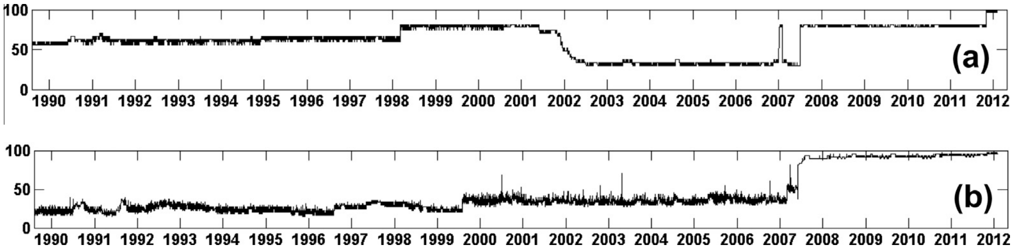

Fig. 3. (a) Percentage of missing data from precipitation stations (out of a total of 27 stations). (b) Percentage of missing data from temperature stations (out of a total of 48 stations).

in the daily streamflow records. The Iberá Lake level at Carlos Pellegrini can be considered a good estimator of the water level of the whole Iberá system as it showed significant correlation with other lakes located to the north and south of it (Cardinali and Chamorro, 2002). Wind-driven currents and slow flow in the Iberá Wetlands may have a considerable influence on the Iberá Lake level at the Carlos Pellegrini station.

3. Model description and application

3.1. The VIC model

VIC is a semi-distributed land surface hydrologic model that balances both surface energy and water budgets (Liang et al., 1994; Liang et al., 1996; Nijssen et al., 1997). It includes the ability to represent vegetation heterogeneity using multiple vegetation tiles in a single grid cell, multiple soil layers with variable infiltration, and non-linear drainage from a lower soil moisture zone (base flow). It calculates sensible and latent heat fluxes according to physical formulations but uses conceptual schemes to compute the surface runoff and base flow. The VIC model has been satisfactorily calibrated and evaluated at scales varying from continental to individual watersheds (e.g. Hamlet and Lettenmaier, 1999; Saurral et al., 2008). In particular, it was selected for the present study as it has also shown good results in the simulation of the hydrological cycle of the La Plata Basin over most of the sub-basins (Su et al., 2008; Saurral, 2010). The most significant deficiencies were found in the representation of the annual cycle and the interannual variability of the marshy region of the upper Paraguay River, probably due to the lack of ability to simulate the Wetlands' hydrology in the version of the model considered (previous to VIC 4.1.1). VIC 4.1.2 was used in this study to simulate the present water balance and to assess the sensitivity to climate change of the Iberá's system as it can simulate the effect of lakes and Wetlands on the regional water and energy balance, as well as their interactions (Bowling and Lettenmaier, 2010; Mishra et al., 2010a). This version has been applied successfully to the study of high latitudes Wetlands of the Northern Hemisphere (Bowling and Lettenmaier, 2010) and of subtropical lakes variability in Africa (Gao et al., 2011). However, it has not been applied to any wetland region in South America.

VIC 4.1.2 has the ability to simulate lakes and Wetlands by creating a lake/Wetlands tile in the grid cell mosaic. This tile represents seasonally flooded ground as well as permanent water bodies, and the Wetlands portion of the tile at a given time is defined as the area not covered by water. The model was designed to be applied to scales large enogh so that the subsurface transfer of moisture between model grid cells can be neglected. In particular, the complete lake/Wetlands tile has to fall in a single grid cell. The model accounts for lake/Wetlands bathymetry as a variable depth-area relationship, allowing the emergence of Wetlands vegetation as the lake area shrinks. When the lake level raises above a certain threshold, lake water flows into the channel network as flow over a broad-crested weir, calculated as a function of the lake's depth. The threshold level as well as the weir width are parameters typically adjusted during calibration.

Total evapotranspiration for a grid cell in the VIC model is defined as the sum, for every tile in the cell, of the evapotranspiration from the tile multiplied by the tile area fraction. For vegetation tiles, evapotranspiration is calculated according to the Penman–Monteith equation (Liang et al., 1994), adding the canopy layer evaporation and vegetation transpiration. If a lake/Wetlands tile is present, the evapotranspiration for the Wetlands fraction is computed as for any other vegetation tile, whereas evaporation from the water surface is calculated by means of a surface energy balance, as described in Hostetler and Bartlein (1990), considering only the surface water layer for energy exchange.

When VIC is run, as in this case, at a sub-daily time step with daily input datasets, the model disaggregates these data, distributing the daily precipitation evenly during the day and interpolating between minimum and maximum temperatures via a cubic spline. Other data necessary to maintain the energy budget – such as humidity, shortwave and longwave radiation – are derived from these datasets and the site location (Bohn et al., 2013) when they are not explicitely provided.

3.2. Model application

The surface area of the model's grid cell is divided into one lake/Wetlands tile and four vegetated area tiles. The fraction of the cell covered by lakes and Wetlands was defined as 0.85 (12,000 km^2 out of 14,000 km^2), and the percentage of runoff from the vegetated tiles that is diverted into the Wetlands tile was set to 20%. Given the lack of accurate information on the bathymetry of the Iberá Wetlands, values of the depth-area relationship, $A(z)$, for open water were calibrated in an initial manual calibration phase (see Fig. 4).

All hydrological simulations were performed at 6-hourly time steps in full energy balance mode (i.e. balancing both energy and water). In each simulation, daily series of the streamflow at Paso Lucero, of the Iberá Lake level at Colonia Carlos Pellegrini, and of the actual evapotranspiration were obtained. The last two series are direct outputs of the VIC model, whereas the streamflow at Paso Lucero is routed from the model's output by simply adding the runoff (that includes Wetlands/lakes channel outflow) and the base flow from the grid cell. Given that the size of the modeled region is moderate, monthly moving-averages were used to compare simulated and observed streamflow, and consequently no unit hydrograph was used as part of the routing algorithm.

4. Hydrologic model calibration and evaluation

4.1. Performance measures

Model performance is evaluated using statistical measures of agreement between observed and simulated series for the Corriente River streamflow and Iberá lake level. The Nash–Sutcliffe efficiency measure (NSE, see Nash and Sutcliffe, 1970), was calculated for the streamflow and lake level time series. Given series of observations and simulations, the NSE value can range from $-\infty$ to 1, being 1 a perfect match between both series. For a series of n observed data Q^{OBS} and the corresponding series of simulated data Q^{SIM}, the NSE can be defined as follows:

$$\mathrm{NSE} = 1 - \frac{\sum_1^n \left(Q_i^{OBS} - Q_i^{SIM}\right)^2}{\sum_1^n \left(Q_i^{OBS} - \bar{Q}^{OBS}\right)^2}$$

where $\bar{Q}^{OBS}$ is the mean over the Q^{OBS} series.

Santhi et al. (2001) suggest that NSE values greater than 0.5 indicate a good model performance. Other calculated performance measures include the mean flow rate (MF_{rate}) between the

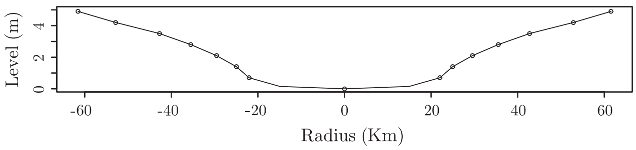

Fig. 4. Profile of a circular basin with the depth-area relationship considered in this study.

Table 1
Calibration parameters with their descriptions, bounds and final calibrated values.

Parameter		Calibration		
Name	Description	Min	Max	Final
b_i	Variable infiltration curve parameter	0.00001	0.4	0.247
$D_{s_{max}}$	Maximum base flow that can occur from the lowest soil layer (mm/day)	1	20	9.80
D_s	Fraction of $D_{s_{max}}$ where non-linear base flow begins	0.00001	0.5	0.483
W_s	Fraction of the maximum soil moisture where non-linear base flow begins	0.5	1	0.828
D_2	Depth of the second soil layer (m)	0.2	1.5	0.64
D_3	Depth of the third soil layer (m)	0.1	2.5	1.80
M_d	Minimum depth for lake channel output (m)	1.60	2	1.896
f	Lake outflow channel width as a fraction of lake perimeter	0.0001	0.05	0.007

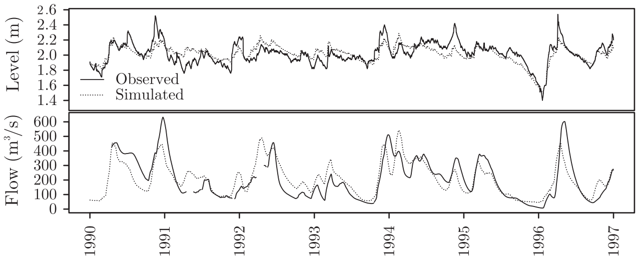

Fig. 5. Observed and simulated streamflow at Paso Lucero (top) and Iberá Lake level (bottom) in the calibration period (1990–1996).

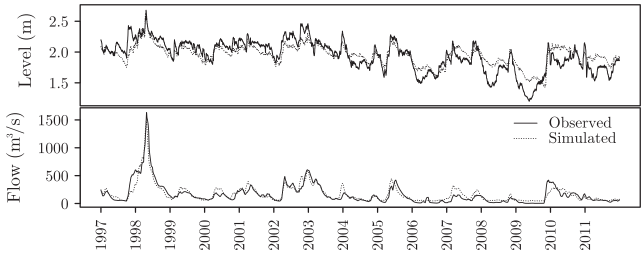

Fig. 6. Observed and simulated streamflow at Paso Lucero (top) and Iberá Lake level (bottom) in the evaluation period (1997–2011).

Table 2
Performance measures for the flow at Paso Lucero and the Iberá Lake level at Carlos Pellegrini during the calibration and evaluation periods.

Period	Flow					Lake level[a]	
	NSE[a]	NSE[b]	r^a	r^b	MF_{rate}	NSE	r
Calibration (1990–1996)	0.533	0.642	0.746	0.802	1.003	0.554	0.746
Evaluation (1997–2011)	0.764	0.847	0.875	0.922	1.050	0.684	0.852

[a] Statistics calculated at daily scale.
[b] Statistics calculated at monthly scale.

simulated and observed mean flow at Paso Lucero and the correlation coefficients (r) between observed and simulated hydrographs and between observed and simulated water levels at Carlos Pellegrini. For mean streamflow, NSE and r were used both at daily and monthly scales. As the time series of observed streamflow series had few missing data, these days were removed from the analysis.

4.2. Calibration method

4.2.1. Parameters

Calibration of the VIC model usually involves the adjustment of the variable infiltration parameter (b_i), three base flow parameters (W_s, D_s, and $D_{s_{max}}$), and the thickness of the second and third soil layers (D_2 and D_3, respectively, *c.f.*Nijssen et al., 1997; Bowling and Lettenmaier, 2010; Mishra et al., 2010a). The use of the lakes and Wetlands module involves the adjustment of two additional parameters: the channel width fraction (f), and the minimum depth for lake channel output (M_d). The calibrated values for these eight parameters and their bounds are summarized in Table 1.

4.2.2. Algorithm

The calibration period ran from 1/1990 to 12/1996, in which the model was automatically calibrated using the downhill simplex method (Nelder and Mead, 1965). The initial simplex was chosen from 200 randomly generated sets of parameters. The objective function to be maximized was defined as follows:

$$OF = (3 \cdot NSE_{level} + NSE_{flow}) \cdot (1 - TF_{error}).$$

This function is based on a linear combination of the statistical measures NSE_{level} (the NSE of the Iberá lake level at daily scale) and NSE_{flow} (the NSE of the streamflow at Paso Lucero at monthly scale). The coefficients in this linear combination were chosen so that both statistical measures fall in a comparable range when the objective function is maximized. The role of the TF_{error} factor (the relative error of the mean modeled flow, defined as $TF_{error} = -|1 - MF_{rate}|$) is to minimize the relative error of the mean modeled flow.

During calibration, values of $NSE_{flow} = 0.642$, $NSE_{level} = 0.554$, and a mean simulated flow of 190.54 m^3/s vs. a mean observed flow of 190.06 m^3/s for the complete period were obtained (see Fig. 5 and Table 2).

The values of the resulting parameters are shown in Table 1. Hereinafter, the model with these parameters is referred to as the *calibrated model*.

4.3. Evaluation

During the evaluation period, considered from 1/1997 to 12/2011, the skill of the calibrated model to represent the flow at Paso Lucero and the level of the Iberá Lake was assessed. Values of $NSE_{flow} = 0.847$, $NSE_{level} = 0.684$, and a mean simulated flow of 172.73 m^3/s vs. a mean observed flow of 164.48 m^3/s were obtained, indicating good model performance (see Fig. 6 and Table 2).

Although calibration was performed for the *monthly* mean streamflow, performance measures indicate that the calibration is also good at the daily timescale. In fact, daily NSE values for the Paso Lucero streamflow time series for the calibration and evaluation periods are 0.533 and 0.764, respectively (see Fig. 7). Surprisingly, better statistical measures were obtained for both streamflow and the lake level series during the evaluation period than during the calibration one. A possible explanation for this finding could be related to the higher availability of meteorological

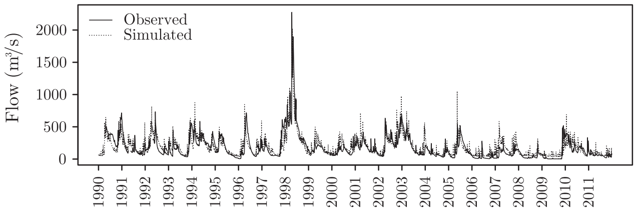

Fig. 7. Daily flow at Paso Lucero for the complete period (1/1990–12/2011).

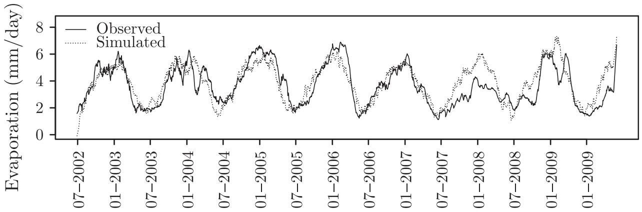

Fig. 8. Observed pan evaporation at Carlos Pellegrini multiplied by 0.75 and lake evaporation given by VIC for the period 2003–2010.

data during 2002–2007 that allowed a better performance of the VIC model during that period.

In terms of evaporation, previous studies (Penman, 1948; Linacre, 1993; Linacre, 1994) suggest that lake evaporation is about 25% lower than pan evaporation (available in many meteorological stations). Fig. 8 shows the comparison between the observed pan evaporation at Carlos Pellegrini multiplied by 0.75 and the lake evaporation given by VIC. As it can be seen, there is a close relationship between both series, with the largest differences found during the warm season of 2007–2008 when VIC overestimated the evaporation.

The calibrated model indicates that for the complete period 1990–2011, 71.42% of the water that gets into the modeled region as rainfall returns to the atmosphere as evapotranspiration, and 28.58% flows through the Corriente River. The evapotranspiration rate is slightly higher and the streamflow rate slightly lower than the rates obtained previously for the whole La Plata basin in similar periods (Berbery and Barros, 2002; Doyle and Barros, 2011).

5. Sensitivity analysis of the Iberá system

5.1. Sensitivity to changes in climatic conditions

The sensitivity of the Iberá system to changes in the precipitation and temperature conditions was assessed by modifying the observed meteorological data for the period 1990–1999 using the delta-change method. This approach is a widely accepted and relatively simple method for constructing climate change scenarios data sets for impact studies (Hay et al., 2000; Fowler et al., 2007; van Roosmalen et al., 2010). This method consists in adding a change factor to the baseline period time series of climate observations. The change factors (percentage change in precipitation and absolute change in temperature) were derived by calculating the differences between annual mean projected and baseline daily maximum and minimum temperature and precipitation simulated by four General Circulation Models included in the CMIP5 multi-model dataset (Taylor et al., 2011): HadGEM2 CC, HadGEM2 ES, inmcm4 and MRI CGCM3. These models were chosen for this study as they adequately represent the present climate in Southeastern South America (Gulizia and Camilloni, 2013). Three future time slices (2020–2039, 2040–2049 and 2070–2079) were considered following the Representative Concentration Pathway (RCP) 4.5 (see Taylor et al., 2011 for further details). The annual mean temperature and precipitation for each period were calculated as the average over all the grid boxes within the Iberá region. Finally, these annual changes between future and present climate were added (multiplied) to the daily observed temperature (precipitation) data for the Iberá region and then used as input for the hydrological model. The advantage of this method is that relative changes between two periods are used and if biases between them are assumed to be equal, then a bias correction for the GCM outputs is not necessary.

Table 3
Variations of precipitation (%) and temperature (°C) for the Iberá region according to the four selected models, for three time slices.

Model	Precipitation (%)			Temperature (°C)		
	2020s	2040s	2070s	2020s	2040s	2070s
HadGEM2 CC	3.3	1.8	2.9	1.3	1.5	2.6
HadGEM2 ES	1.9	19.9	19.0	0.8	1.6	2.6
inmcm4	10.8	−6.1	3.6	0.5	1.0	1.5
MRICGCM3	14.2	5.5	13.7	0.2	0.9	1.0

Precipitation projections show a large uncertainty over the Iberá region with changes ranging from −6% to 20% in all three periods considered (Table 3). All models, except HadGEM2 ES, show a similar behavior in changes in precipitation along the 21st century, with the largest increments for the near and far future. Temperature projections vary strongly between models, but they are all consistent in showing a positive trend towards the end of the century. As a result, annual streamflow and lake level changes are highly variable among models and they respond essentially to the variations in precipitation (Table 4). The hydrologic simulations project increments of up to 7 cm in the Iberá Lake level and only the inmcm4 model suggests a decrease of 3 cm for the 2040 decade in agreement with the sign of changes in precipitation and evapotranspiration projected by this model. Remarkably, the simulations corresponding to the HadGEM2 ES for the periods 2040–2049 and 2070–2079 predict an increase of about 45% in the streamflow while the increment in evapotranspiration remains bounded by 7%.

As expected, increments in temperatures lead to more evapotranspiration and less water availability, with less streamflow and a lower lake level. When precipitation is increased in the original dataset, the net effect of the increment in temperature on streamflow is largely compensated by the additional rainfall. For example, according to the HadGEM2 CC model for the 2040 s, an increase of 1.5 °C in the mean temperature of the basin requires only 1.8% extra rainfall to have an almost null effect on the mean flow of the Corriente River (see Tables 3 and 4). Streamflow elasticity with respect to precipitation (fractional change in streamflow divided by fractional change in precipitation) is about 2.5, showing that the Iberá system is very sensitive to changes in precipitation.

5.2. The no-Wetlands simulation

In order to evaluate the impact of the lakes and Wetlands module in the model's performance, a new simulation without considering this module was carried out and compared against the original calibrated model. This new test is referred to as the NO-WETLAND simulation and the original calibrated model as the WETLANDS-ORIGINAL simulation. In the NO-WETLAND test, the landcover tiles corresponding to the lake/Wetlands class in the original calibrated model were set to 'mixed vegetation' (vegetation type 6 in the University of Maryland data set), which is the vegetation class used as the emergent Wetlands vegetation type of the original model. Since there are neither lakes nor Wetlands in the

Table 4
Results of the sensitivity tests to rain and temperature, expressed as percentage variations and level differences with respect to the reference period.

Model	Flow (% var)			Evapotranspiration (% var)			Avg. lake level (cm)		
	2020s	2040s	2070s	2020s	2040s	2070s	2020s	2040s	2070s
HadGEM2 CC	5.03	1.06	1.73	2.41	2.18	3.51	0.7	0	0.1
HadGEM2 ES	2.73	45.71	41.29	1.47	6.54	7.45	0.4	6.6	5.9
inmcm4	25.17	−16.58	5.33	3.36	−0.67	2.71	3.9	−3.2	0.7
MRICGCM3	34.48	11.13	31.16	3.71	2.59	4.66	5.2	1.7	4.7

Table 5
Comparison of the performance measures for the flow at Paso Lucero considering the original Wetlands simulation, the re-calibrated Wetlands test, and the no-wetland simulation (1990–2011). These last two experimets were calibrated using NSE_{flow} as objective function.

Simulation	Level	Flow				
	NSE_{level}[a]	NSE[a]	NSE[b]	r[a]	r[b]	MF_{rate}
WETLANDS-ORIGINAL	0.673	0.719	0.808	0.849	0.901	1.04
WETLANDS-MODIFIED	0.481	0.744	0.810	0.865	0.901	1.05
NO-WETLAND	–	0.663	0.801	0.831	0.900	1.13

[a] Statistics calculated at daily scale.
[b] Statistics calculated at monthly scale.

NO-WETLAND experiment, the calibration was done using only NSE_{flow} as the objective function.

When the NO-WETLAND test is considered, mean evapotranspiration decreases by 4% while annual mean runoff increases by almost 8% with respect to the WETLANDS-ORIGINAL experiment. This can be interpreted as a consequence of the delay effect on the hydrological cycle caused by the presence of lakes and Wetlands that leads to an increment in evapotranspiration.

To perform an unbiased comparison, a third test scenario was considered, including the lakes and Wetlands module but calibrated using NSE_{flow} as objective function. We refer to this new simulation as the WETLANDS-MODIFIED experiment.

The inclusion of the lakes and Wetlands module leads to a substantial improvement of the simulated streamflow, as is observed using all the performance measures considered, comparing any of both Wetlands tests with the no-wetland one (see Table 5). Using the lakes and Wetlands module, the calibration based on the original objective function OF leads to a slightly worse performance in the simulated streamflow than that based on NSE_{flow} alone as objective function. However, the OF function leads to good results for both streamflow and lake level while the NSE for the lake level in the WETLANDS-MODIFIED simulation is less than 0.5, which indicates poor performance of the model.

6. Conclusions

This paper presents, for the first time, the calibration of the new version of the VIC hydrological model, which is capable of accounting for the presence of lakes and Wetlands, on the Iberá Wetlands basin. The Iberá Wetlands water levels and Corriente River streamflow were simulated using the VIC model version 4.1.2 at a 6-h time step. The simulation period ran from 1/1990 to 12/2011 and was divided into a calibration period (01/1990–12/1996) and an evaluation period (01/1997–12/2011). Calibration was performed on a monthly basis for streamflow and on a daily basis for the Iberá Lake level via an objective function. Both the streamflow of the Corriente River and the lake level were successfully represented. Moreover, the model estimated the streamflow adequately at a daily scale, despite the fact that VIC's lakes and Wetlands module only allows for a single vegetation type to be defined within the Wetlands area. Evaporation simulated by VIC was also shown to be representative of the actual evaporation within the basin, with small errors, mainly in the warm seasons.

Sensitivity tests showed a large dependence of the hydrological cycle of the Wetlands on precipitation and temperature. When variations in both variables were introduced in the simulations, the largest dependence was found on precipitation. In fact, the diminishment of streamflow caused by a warming of +1.5 °C in the regional mean temperature would be largely compensated by an increment of only 1.8% in the rainfall.

The comparison between both Wetlands simulations and the no-wetland one showed the improvement when using the lake and Wetlands module. These comparisons suggest that the lakes and Wetlands algorithm is able to capture the delay in streamflow caused by the storage delay effect of lakes and Wetlands.

Future activities regarding the simulation of the hydrological cycle of the region include improving the landcover and evapotranspiration algorithm, particularly to consider the option of combining various vegetation types within the lake/Wetlands tile of the grid cells used in the modeling. For instance, the new model for this region should account for the presence of at least three different kinds of vegetation present in the region: rooted, dammedlands (*embalsados*) and floating vegetation, all of which are abundant throughout the Wetlands. Another unsolved question is whether the underground connection of water is in fact negligible as suggested in previous studies. These issues will be addressed in future studies.

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