Assessment of climate change on the future water levels of the Iberá wetlands, Argentina, during the twenty-first century

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ABSTRACT

The Iberá wetlands, located in La Plata Basin, is a fragile ecosystem habitat of several species of flora and fauna and it also constitutes one of the largest inland freshwater of the world. In this study, the hydroclimatologic response to projected climatic changes in the Iberá wetlands is assessed. Bias corrected temperature and precipitation data from four Regional Climate Models (RCMs) developed for the CLARIS-LPB project were used to drive the calibrated variable infiltration capacity (VIC) hydrological model for different time slices. Derived future scenarios consist on changes in temperature, precipitation and water level of the Iberá Lake for the periods 2021–2040 and 2071–2090 with respect to present. All RCMs are consistent in predicting a warming for the near future (0–2°C) and also to the end of the century (1.5–4.5°C) in the study region, but differ in the sign and percentage of precipitation changes. VIC modelling results suggest that the Iberá Lake level could increase in the twenty-first century and that this increment would be higher in the summer months. Nevertheless, the projected 10 cm of water-level increase could be not so relevant as it is of the same order of magnitude than the observed interdecadal variability of the system.

Keywords: Wetland hydrology simulation; climate change; Iberá wetlands; VIC hydrologic model

1 Introduction

The La Plata Basin (LPB) in southeastern South America hosts the Iberá wetlands (or Esteros del Iberá in Spanish), one of the largest continuous freshwater wetland in South America. Due to its high level of conservation and biodiversity, it was included in the Ramsar Convention list of the most important wetland of the world. Southeastern South America is an area where climate change is particularly evident, with a remarkable increment in precipitation (Giorgi 2002, Barros et al. 2008), and positive trends in river discharges since the 1970s (Bischoff et al. 2000, Camilloni and Barros 2003, Barros et al. 2004). Climate variability and change could modify the Iberá wetlands hydrological conditions and consequently affect its biodiversity (Ferrati et al. 2005, Solomon et al. 2007). It is therefore essential to advance in understanding the hydrological variations of this wetland as a consequence of climate change in order to design better management practices and appropriate adaptation strategies for the conservation of this regional ecosystem considering that small changes in water levels may produce
dramatic changes in the wetland biotic components and ecological functioning.

The most popular tool to understand and project the climate variability and change is the Global Climate Models (GCMs). Frequently, future climatic scenarios derived from GCMs are used in combination with hydrological models to determine the hydrometeorological impacts due to climate changes at a basin level. Nevertheless, many authors have analysed the skill of GCMs (Camilloni and Bidegain 2005, Vera et al. 2006, Boulanger et al. 2007, Silvestri and Vera 2008, Vera et al. 2009, Gulizia et al. 2012) and they all show that GCMs still have difficulties in representing the current climate over South America. Moreover, their coarse resolution (typically, 2.5° × 2.5°) makes almost impossible to use meteorological information directly from GCMs in the hydrological models without bridging the gap between the resolution of these climate models and local scales such as basins through downscaling techniques. The use of Regional Climate Models (RCMs) to bridge this gap has recently become more popular as a basis for hydrological studies (Fowler et al. 2007, Teutschbein and Seibert 2012). RCMs transfer the large-scale information provided by GCMs into smaller scales which are closer to a catchment level. However, RCMs spatial resolution still exceeds the scale of a watershed such as the Iberá wetlands. Consequently, to reduce the uncertainties associated to the systematic errors of climate models and generate high-resolution scenarios, many authors propose different methods to produce bias corrected meteorological information for hydrological impact studies (Hay et al. 2002, Wood et al. 2002, 2004, Vidal and Wade 2007, van Roosmalen et al. 2010, Piani and Haerter 2012).

The objective of this study is to derive hydroclimatic scenarios for the Iberá wetlands for the rest of the twenty-first century. To achieve this goal, the ability of a set of RCMs to represent regional temperature and precipitation patterns is evaluated. Bias corrected RCMs outputs are used to develop projections of future changes of temperature and precipitation for two time slices (2021–2040) and (2071–2090) under the A1B emission scenario (see Solomon et al. 2007 for further details on the scenarios). Finally, projections on water-level changes of the Iberá system for the same time slices are obtained using the bias corrected RCMs data as input of a hydrologic model.

2 Data and methodology

2.1 Region of study

The Iberá wetlands are located in the province of Corrientes in the northeast end of Argentina, between 27°30’S and 29°S and 56°25’W and 58°W (Figure 1). The climate of this region is sub-tropical with seasonal average temperatures that vary between 26°C in summer and 16°C during winter and a precipitation regime with two maxima (April and December) and an absolute

Figure 1 Location of the Iberá wetlands (Esteros del Iberá) and Paso Lucero gauging station. Note: Elevation is indicated in metres (shaded).
minimum in August. Ibera constitutes one of the largest inland freshwater wetlands in South America with an area of approximately 12,000 km² (Neiff 1997, Giraut et al. 2009). Because of its small slope, the water flows very slowly through the region and leads to a hydrologic balance that is predominantly vertical. The system drains into the Corriente River which finally contributes to the Parana River. The annual mean flow of the Corriente River is 332 m³/s at Paso Lucero gauging station (Figure 1) and its annual cycle shows a one-month lag with rainfall with maxima in May and in January and an absolute minimum of 189 m³/s in September.

The Ibera region comprises a complex system of marshes that are interconnected with large shallow lakes. One of the most important is the Ibera Lake located in Carlos Pellegrini (28°32’17”S, 57°11’13”W; see Figure 1) which was proved to be a good estimator of the level of the whole Ibera system (Cardinali and Chamorro 2002). Figure 2 shows the annual mean Ibera Lake level for the period 1929–2011. The average level for this period is 1.82 m with an interdecadal variability of 0.14 m derived from the 11-year running mean. Both Corriente River flows and Ibera Lake level data were taken from the Integrated Hydrological Database of Argentina.

### 2.2 The hydrology model

The variable infiltration capacity (VIC) hydrology model (Liang et al. 1994, 1996, Bowling and Lettenmaier 2010, Mishra et al. 2010) version 4.1.2 was used in order to assess the future water balance of the Ibera wetlands due to the climate change. VIC is a grid-based hydrologic model that solves both water and energy balances in each of the cells in which the catchment is divided. Input data for VIC include basin topography, land cover, soil properties and meteorological data. The model has been successfully calibrated and applied over a large number of basins all over the globe, including LPB (Saurral et al. 2008, 2013, Su and Lettenmaier 2009, Saurral 2010) and the Ibera wetlands (Grimson et al. 2013, Montroull et al. 2013).

In order to deal with more complicated hydrological processes, VIC was updated a number of times since it was created in 1992 (Wood et al. 1992). The most recent version (VIC 4.1.2) has the ability to simulate the effect of lakes and wetlands within a portion of a grid cell. The lake/wetland tile contains a body of permanent open water whose areal extent is allowed to change in response to the water balance, which constitutes the seasonally flooded area or wetland (Bowling and Lettenmaier 2010, Gao et al. 2011). In the VIC model, the bathymetry of a lake/wetland is represented by a variable depth–area (A(z)) relationship. When the lake shrinks a portion of wetland vegetation emerge and when the lake level rises above a specific threshold (Md), water flows into the channel network as flow over a broad-crested weir, calculated as a function of the lake’s depth. One of the limitations of the model is that it only simulates lakes that receive all of their inflows from within the same grid; therefore, we choose to simulate the Ibera system as a single grid cell of 14,000 km² where 85% was estimated to be covered by lakes and wetlands (12,000 km²) using satellite imagery over the region.

The calibration of the model for the study region was done by adjusting soil and lake parameters and obtaining the best Nash–Sutcliffe efficiency (NSE) coefficient (Nash and Sutcliffe 1970) for the Ibera Lake daily level for the period 1990–1997. The soil variables involved in the calibration process were the infiltration parameter bi, the maximum velocity of baseflow Dsmax, the fraction of the Dsmax parameter at which non-linear baseflow occurs Ds, the fraction of maximum soil moisture where non-linear baseflow occurs Os and the thickness of the second and third soil layers (D2 and D3). Regarding the lake model, the channel width fraction f and the minimum depth for the lake channel output Md were adjusted for the Ibera wetlands. The meteorological data used to force the model for the calibration consisted of daily precipitation, minimum and maximum temperature and wind speed obtained from the National Weather Service of Argentina, Agricultural Technology National Institute and CLARIS-LPB European-South American Project databases.
Soil type information was obtained from the five-min Global Soil Data Task data-set (Distributed Active Archive Center 2000) and the land-cover information from the University of Maryland’s 1 km Global Land Cover data-set (Hansen et al. 2000). Since the Iberá wetlands were modelled as a single grid cell, the meteorological, land-cover and soil information was spatially averaged over the study area. More details of the model calibration and validation for an independent period (1997–2012) can be found in Grimson et al. (2013). The NSE coefficient obtained for the period of calibration was .554, which indicates an acceptable performance of the model considering the lower limit of .5 proposed by Santhi et al. (2001) for a good model performance. Figure 3 shows the observed and simulated with observed meteorological data daily level of the Iberá Lake at Carlos Pellegrini for 1991–2000. The NSE for this period is .47 and the correlation coefficient between the two series is .73. These statistical results show that the VIC model has good performance not only for the calibration period, but also for the 1991–2000 period considered as baseline to estimate future scenarios of Iberá Lake-level changes as a result of an increased atmospheric greenhouse gases concentration.

2.3 RCM data and bias correction methodology

The calibrated VIC model was forced with data from four RCMs generated within the CLARIS-LPB project (http://www.clarlis-eu.org) in order to simulate the present and future water balances of the Iberá wetlands. The RCMs used in this paper were 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, Dominguez et al. 2010), the ICTP Regional Climate Model version 3 (RegCM3), (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) for the present climate and for 2021–2040 and 2071–2090 for future climate projections considering the A1B emission scenario. Present climate was considered as the period 1991–2000 for all the RCMs except for RegCM3 where the period used was 1981–1990 given that no information on the period 1991–2000 was available for that model. The hydrological projections were made under the assumption that vegetation and the geomorphology of the Iberá wetlands will remain unchanged as there are no scenarios of possible vegetation changes available for this region.

Both GCMs and RCMs are characterized by systematic errors in the representation of the atmospheric circulation and related variables. In this study, systematic biases in temperature and precipitation were removed by applying the ‘quantile-based mapping’ bias correction method to the monthly data (Wood et al., 2002, Saurral, 2010). This methodology consists in constraining the distributions of these variables produced by the RCM to the observed climatology for a target period. The correction factors were calculated for the 1981–1990 decade and verified for the 1991–2000 period, for those models that had both periods. In the case of RegCM3, the correction factors were calculated and applied to the same period (1981–1990). The observational data-set used for the application of the bias correction procedure for both temperature and precipitation was CRU v3.1 (Mitchell and Jones 2005), which has a spatial resolution of 0.5° lat × 0.5° lon. All RCMs outputs were interpolated to the same grid as the observational data-set to make comparison possible. In order to make simulations with the VIC model, the bias corrected and raw RCMs outputs were spatially averaged over the Iberá area in order to obtain single meteorological data series for each variable.

3 Results and discussion

3.1 RCMs representation of the present climate for the Iberá wetland region

The annual and seasonal (December–January–February, DJF and June–July–August, JJA) precipitation and mean temperature fields for the Iberá region as modelled by each RCM along with the observed data for the present climate period are presented in Figures 4 and 5, respectively. The observed precipitation field shows a gradient with a maximum to the northeast of the domain and a minimum to the southwest, which are well
captured by RegCM3, PROMES and LMDZ models. In general, all RCMs have a drier climatology than the one depicted by the observations. The only exception is the LMDZ model that has rainfall values larger than the observed ones during DJF. In the austral winter (JJA), CRU shows a very marked gradient with precipitation rates of 20 mm/month to the west of the region and over 100 mm/month to the east. Although all RCMs outline this gradient, none can capture its magnitude (Figure 4). In terms of temperature, all RCMs are somewhat warmer than the observations both annually and seasonally. The observed annual mean temperature ranges from 20°C at the south end of the basin to 22°C at the north end. However, modelled values vary from 21°C for RegCM3 to 25°C for PROMES for the whole basin. In the austral summer (DJF), the observed temperatures are mostly uniform in the Iberá region (25–26°C) and the differences with the modelled temperatures are from 2°C for RCA up to 7°C for PROMES. In JJA, differences are lower (2–5°C) and RegCM3 shows even a colder climatology than the observed one.

Biases in the modelled vs. observed climatology are of special interest when using meteorological information from RCM as input data for hydrological models. The requirement of removing errors of climate models prior to their use in impact models is widely discussed in many papers (e.g. Vidal and Wade 2007, 2008, 2009, Quintana Seguí et al. 2010, Piani and Haerter 2012, Teutschbein and Seibert 2012). In this study, we evaluate the relative performance of the models before and after the application of a bias correction method by means of the Normalized Root Mean Square Error (NRMSE) (Eq. 1),

\[
\text{NRMSE} = \frac{\sqrt{\sum_{i=1}^{N} (X^{\text{Mi}}_i - X^{\text{OBS}}_i)^2}}{N (X^{\text{MAX}} - X^{\text{MIN}})},
\]

where \(X^{\text{Mi}}_i\) and \(X^{\text{OBS}}_i\) are, respectively, the mean values of a meteorological variable derived from the model \(M\) and the observations (OBS) in the grid point \(i\) for the period 1991–2000. \(X^{\text{MAX}}\) and \(X^{\text{MIN}}\) correspond to the maximum and minimum values of the observations for the whole period. The mean values of observed precipitation and temperature for the Iberá region for the period 1991–2000 are summarized in Table 1. Figure 6 shows the NRMSE values for the bias corrected and uncorrected precipitation and temperature data for the Iberá area. Results for the annual precipitation indicate that the corrected data has, as expected, a better performance than the uncorrected data. In DJF, bias corrected models present overall lower NRMSE values, and only the LMDZ model does not present a clear improvement of the summer precipitation respect to the observed values. However, this RCM is the only one that has a better skill in JJA when considering the corrected data, while the other three models present no improvement at all. On the other hand,

![Figure 4](image-url)
temperature representation in the Iberá region is always better estimated when the correction is applied and the NRMSE values are below .5 both for the annual and seasonal averages.

3.2 Future climate and hydrological projections

Future daily precipitation and maximum and minimum temperatures, as simulated by the four RCMs, were bias corrected using the correction factors derived in the 1981–1990 decade and used as forcing data to simulate future hydrological conditions for the Esteros del Iberá. Figure 7 shows the differences between two future time slices (2021–2040 and 2071–2090) and the validation period for precipitation, temperature and lake water level in the wetland region.

Differences in precipitation between the near future (2021–2040) and the present climate show a great dispersion among the models, especially in the austral winter months. For instance, PROMES has little or no variation in precipitation compared to 1991–2000 period, but LMDZ has a negative difference in DJF and an increment of more than 100% in JJA. On the contrary, RCA shows a decrease in precipitation in the winter of about 20%. When rainfall is considered annually, all models show an increase between 10 and 40% (about 13 mm/day–51 mm/day). Annual temperature differences are of about 1–1.5°C for almost all models except RCA, which predicts no variations in temperature for the region. Summer projections shows the same pattern of warming between 1.5°C and 2°C in most models. Projected differences in the lake level for the Iberá are also very different among RCMs. LMDZ, which shows the maximum increase in precipitation, also shows the greatest increment in the lake level (around 35 cm). For the remaining RCMs, the VIC model predicts variations in the mean with respect to the baseline period that range between -5 cm and 5 cm both annually and seasonally when forced with the corrected climate model data.

By the end of the century, (2071–2090) climate models predict an increment of the annual mean precipitation between 20% and 30%, but the uncertainty is high for the winter months with differences ranging from -20% to 50%. Annual temperature changes predicted by these models are between 2°C and 4°C, whereas in summer the dispersion is higher (1.5–4.5°C). In winter, the region is also expected to be warmer by the end of the century with temperatures 2.5–4.5°C.
higher than for the present climate. Lake level projected changes are not higher than 20 cm both annually and seasonally. In JJA, for PROMES, these changes are negative probably due to the decrease in precipitation and the increment in temperature of more than 4 °C which would contribute to increase evapotranspiration with the consequent decrease in the lake level. The ensemble mean of projected lake-level changes considering all RCMs indicates that the increments for the near and far future in the Iberá Lake annual mean water level could be around 10 cm with the maximum rise during summer (Table 2). However, this result must be considered only as a preliminary estimation as the dispersion among the models is high particularly for the near future and the cold season.

4 Conclusions

The Iberá wetlands in LPB represent a unique ecosystem that is very vulnerable to changes in its hydrodynamics. This study assessed the impacts of projected climate change on the
hydrology of the Iberá system using the VIC hydrology model and four RCMs from the CLARIS-LPB project.

The hydrology model was calibrated and validated with historical observed daily data and was able to satisfactorily replicate the observed lake level for the target period 1991–2000 with a correlation coefficient of .73. However, to assess the impacts of projected temperature and precipitation changes in water availability in the Iberá region, climate model outputs are necessary. Meteorological data from four RCMs were used as input in the VIC hydrology model, but as all climate models present systematic errors, the application of a bias correction scheme was required. In this study, we applied the quantile-based mapping bias correction methodology to both monthly temperature and precipitation fields. The corrected data had better skill in the representation of the annual and seasonal means in almost all RCMs with the only exception being the RCA model winter precipitation. This model also has the poorest representations of the observed precipitation field compared with the other RCMs.

Regarding future projections, all models are consistent in predicting a warming for both the near future and for the end of the twenty-first century in the region of Iberá, but differ in the sign and percentage of change in precipitation. As a result, future water-level changes highly vary among models. Despite these differences, an indication of possible changes in the lake level can be obtained when considering the average among all RCMs results. This average indicates that the Iberá water level could increase during the twenty-first century and that this increment would be higher in the summer months than during winter. Nevertheless, the projected 10 cm of water-level increase could be not so relevant as it is of the same order of magnitude than the observed interdecadal variability of the system.

In order to assess the impacts of climate change on the ecological dynamics, not only future scenarios of water levels in the wetland and lakes are important but also changes in the inundation area. However, since the natural shorelines of the Iberá Lake are floating islands (Ferrati et al., 2005), it is expected that they will rise when water level rises maintaining the shape of the lake probably unchanged. Therefore, even having an estimation of possible changes in the lake level, future changes in the inundation area are still highly uncertain.

### Table 2

| Annual | DJF  | JJA  |
|--------|------|------|
| (2021–2040) – baseline | 10 (17.6) | 10.8 (17.2) | 8.6 (18.9) |
| (2071–2090) – baseline | 9.1 (7.7) | 11.2 (6.8) | 6.1 (10) |

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