Influence of climate variations on Chascomús *shallow lake thermal conditions and its consequences on the reproductive ecology of the Argentinian Silverside (*Odontesthes bonariensis*—Actinopterygii, Atherinopsidae)*

Mariano Elisio, Alejandro Vitale & Leandro A. Miranda

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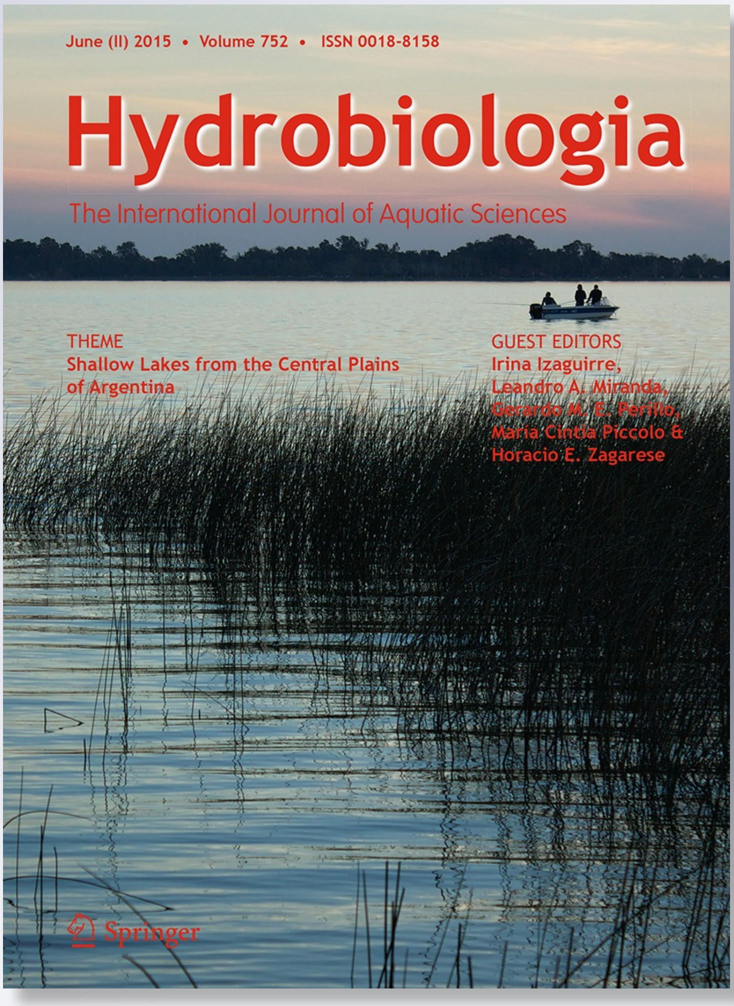

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ARGENTINE PAMPEAN SHALLOW LAKES

Influence of climate variations on *Chascomús* shallow lake thermal conditions and its consequences on the reproductive ecology of the Argentinian Silverside (*Odontesthes bonariensis*—Actinopterygii, Atherinopsidae)

Mariano Elisio · Alejandro Vitale ·
Leandro A. Miranda

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Abstract It is well known that water temperature directly affects fish reproduction. The aim of this study was to develop a predictive model to determine water temperature conditions on a typical Pampas shallow lake (*Chascomús*, 35°36′S, 58°02′W) from local climate variables (specifically air temperature and rainfall). In addition, this model was used to assess the variability of local climate and water temperature conditions in this lake over the last 47 years, and predict possible effects on pejerrey reproductive phenology. The temperature model showed a good fit demonstrating a direct influence of the local climate into the lake water temperature. As consequence of a demonstrated warming in *Chascomús* City, an average increase of 1.4°C was evident in *Chascomús* lake over the analyzed period, which was mainly due to a thermal increase during the warmer seasons (spring, summer, and autumn). This pattern of warming drove to a shortening in the pejerrey spawning season length, estimating a decrease of 19 days over the period of 47 years. Thus, this study showed that a tight association between the climate variability and the change in fish reproductive phenology can occur in species inhabiting shallow lakes.

Keywords Climate variability · Numerical modeling · Pejerrey fish · Reproductive phenology · Water temperature

Introduction

Temperature is one of the most important environmental variables determining the functioning of aquatic communities (Ficke et al., 2007; Pörtner & Farrell, 2008; Mooij et al., 2008; Jeppesen et al., 2010). All physiological processes of living organisms occur within a limited range of temperature, which can be different depending on the molecular and cellular mechanisms associated to each particular process (Pörtner & Farrell, 2008). Depending on geographic region, each species is adapted to a particular thermal variation range which can largely determine their different phenological responses to the climate variability pressure (Parmesan, 2007).

As in all ectothermic organisms, body temperature in most teleost fish is similar to environmental temperature, and consequently any variation of this variable will

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M. Elisio · L. A. Miranda (✉)
Laboratorio de Ictiofisiología y Acuicultura, Instituto de Investigaciones Biotecnológicas-Instituto Tecnológico de Chascomús (CONICET-UNSAM), Intendente Marino Km. 8.200 (B7130IWA), Chascomús, Buenos Aires, Argentina
e-mail: lmiranda@intech.gov.ar

A. Vitale
Instituto Argentino de Oceanografía (CONICET-UNS)., Florida 8000 (Camino La Carrindanga Km. 7.500 (B8000FWB), Bahía Blanca, Buenos Aires, Argentina

affect them directly (Ficke et al., 2007). The only thermoregulation way in fish is the selection of different thermal microhabitats, which is limited by the thermal range of each particular aquatic ecosystem (Ficke et al., 2007). Hence, fish from isolated habitats, such as some lakes, are unable to migrate in order to find a thermal refuge. For these reasons, water temperature represents a key variable in the geographical distribution of different fish species (Cussac et al., 2009), and changes in the "normal" thermal regimens may generate consequences such as increase or decrease in abundance, variations in the distribution range and, in an extreme case extinction (Ficke et al., 2007).

Reproduction in fish, compared with other physiological processes, only occurs in a bounded thermal range (Pörtner & Farrell, 2008), and slight variations in environmental water temperature can affect considerably fish reproductive cycle (Van der Kraak & Pankhurst, 1997). Thus, water temperature jointly with day length determines fish reproductive seasonality (Pankhurst & Porter, 2003; Migaud et al., 2010). This last fact is commonly interpreted as an evolutionary event that selects fish that spawn only when environmental conditions increase the probability of survival and development of the offspring (Bromage et al., 2001; Pörtner & Farrell, 2008). In this context, anomalous temperatures in aquatic ecosystem could generate a mismatch between the spawning season and the optimal environmental conditions for progeny development (Durant et al., 2007). Besides, shortening or even loss of the breeding season could also happen (Elisio et al., 2012a). It is important to note that any of these last possible scenarios could generate a loss in the reproductive output of a given population and a consequent change on its structure, which may jeopardize its sustainability (Durant et al., 2007; Strüssmann et al., 2010).

It is known that water temperature conditions from different aquatic ecosystems are influenced by the atmospheric climatic variations, although this fact depends largely on the geomorphology and the thermal inertia of each particular water body (Jacobs et al., 1997; Livingstone & Lotter, 1998; Stefan et al., 1998; Piccolroaz et al., 2013). Shallow lakes compared with other deeper water bodies, posses a low thermal inertia, and thus are considered extremely sensitive to prevailing climatic variation (Mooij et al., 2008). Therefore, the knowledge of the climatic events and their influence on water temperature fluctuations in aquatic ecosystems can contribute to understand and predict changes in the population structure or distribution of a given species, as well as other changes at ecosystem level (Mooij et al., 2008).

Pejerrey (*Odontesthes bonariensis*) is a native fish from Argentina that typically inhabits shallow lakes from the Pampas region (Gómez et al., 2007; Somoza et al., 2008). This specie is commonly subjected to a great fishing pressure, and its populations can sharply decline temporally (Sendra, 2003), being its recovery capacity and sustainability largely dependent on its reproductive performance. Pejerrey spawning in the wild begins when photoperiod increases during the end of winter and extends until water temperature rises up to critical values for gonadal development, generally at the end of spring or early summer (Elisio et al., 2012b). Although, it was recently recorded in *Chascomús* shallow lake that water temperature conditions blocking pejerrey spawning can also occur earlier, even during mid-spring (Elisio et al., 2012a). Hence, variations of water temperature conditions in shallow lakes could represent an important source of variability in the length of pejerrey spawning season.

Pejerrey inhabits in shallow lakes ranging usually between 30 and 6,078 ha with deeps in general below to 4 m, and which represent the most common water bodies on the Pampas region from Argentina (Gómez et al., 2007). It was recently observed that water temperatures in these water bodies show a tight coupling with air temperature, therefore suggesting that their thermal conditions depend largely on the local climate (Elisio et al., 2012a).

In this context, the aim of this study was to develop a predictive model to determine water temperature conditions on a typical Pampas shallow lake (*Chascomús*, 35°36′S, 58°02′W, mean depth 1.53 m, surface 3,000 ha, Dangavs, 1976) from the local climate variables (specifically air temperature and rainfall). In addition, this model was used to assess the variability of local climate and water temperature conditions in *Chascomús* lake over a 47-year period, and predict possible effects on pejerrey reproductive phenology.

Materials and methods

Water temperature and maximum depth in *Chascomús* shallow lake

Water temperature in *Chascomús* lake was recorded every hour from October 2008 to October 2012, using waterproof electronic data loggers (Thermochron® iButton, Sunnyvale, CA, USA) at 1.0 m of mean depth. Daily maximum, minimum and mean water temperatures, and daily thermal variation range were calculated.

The hydrometric level was registered every 15 days from April 2001 to July 2012 as the distance from the water surface of lake to a fixed landmark. Maximum depths were calculated from these levels using the bathymetric maps developed by Dangavs et al. (1996). From these data, monthly averages of maximum depth were calculated.

Historical air temperature and rainfall in *Chascomús* City

The maximum and minimum air temperatures and rainfall were recorded daily in the "El Espartillar" experimental field in *Chascomús* City (35°34′S, 58°01′W) from January 1966 to December 2012, using a thermometer and a pluviometer, respectively. Air temperatures were then interpolated every hour considering the time change in which occur the daily maximum and minimum temperatures according to the photoperiod variation. From these data, the daily maximum, minimum and mean air temperatures, and the accumulated monthly and yearly rainfalls were calculated.

Predictive model of water temperature in *Chascomús* lake

Since there are no historical data of water temperature in *Chascomús* lake, a mathematical model was developed based on that used by Mooij et al. (2008) for predicting water temperature in different shallow lakes from air temperature. The model assumes that changes in water temperature result from the additive effects of thermal conduction in the water–atmosphere interface and the incoming and emitted radiation (Jeppesen & Iversen, 1987; Jacobs et al., 1997). The basic model used was as follows:

$$T_{\mathrm{w}}(t+\Delta t) = T_{\mathrm{w}}(t) + h(T_{\mathrm{a}}(t) - T_{\mathrm{w}}(t)) + f + g\sin\left(\frac{2\pi(80.8-\mathrm{Day})}{365.25}\right)$$

being, $T_{\mathrm{w}}(t+\Delta t)$ the water temperature (°C) at the time $t+\Delta t$, $T_{\mathrm{w}}(t)$ the water temperature (°C) at the time t, $T_{\mathrm{a}}(t)$ the air temperature (°C) at the time t, *Day* the number of days from the first of January. The parameter h represents the rate of change in water temperature per °C difference between air and water temperature $(T_{\mathrm{a}}(t) - T_{\mathrm{w}}(t))$ during a Δt period and $f + g\sin(\frac{2\pi(80.8-\mathrm{Day})}{365.25})$ represents the change in water temperature during a Δt period due to the radiation. Because actual radiation data were not available, the impact of radiation throughout the year was approximated by a sinus with an annual period, being 80.8 a number chosen such that the maximum radiation impact is reached during the longest day (December 21), and its minimum during the shortest day of the year (June 21).

The predictive model was fitted using data of air and water temperatures (interpolated every 10 min) and of maximum depths (monthly averages) from two whole consecutive years (2010–2011). The model parameters were determined as follows: h was monthly determined by the slope of the linear regression line fitted to the following equation: $Y = hx + b$, being $Y = T_{\mathrm{w}}(t+\Delta t) - T_{\mathrm{w}}(t)$, $x = T_{\mathrm{a}}(t) - T_{\mathrm{w}}(t)$, and $b =$ monthly average impact of radiation, containing the $f + g\sin\left(\frac{2\pi(80.8-\mathrm{Day})}{365.25}\right)$ term. Different Δt periods were evaluated, and a Δt period of 20 min was chosen by the optimization of the coefficient of determination (R^2) obtained in linear regressions. Since absolute values of b calculated for June and July (negative values) and for December and January (positive values) were similar, f parameter was considered as 0. Therefore, g was monthly calculated from the b values of the fitted linear functions, considering the *Day* variable as the 15th day of each month.

As the depth in *Chascomús* lake was changing over the period used to fit the model (with up to 2 m of variation), monthly values of h and g parameters were analyzed in relation with depth. Mathematical equations describing the change in the h and g parameters as a function of depth were fitted (data not shown). Then, h and g parameters were considered in the model as dependent variables of depth through the following equation:

$$h(\text{per 20 min}) = 0.0227D(t)\exp{-2.17}$$

$$g(°\text{C per 20 min}) = 0.032D(t)\exp{-3.088}$$

being $D(t)$ the monthly average of maximum depth (m) in *Chascomús* lake at the time t.

Predictive model of maximum depth in *Chascomús* lake

Since depth in *Chascomús* lake was used as predictor variable for the water temperature predictive model, and these data were unavailable for the whole analyzing period, a model for predicting the maximum depth from the local rainfall data was developed. The basic model used was:

$$D(t) = m \sum_{t-\Delta t}^{t-1} R(t) + b$$

Being $D(t)$ the monthly average of maximum depth (m) at the month t; $R(t)$ the accumulated monthly rainfall (mm) at the month t; m represents the average contribution of rainfall to the lake depth per mm of accumulated rainfall over a Δt period; b represents the average contribution of other factors (such as evaporation) to the lake depth over a Δt period. For the estimation of m and b parameters, a linear regression line was fitted between $D(t)$ and $\sum_{t-\Delta t}^{t-1} R(t)$. Different Δt periods (months) were evaluated, and a Δt period of 20 months was chosen by the optimization of the coefficient of determination (R^2) obtained in the linear regression.

The estimated values of parameters model considering a Δt period of 20 months were:

$$m(m/\text{mm}) = 0.0018$$

$$b(m) = -0.7411$$

The predictive model previously shown was applied to predict the historical monthly averages of maximum depth in *Chascomús* lake since 1968–2012 from the historical data base of rainfall in *Chascomús* City (“El Espartillar” experimental field).

Historical data of water temperature in *Chascomús* lake

The predictive model of water temperature was applied to model the historical water temperatures in *Chascomús* lake (each 20 min) since 1966–2012. The historical data of air temperature (interpolated every 20 min) in *Chascomús* City and the modeled maximum depth in *Chacomús* lake were used to generate the database of the predictor variables. The monthly averages of maximum depth in *Chascomús* lake for predicting water temperatures during the 21 months (from January 1966 to August 1967) were considered as 2.3 m (historical average of maximum depth in the lake).

The daily maximum, minimum, and average water temperatures in *Chascomús* lake were then calculated from the historical modeled data.

Assessment of the end of pejerrey spawning season

In previous studies, spawning impairment and gonadal regression were induced in pejerrey after 8 days of exposition at daily maximum temperatures above 23°C (Soria et al., 2008; Elisio et al., 2012a). Also, first signs of gonadal regression in pejerrey population from the *Chascomús* lake was observed just after 1 week in which daily maximum water temperatures reached 21–22°C (Elisio et al., 2012b). Taking in consideration these findings, it was considered the end of pejerrey spawning season as the period in which the maximum daily water temperatures surpass 21°C during at least eight consecutive days.

Assessment of historical variation of *Chascomús* City climate, *Chascomús* lake water temperature, and pejerrey reproductive phenology

The yearly variation trends (rates of change) of the daily maximum, minimum, and average air and water temperatures, the accumulated yearly and monthly rainfall, the yearly average of maximum depth, and the end of pejerrey spawning season were analyzed over the 1966–2012 period. The water and air temperatures variables were analyzed considering the averages of each entire year or of each month.

Statistical analysis

The linear regressions used to determine the predictive models parameters were performed by means of the least squares method. The fit of the models was evaluated by the coefficient of determination (R^2) and the residual standard deviation (RSD).

The variation trend of each variable over the 1966–2012 period was evaluated by analyzing of the slope of the line fitted to the data using the least squares method. The statistical significance of the slopes was evaluated by the Fisher’s test ($P < 0.05$).

The methodology used for the fit of the predictive models and the statistical analysis were performed using GraphPrism 5.0 and GNU Octave Software.

Results

Water temperature and depth in *Chascomús* lake in relation to air temperature and rainfall in *Chascomús* City

During the period in which water temperature was registered (October 2008–October 2012), the monthly average of water temperature in *Chascomús* lake showed a similar pattern to that observed for the air temperature in *Chascomús* City ("El Espartillar" experimental field). The minimum and maximum water temperatures were registered during June 2009 (3.5°C) and January 2010 (36°C) respectively, coincidently with the lowest depth values observed (below to 1.5 m of maximum depth, Fig. 1).

The daily thermal variation range showed a sharp difference between the water and air temperatures, being around five times higher for the last one. Also, the monthly average of daily water thermal variation range showed an inversely proportional relation to the lake depth, reaching mean values of 8°C (with maximum values of up to 14°C) under the lowest depth conditions registered (Fig. 1).

The maximum depth in *Chascomús* lake fluctuated approximately 2 m from October 2008 to October 2012, showing its minimum value between May and June 2009 (1 m), and its maximum value between August and September 2010 (3 m). It must be noted that the months in which were registered higher depth values were preceded by periods with elevated accumulated rainfalls, while the opposite fact was observed after dry periods (Fig. 1).

Fit of depth and water temperature models

Both depth and water temperature predictive models showed a good fit (Fig. 2). The explained variance in the monthly average of maximum depth in *Chascomús* lake was 83% ($R^2 = 0.83$) and the RSD was 0.33 m (Fig. 2A). In the case of temperature model, the 95% of water temperature variation (each 20 min) in *Chascomús* lake was jointly explained by the air temperature and depth variations ($R^2 = 0.95$), with a RSD of 1.296°C (Fig. 2B).

Variation trends in air temperature and rainfall in *Chascomús* City

Analysis of yearly variation trends of the air temperatures in *Chascomús* City showed a significant warming over the 47 evaluated years (Fig. 3A). The highest rate of thermal increase (0.04°C/year) was observed in the daily average maximum temperature, showing an increase on average of 1.98°C over the whole period. In the case of average air temperature, a warming rate of 0.03°C/year was observed with an increase of 1.4°C over the analyzed period. On the other hand, the daily average minimum air temperature showed the lowest rate of warming (0.018°C/year). It must be noted that some inter-annual oscillations in air temperatures were recorded over the analyzed period, such as it was observed between 1983 and 1988, when temperatures increased significantly (Fig. 3A).

Although no significant variation trend was observed in the accumulated yearly rainfall, this variable showed a great inter-annual fluctuation over the 47 analyzed years (Fig. 3A).

The analysis of yearly thermal variation rate in the different months showed that the increase in temperature was dependent on the season. Considering all analyzed variables (daily maximum, minimum, and average temperatures), a significant rate of warming was observed during January, March, and October. In contrast, no evidence of thermal increase was observed during July, when even the daily minimum and average temperatures showed a negative variation rate (Fig. 3B). During the remaining months, positives and significant variation rates were observed in at least one of the analyzed variables (mainly the daily maximum and average temperatures, Fig. 3B).

No significant yearly variation rates in the accumulated monthly rainfalls were observed (Fig. 3B).

Variation trends in water temperature and maximum depth in *Chascomús* lake

Similarly to that observed for air temperature in *Chascomús* City, water temperature in *Chascomús* lake showed a significant increase over the analyzed period, 1966–2012 (Fig. 4A). The yearly variation rates for daily maximum, minimum, and average water

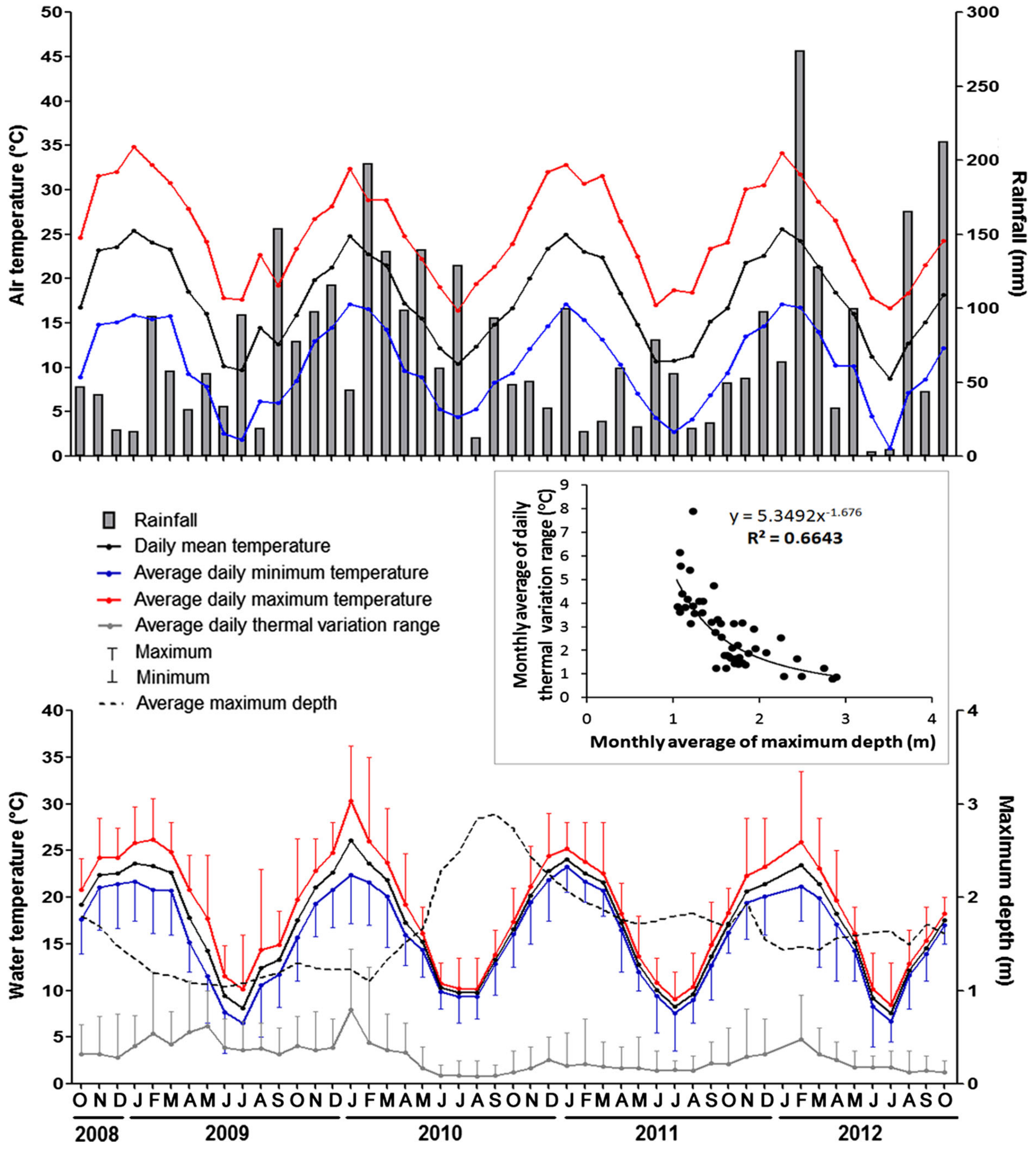

Fig. 1 Air temperature and monthly rainfalls in *Chascomús* City (upper half of the figure), and water temperature and maximum depth in *Chascomús* lake (lower half of the figure) from October 2008 to October 2012. The daily water thermal variation range in relation to the lake depth is plotted on the center of the figure

temperature were similar to that registered for the mean air temperature, with an approximate value of 0.03°C/year. This yearly rate of warming showed that *Chascomús* lake became on average 1.4°C warmer over the whole period of 47 years (Fig. 4A). As in the air temperatures, inter-annual oscillations were observed in the water temperatures from the *Chascomús* lake during the analyzed period. For instance, the mean water temperature increased on average at least 1.5°C between 1983 and 1985 (Fig. 4A).

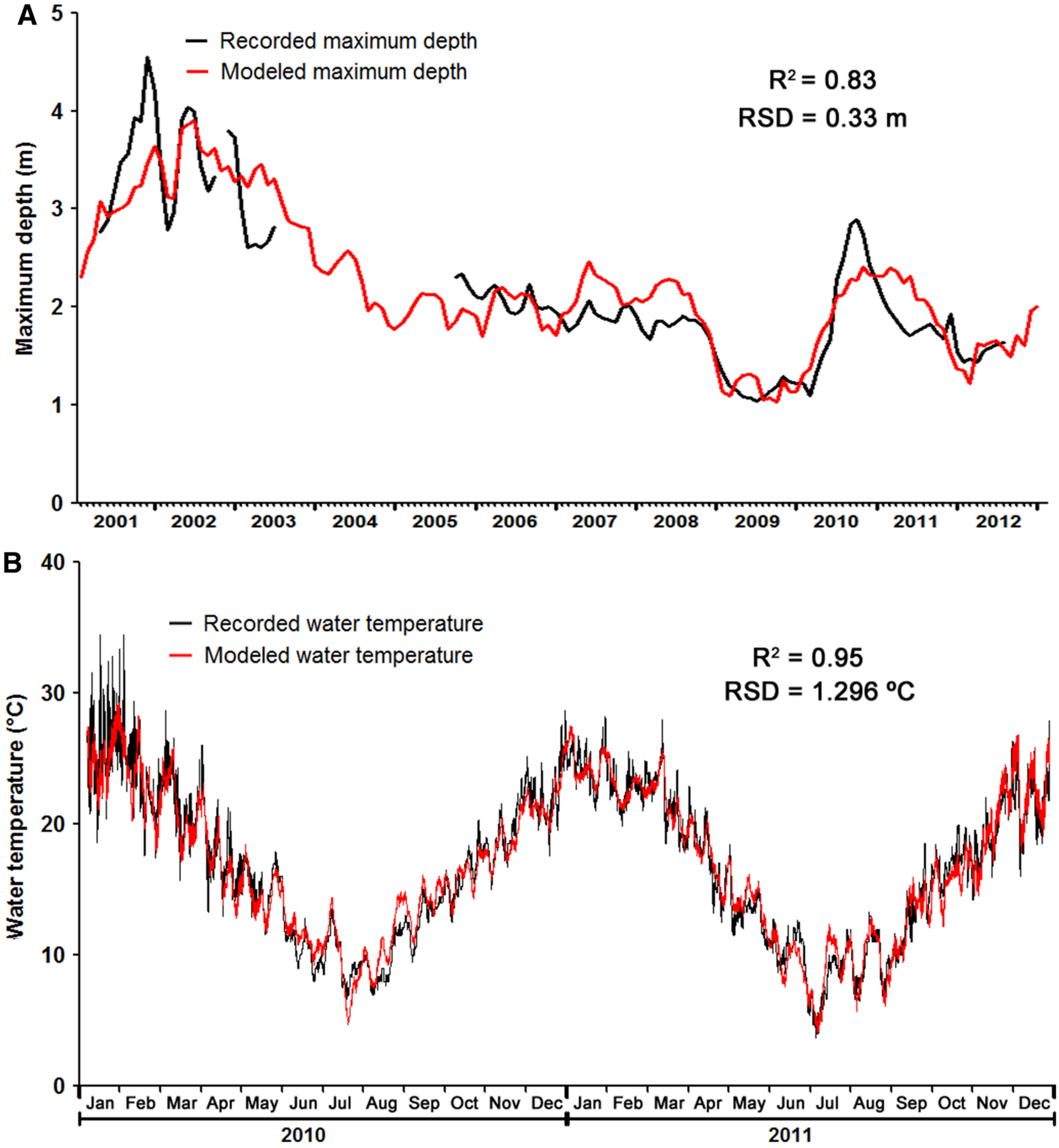

Fig. 2 Recorded and modeled data of the maximum depth from January 2001 to December 2012 (**A**) and the water temperature from January 2010 to January 2011 (**B**) in the *Chascomús* lake. The values of the coefficient of determination (R^2) and the residual standard deviation (RSD) for each model are shown in the figure

As it was observed for the air temperatures, the yearly variation rate in water temperatures was dependent on the season. The months between October and April (excepting December) showed significant rates of warming for all analyzed variables (daily maximum, minimum, and average temperatures). Also, significant rates of thermal increase were obtained in September for the case of the daily minimum and average temperatures. In contrast, no significant increases in temperature were observed between May and August, and even a negative variation rate was observed in July (Fig. 4B).

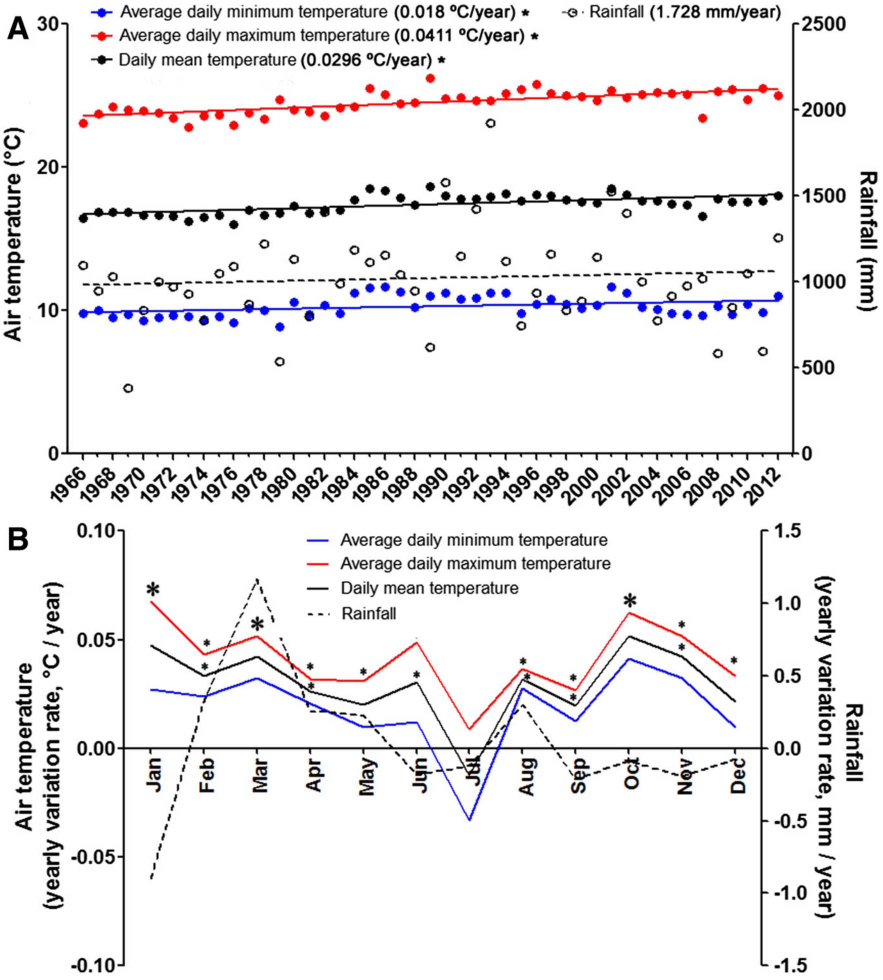

Fig. 3 Yearly variation trends in air temperature and rainfall in *Chascomús* City from January 1966 to January 2012. Data are shown considering the averages of each entire year (**A**) or of each month (**B**). The yearly rate of change for each variable is shown in *brackets* next to each corresponding legend. The statistically significant rates of changes (Fisher's test, $P < 0.05$) are indicated by *small asterisks* for each separately variable, and by *large asterisks* for all water temperatures

Variation trends in the end of pejerrey spawning season from *Chascomús* lake

The end of pejerrey spawning season modeled between 1966 and 2012 showed a negative yearly variation trend, with a statistically significant variation rate of −0.4 days/year. This last result showed that the end of pejerrey spawning season was ahead on average 19 days over the whole period of 47 years. According to the modeled data, the average end of pejerrey spawning season in *Chascomús* lake was on December 7. On the other hand, the earliest and latest end of the spawning was on November 9 and January 1, respectively (Fig. 5).

Discussion

This study demonstrated the existence of a tight association between the changes in climate (air temperature and rainfall), the water temperature on a typical Pampas shallow lake, and the reproductive phenology of an emblematic fish species from those water bodies. Several studies have evaluated and discussed possible effects of climate variability on aquatic ecosystem, including different effects on fish, as a consequence of changes in water temperature (Ficke et al., 2007; Mooij et al., 2008; Jeppesen et al., 2010; Pankhurst & Munday, 2011). However, few of this works reported a detailed analysis of the coupling existent between climate and water temperature. In this sense, the predictive model developed in this study predicts the daily water temperature fluctuations from the variations in air temperature and rainfall, and represents a valuable tool to explain and predict different ecological responses to the climatic variability.

The predictive model of water temperature developed in this study showed a comparable fit to those

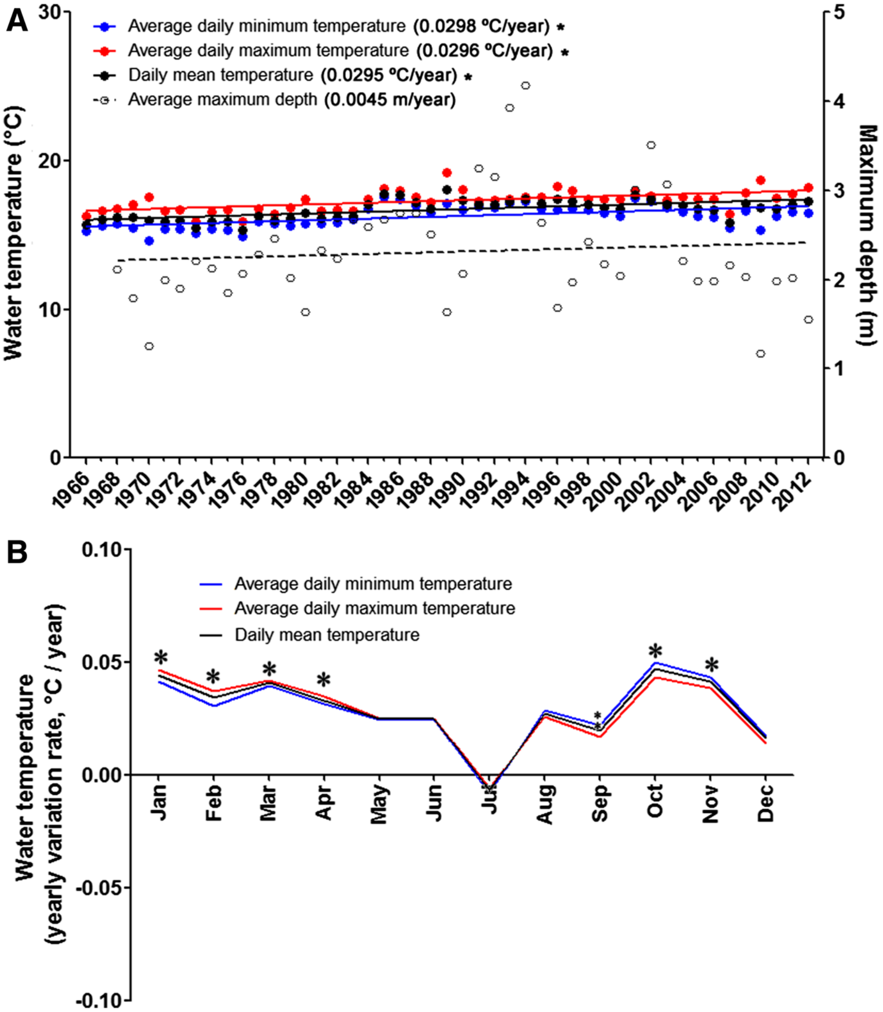

Fig. 4 Yearly variation trends in water temperatures and maximum depth in *Chascomús* lake from January 1966 to January 2012. Data are shown considering the averages of each entire year (**A**), or of each month for the case of the water temperatures (**B**). The yearly rate of change for each variable is shown in brackets next to each corresponding legend. The statistically significant rates of changes (Fisher's test, $P < 0.05$) are indicated by *small asterisks* for each separately variable, and by *large asterisks* for all water temperatures

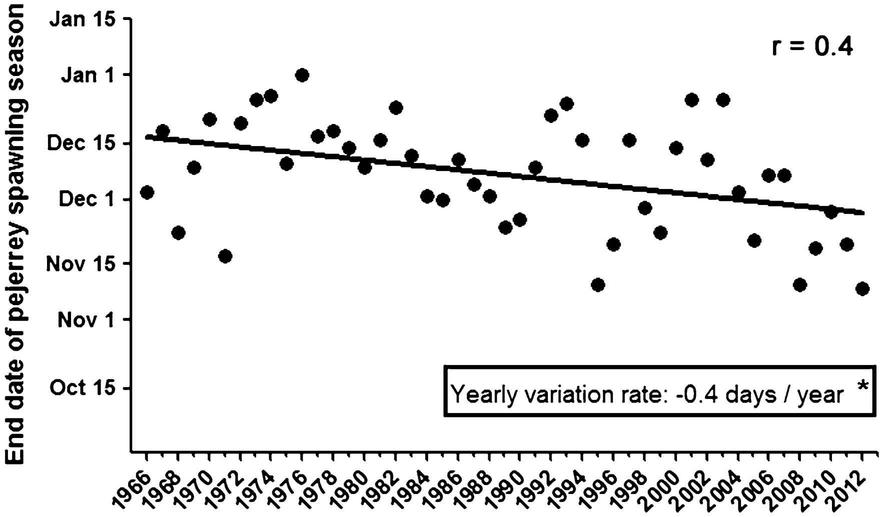

Fig. 5 Yearly variation trend of the end of pejerrey spawning season in *Chascomús* lake according to the water temperature conditions, from 1966 to 2012. The Pearson correlation coefficient (r) is shown in the figure. The *asterisk* indicates a statistically significant rate of change (Fisher's test, $P < 0.05$)

obtained by Mooij et al. (2008) in different shallow lakes from Netherlands with bathymetric features similar to those observed in *Chascomús* lake. However, the model developed by Mooij et al. (2008) predicts water temperature each 3 h and the present model each 20 min, allowing a better description of the daily thermal fluctuations. Moreover, another important feature of this model is the consideration of the change in thermal inertia according to the lake depth variation. It must be noted that the results obtained showed that the daily thermal variation rate in *Chascomús* lake depends on the lake depth, being able to increase up to six times with approximately 2 m of decrease in depth. Hence, the h and g parameters in this model (which describe the change in water temperature due to the air temperature and the radiation, respectively) were considered as inverse functions of the depth. Thus, the h and g values were lesser (higher thermal inertia) when the lake became deeper, and vice versa. In accordance with this, Mooij et al. (2008) observed that the estimated values for these parameters in deeper water bodies were lesser than those estimated in other shallower lakes. These results show that the temporal thermal inertia variation should be considered for evaluations of the impacts of environmental factors on temperature fluctuations in water bodies in which depth can change quickly and significantly, such as occurs in *Chascomús* lake. In this context, another important outcome of this study was the model developed for predicting the maximum depth in *Chascomús* lake from the local accumulated rainfalls, which can be a useful tool for different limnological studies.

Since water temperature in *Chascomús* lake has resulted highly dependent on air temperatures, it is expected a direct translation of the climate variability into the thermal change of the lake. Interestingly, this fact was already demonstrated for different shallow lakes in Netherlands (Mooij et al., 2008). It is worth to note that almost the same yearly warming rate (approximately 0.03°C/year) for the mean air temperature in *Chascomús* City was observed for the water temperatures (modeled data) in *Chascomús* lake. Hence, as consequence of the warming in *Chascomús* City, an average increase of 1.4°C was evident in *Chascomús* lake over the whole period of 47 years. Also, a significant increase of yearly average air temperature was reported in another Pampean city (Junín, Buenos Aires, Argentina), however, the value of warming rate observed (0.01°C/year, Barros et al., 2004) resulted lesser than that obtained in this study. It is important to note that the yearly increase in the air and water temperatures in this study resulted to be dependent on the season of year. In general, the months from the warmer seasons (spring, summer, and autumn) were associated to a significant increase in temperatures, whereas no evidence of warming (even with negative variation rates) was observed during winter. A similar seasonal pattern of thermal change between 1961 and 2012 was reported by the meteorological service of Argentina in Buenos Aires province. Interestingly, it was also demonstrated in De Bilt City (Netherland) that the yearly increase in temperature during 1961–2006 period was not equally spread over the season (Mooij et al., 2008). It must be noted that this last fact should be taken into account to evaluate possible phenological responses driven by the climate change, such as the possible shifts on fish reproductive cycle under the pressure of global warming.

Based on the predictions performed in this study, a shortening of 19 days (on average) in pejerrey spawning season was observed in *Chascomús* lake during the 1966–2012 period. This fact appears to have been associated to the significant increase in temperature observed during November. Note that the end of pejerrey spawning in *Chascomús* lake over the last modeled years occurred during this month, and in the case of the spring 2012, this fact was also demonstrated by evidences in situ (Elisio et al., 2012b). The yearly variation rate in water temperature showed the highest values during October (0.05°C/year), however no evidences of water temperature conditions impairing pejerrey spawning were observed during this month. In fact, the October averages of daily maximum temperature in *Chascomús* lake during the last five evaluated years were around 19°C, optimal temperature for pejerrey reproduction (Strüssmann, 1989; Toda et al., 1995; Miranda et al., 2006). However, if this yearly trend of thermal increase remains over the next years, a stronger shortening of the pejerrey spawning season could happen.

It must be noted that in some spring spawner fish, the occurrence of an earlier spawning (by an acceleration of gonad development) was predicted as a possible response to global warming (Hutchings & Myers, 1994; Nõges & Järvet, 2005; Gillet & Quétin, 2006; Newman et al., 2010; Zięba et al., 2010; Jansen & Gislason, 2011; Zucchetta et al., 2012; Lahnsteiner & Kletzl, 2012; Fincham et al., 2013). However, since no significant warming was observed during July and August (main period of pejerrey vitellogenesis) in *Chascomús* lake, the occurrence of an earlier spawning would be unexpected.

Furthermore, the yearly increase in water temperature observed during summer and beginning of autumn supports other suggested responses of pejerrey populations to global warming, such as sterility (Cornejo, 2003; Ito et al., 2008), shortening or overall disruption of the autumn spawning season, and skewed temperature-dependent sex determination (Strüssmann et al., 2010).

The yearly rate of increase in temperatures and the consequent effects on the pejerrey reproductive phenology observed in this study could have been driven in part by the global warming event (Barros et al., 2004; IPCC, 2007; Brander, 2010). However, it must be noted that the inter-annual oscillations in temperatures observed over the analyzed period could indicate also the influence of other climatic variability events, which would be interesting to asses in futures studies.

In conclusion, this study showed that a shortening in the pejerrey reproductive season could have happened in *Chascomús* lake over the 1966–2012 period as a direct consequence of the yearly increase in air temperature in *Chascomús* City. It must be noted that the reliability of such kind of ecological predictions depends largely on the methodology used (Parmesan, 2007). In this sense, the assumptions used in this study for modeling the of the end of pejerrey spawning season according to the water temperature conditions were based on physiological evidences demonstrated both in experimental conditions and in the wild, which represent an important advantage for this kind of studies (Pörtner & Farrell, 2008). It remains to be evaluated to what extent the findings predicted by this study occur in the pejerrey wild populations from the *Chascomús* lake, as well as from other Pampas shallow lakes.

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