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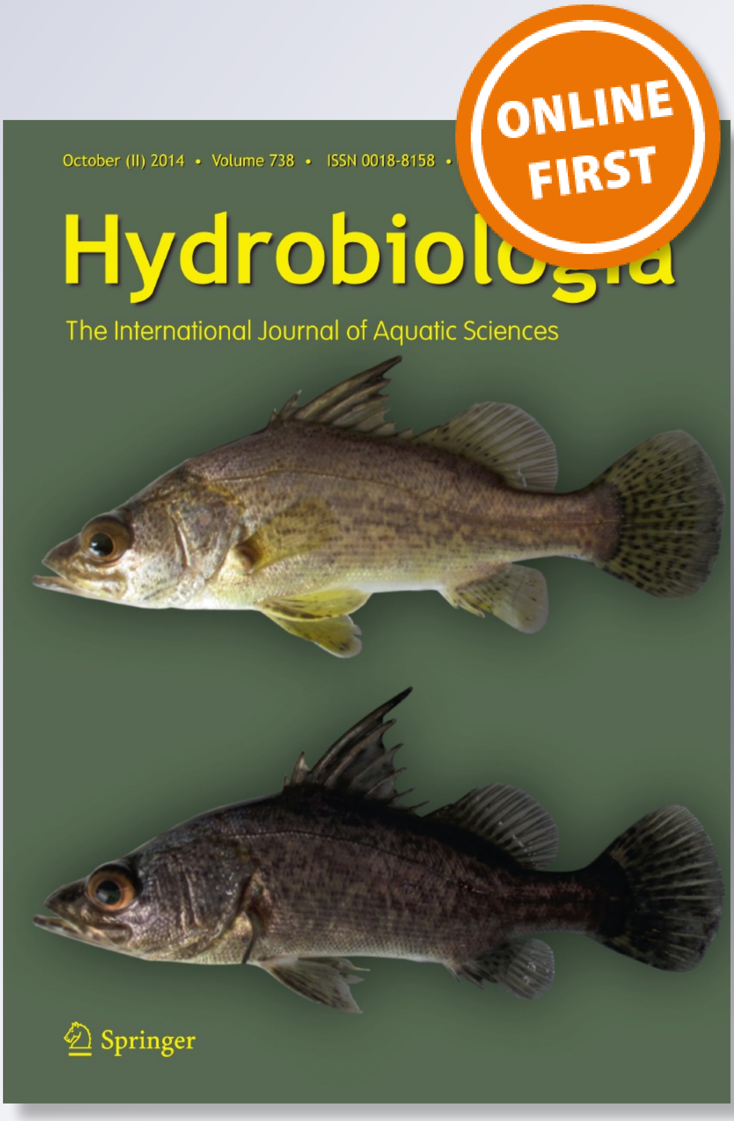

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ARGENTINE PAMPEAN SHALLOW LAKES

Diel patterns of total suspended solids, turbidity, and water transparency in a highly turbid, shallow lake (Laguna Chascomús, Argentina)

**Leonardo Lagomarsino · Nadia Diovisalvi ·
José Bustingorry · Roberto Escaray ·
Horacio E. Zagarese**

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Abstract The effects of external physical forcing variables (solar radiation and winds) on short-term dynamics of total suspended solids (TSS), Chlorophyll-*a* (Chl-*a*), turbidity levels, and water transparency were studied during 15 days in a highly turbid, shallow lake (Laguna Chascomús, Argentina). Water samples were taken three times per day (8, 14 and 20 h.). Solar radiation and wind velocity showed a repeatedly bell-shaped diurnal pattern, with significant higher values during morning and afternoon, respectively. TSS and turbidity displayed a general decreasing trend during the sampling period, while water transparency showed the opposite trend. Also Chl-*a* displayed a decreasing trend and was closely correlated to TSS levels. We assayed a first-order kinetics model to detrend the series, obtaining the rate of change during the night, morning, and afternoon. We observed higher values on afternoon compared to morning for TSS, Chl-*a*, and turbidity levels and the opposite pattern for water transparency. We conclude that this pattern may result from a combination of biological activity, as it took place after a period of intense photosynthetic activity, together with resuspension by winds during the afternoon, (windiest time of the day).

Keywords Shallow turbid lake · Physical forcing · Total suspended solids · Turbidity · Water transparency

Introduction

Shallow lakes are highly dynamic ecosystems. Shallow depth prevents stable thermal stratification and promotes the continuous mixing of the water column through wind-driven turbulence, which in turn translates into a closer interaction between water column and sediments. As a result, shallow lakes tend to display fast nutrient turnover, which increase nutrient availability to primary producers throughout the year (Scheffer, 1998).

There is substantial evidence that shallow lakes are particularly sensitive to changes to weather conditions (Adrian et al., 2009, and cites therein) and to human impacts (Genkai-Kato & Carpenter, 2005; Søndergaard et al., 2007). For instance, it is well known that these ecosystems respond quickly to changes in solar

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L. Lagomarsino (✉) · N. Diovisalvi · J. Bustingorry · R. Escaray · H. E. Zagarese
Instituto de Investigaciones Biotecnológicas-Instituto Tecnológico de Chascomús (IIB-INTECH), Universidad Nacional de San Martín (UNSAM) - Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET),
CC 164, (B7130IWA) Chascomús,
Provincia de Buenos Aires, Argentina
e-mail: lagomarsino@intech.gov.ar

radiation and air temperature. Furthermore, there is extensive evidence showing that changes in hydrological regimes not only affect water column depth and lake area, but also have relevant impacts on light climate, population dynamics, and trophic interactions (Coops et al., 2003; Nõges et al., 2003, 2010; Beklioglu et al., 2006). Sensitivity to weather variables and nutrient levels could explain the rapid shifts in biotic structure experienced by many shallow lakes (Bayley et al., 2007; Scheffer & Jeppesen, 2007).

Wind-driven turbulence is frequently considered a key factor in many shallow lakes, especially those lacking submerged aquatic vegetation (James et al., 2004). Even a low amount of turbulence may suffice to slow down the settling of phytoplankton cells and other particles. At higher wind speeds, the resulting turbulence may cause sediment resuspension, resulting in increased nutrient and seston concentrations, and consequently affecting primary production and growth rates, as well as the underwater light climate (Luettich et al., 1990; Hellström, 1991; Qin et al., 2004; Cózar et al., 2005; Pannard et al., 2007; Niemistö et al., 2008; Tammeorg et al., 2013).

Over the last few decades, a multiplicity of ecological models and theories has emerged, aimed at explaining the ecology and functioning of shallow lakes (Scheffer, 1993; Janse, 1997; Schippers et al., 2006; Van Nes et al., 2007). However, there are some regional (climate) and lake-specific (morphometry, particular trophic interactions, etc.) properties that difficult generalization and the extrapolation of factors that govern the functioning of these ecosystems.

Laguna Chascomús is a highly eutrophic and very turbid shallow lake. Its turbidity is mostly due to suspended material, with phytoplankton and unpigmented particulates contributing similarly to total light absorption (Pérez et al., 2011). On a seasonal time scale, primary production, the amount of suspended particulates, and water transparency display remarkable and predictable patterns in response to incident solar radiation and wind speed (Torremorell et al., 2007, 2009). Moreover, these variables display larger variability during summer, probably due to higher variability in solar radiation (Lagomarsino et al., 2011). Here, we investigate the lake responses on a daily timescale. Specifically, we test the hypothesis that suspended particulates and water transparency should exhibit daily and diel variability in response to solar radiation and wind speed. A detailed knowledge of the lake responses to variability in weather conditions would also be of great practical importance within the framework of our long-term monitoring of Laguna Chascomús.

Methods

Study site

Most Pampean lakes are highly eutrophic, due to high loads of nitrogen and phosphorus, resulting in high concentrations of chlorophyll-*a* (Quirós & Drago, 1999). The climate in this region is temperate, with mild winters and warm summers. Mean annual temperature varies between 13 and 16°C, and the annual average rainfall is around 900 mm (Iriondo & Drago, 2004). The region is characterized by large inter-annual variability alternating dry and wet periods (Laprida et al., 2009), which affects the water residence time of lakes.

Laguna Chascomús (35° 36′S 58° 02′W) has an area of 30.1 km^2 and a mean depth of 1.9 m. It is a highly eutrophic alkaline lake, permanently mixed due to the intensity and persistence of winds (Torremorell et al., 2007). Among the major dissolved ions, sodium (Na^+) and bicarbonate (HCO_3^-) are the most abundant (Miretzky et al., 2000). The lake is characterized by high primary production (Torremorell et al., 2009) and a rich and diverse phytoplankton community, mostly composed by Cyanobacteria colonies of small-cell *Aphanocapsa delicatissima*, co-occurring with filamentous Cyanobacteria (*i.e. Planktolyngbya contorta* and *Planktolyngbya limnetica*), small chlorococcales (*i.e. Monoraphidium spp*. and *Scendesmus spp*.), and the diatom *Synedra berolinensis*. In terms of biovolume, cyanobacteria contribute 50% to total phytoplankton biovolume, followed by Chlorophyceae and Bacillariophyceae (Llames et al., this issue).

Sampling and water quality measurements

Laguna Chascomús was sampled from 12 to 28 February 2008. Sampling was performed three times a day, i.e., at 8, 14, and 20 h. (Notice that local noon at this location is ~14 h Argentine official time). Subsurface water samples were collected at a central point (Z ~ 1.8 m) of the lake and immediately transported to the laboratory. Previous studies (Torremorell et al., 2007) have shown that the lake is permanently mixed, and that there is little variability between sampling sites (Torremorell et al., 2007). Measurements of temperature, pH (Orion pH meter), conductivity (Hach conductimeter), dissolved oxygen (DO) (YSI 5000 oximeter), turbidity (Hach turbidimeter), and Secchi disk depth were performed in situ. Water column depth was measured at a gaging site, and the value was used to estimate mean water depth using bathymetric maps (Dangavs et al., 1996).

Total suspended solids (TSS) were measured after filtration onto weighted precombusted GF/F filters, drying at 105°C to constant weight (APHA, 1992). The ash-free dry weight concentration (AFDW) was estimated as the difference between dry and combusted filtered seston (550°C for 2 h). Total phosphorus (TP, unfiltered water samples) and total dissolved phosphorus (TDP, from GF/F filtered water) were estimated after an acid digestion with potassium persulfate (120°C for 1 h). Soluble reactive phosphorus (SRP) was determined as molybdate reactive P according to standard analytical procedures (APHA, 1992). Particulate phosphorus (Ppart) was calculated as the difference between the two fractions (Ppart = TP-TDP). Nitrates (NO_3-N) were reduced to nitrites using a reduction cadmium column. In turn, nitrites (NO_2-N) were determined by diazotization (APHA, 1992). Ammonia (NH_4^+-N) was determined by the indophenol blue method (APHA, 1992). Total organic nitrogen (TON, unfiltered water) and total dissolved organic nitrogen (TDON, GF/F filtered water) were determined by Kjeldahl method (APHA, 1992). Total nitrogen (TN) was estimated as the sum of nitrites, nitrates and total organic nitrogen. Chlorophyll-*a* concentration (Chl-*a*) was estimated after extraction with methanol (Lopretto & Tell, 1995).

Physical parameters

Wind speed and direction and rainfall were recorded at 30-min intervals (the average and maxima) at a weather station (Davis Vantage Pro 2) located approximately 3 km from the sampling site. Incident solar radiation was obtained using an IL-1700 radiometer (International Light) equipped with PAR (400–700 nm) and UVR (295–380 nm) sensors.

Statistical analyses

The series of water column variables often showed well-defined trends (either to increase or decrease). As these trends could preclude one from detecting differences between sampling times, we decide to detrend the series by subtracting the previous value for each observation. In addition, given that the series was not evenly spaced in time, the resulting difference was divided by the amount of time elapsed between samplings, as follows:

$$\Delta X = (X_t - X_{t-1}) / \Delta t,$$

where X stands for the variable of interest, X_t and X_{t-1} are the values of X measured at times t and t−1, and Δt is the time elapsed between two successive measurements. Physically, ΔX may be interpreted as the rate of change of variable X, assuming that the process responsible for the variation in X has a zero-order kinetics. We also assayed transforming the series under the assumption of a first-order kinetics model (i.e., by taking the natural log of X), but given that this procedure resulted in qualitatively identical results, only the first analysis is shown in the figures. Hereinafter, we refer to the ΔX corresponding to 8, 14, and 20 h as the rate of change occurred during the night (from 20 to 8 h), the morning (from 8 to 14), and the afternoon (from 14 to 20). Differences raw (X) or detrended (ΔX) variables were assessed between sampling hours (8, 14, and 20 h) or day periods (night, morning, afternoon) using one way analysis of variance (ANOVA), followed by post-hoc comparisons (Holm–Sidak method). Before each analysis, Kolmogorov–Smirnov test was run in order to check data for normality. Whenever the assumption of normality did not hold, we used non-parametric Kruskal–Wallis ANOVA on Ranks, followed by a posteriori Tukey Test. Pearson correlations were used to investigate the relationship between physical and chemical variables. Recursive partitioning analysis was utilized to sort the dataset into either low or high TP and TDP groups (Hessen, 2006). A paired *t* test model was employed to compare the significance of the differences between the two groups of TP and TDP data. Whenever the assumptions of *t* test were not met, we performed a non-parametric Mann–Whitney Rank Sum test.

Results

Weather conditions

Incident solar radiation showed the typical daily variability in accordance to the period of the year

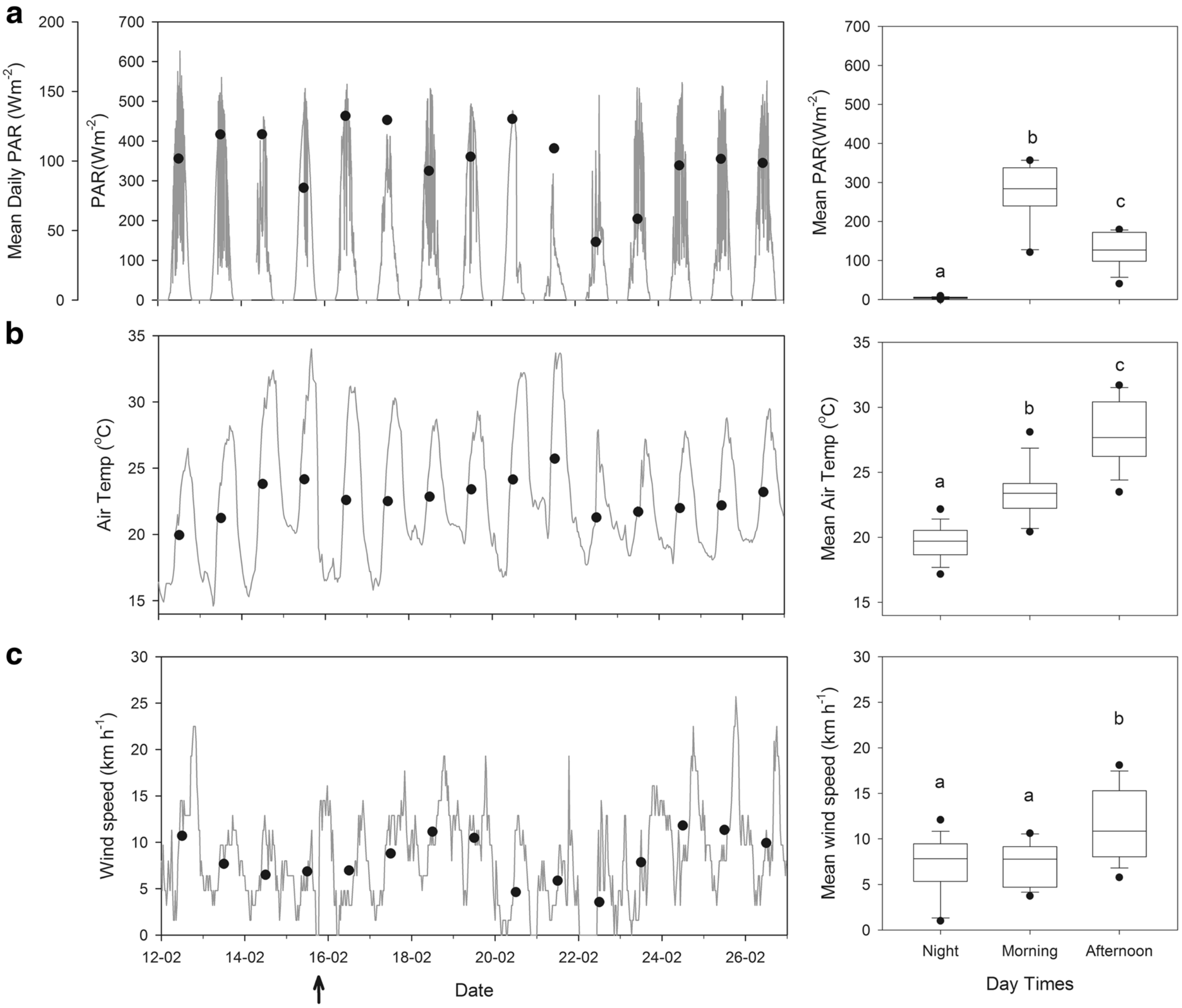


Fig. 1 *Left panels*: time evolution during the study period of: **a** PAR irradiance, **b** air temperature, and **c** wind speed. *Filled circles* represent the mean daily value of each variable. The *arrow* indicates the storm event. *Right panels*: Box plots of each variable for the three day times (i.e., treatments): night (20–8 h), morning (8–14 h), and afternoon (14–20 h). Treatments labeled with different letters are significantly different

(Fig. 1a). Mean daily values of solar radiation ranged from 42 to 132 Wm^{-2}. Considering the average solar radiation between sampling times, the differences were significant (ANOVA, $P < 0.001$) (Fig. 1a, right panel). Air temperature showed a predictable diurnal pattern, with values ranging from 15°C to values close to 30°C in the afternoon (ANOVA, $P < 0.001$) (Fig. 1b, right panel). The study was performed during a period of relatively calm weather. The 30-min averaged wind speed ranged from 0 to 25.7 km h^{-1} (Fig. 1c), averaging 8.3 km h^{-1} (± 5.0 km h^{-1} SD). Total calm (0 km h^{-1}) was observed only in 1.6% of the observations, whereas 64.6% of the dataset corresponded to winds between 1 and 10 km h^{-1}, 31.4% to winds between 10 and 20 km h^{-1}, and 2.4% to winds between 20 and 25.7 km h^{-1}. The relatively calm weather conditions were interrupted by a brief storm (20 h on February 15). Maximum and 30-min averaged wind speeds during this event were 54.7 and 14.5 km h^{-1}, respectively. During the 15 days of study, wind speed showed a recurrent diurnal pattern, with significant higher values in the afternoon (Fig. 1c, right panel).

Physical and chemical conditions

Water temperature (T) ranged from 22 to 29°C, with higher values in the middle of the study period (Fig. 2a). The lowest values of T were observed at 8 h, while for the detrended variable (ΔT), the highest values corresponded to the morning (T ANOVA, $P < 0.05$; ΔT ANOVA, $P < 0.05$) (Fig. 2a, middle and right panel, respectively). The DO concentration displayed daily variability but without a definite trend over the study period (Fig. 2b). Measured values of DO ranged from 7.0 to 13.6 mg l^{-1} (Table 1). The lowest DO concentrations were observed at 8 h, while the greatest rate of change (ΔDO) occurred during the morning (Fig. 2b, middle and right panel, respectively). The pH was typically alkaline, ranging from 8.3 to 9.2, and did not exhibit a definite trend during the study (Fig. 2c). The lowest pH values were observed at 8 h, while the larger variation (ΔpH) took place during the morning (pH ANOVA, $P < 0.05$; Δ pH ANOVA, $P < 0.05$) (Fig. 2c). Conductivity was high and remained relatively stable over time (mean 2.44 ± 0.10 mS cm^{-1}) (Table 1).

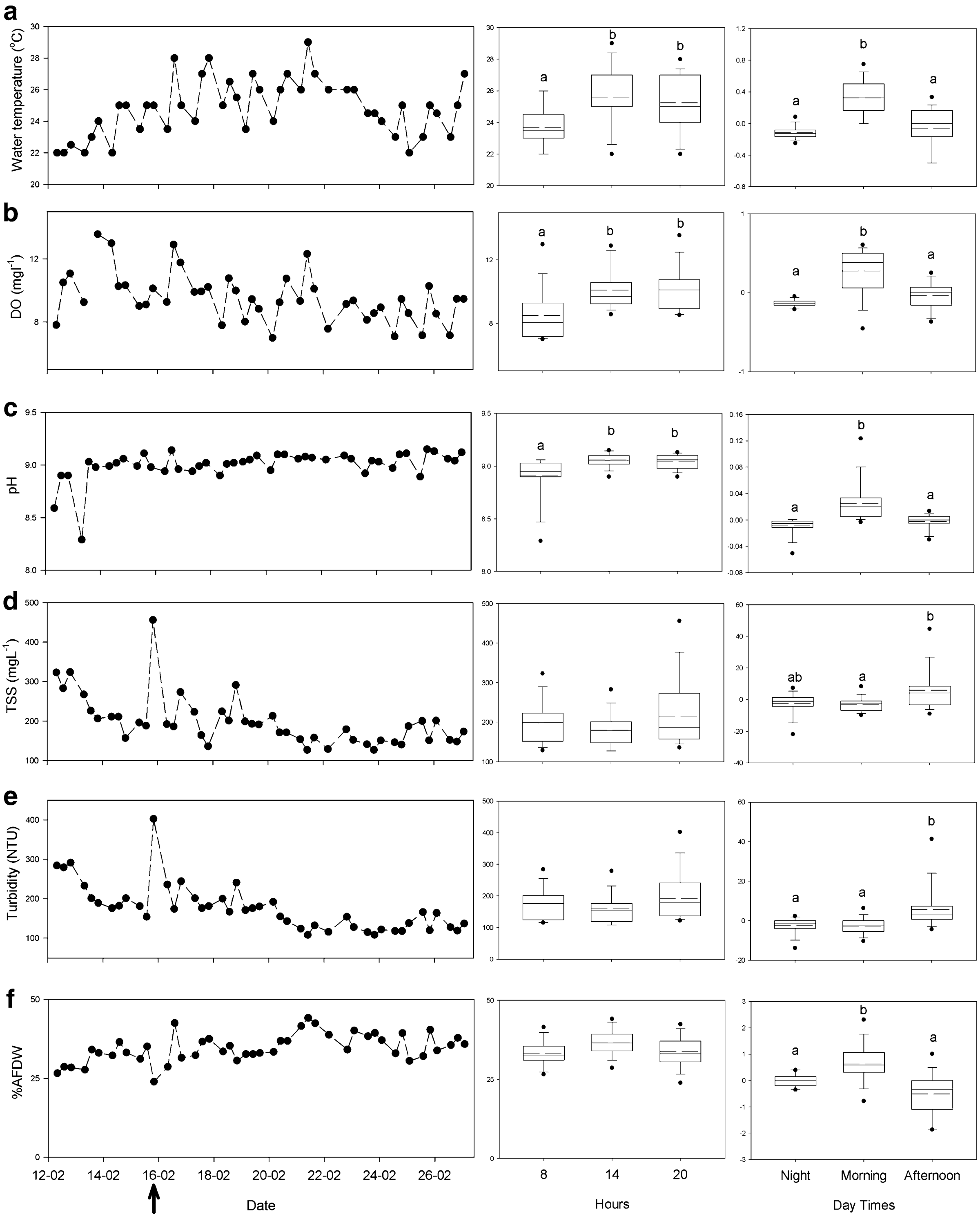
Total suspended solids and nephelometric turbidity displayed an overall decreasing trend during the sampling period ($R^2 = 0.33$, $n = 45$, $P < 0.001$; $R^2 = 0.49$, $n = 45$, $P < 0.001$, respectively, when regressed vs time) (Fig. 2d, e). Mean values of TSS and nephelometric turbidity were 197.6 mg l^{-1} (± 63.2 SD) and 176 NTU (± 59 SD), respectively (Table 1). Both variables were highly correlated ($R = 0.89$, $n = 45$, $P < 0.001$). No significant difference in TSS was observed between sampling times (ANOVA, $P > 0.05$). Nevertheless after detrending the series, significant differences were observed, i.e., the rate of change was higher during the afternoon than in the morning (ΔTSS ANOVA, $P < 0.05$) (Fig. 2d, middle and right panel, respectively). Similarly, there were no significant differences in measured values of turbidity between sampling times (ANOVA, $P > 0.05$), but the detrended series showed higher values during the afternoon (Δ Turbidity ANOVA, $P < 0.05$) (Fig. 2e). The percentage of volatile components of seston (%AFDW) showed an increasing trend during the study period ($R^2 = 0.24$, $n = 45$, $P < 0.001$ when regressed vs. time) (Fig. 2f). Values of %AFDW ranged from 24 to 44% of the total dry weight of seston. The %AFDW did not show significant differences between sampling times (Fig. 2f, middle panel), but the detrended variable (Δ %AFDW) presented a clear daily pattern, with higher values corresponding to morning time (Δ %AFDW ANOVA, $P < 0.05$) (Fig. 2f, right panel).

Chl-*a* concentrations showed a slight decreasing trend with time ($R^2 = 0.18$, $n = 45$, $P < 0.001$) (Fig. 3a). Chl-*a* levels did not display significant differences between sampling times (Fig. 3a, middle panel). But, when considering the detrended series, significant higher values were observed in the afternoon as compared to morning values (ΔChl-*a* ANOVA, $P < 0.05$) (Fig. 3a, right panel). Chl-*a* concentration was positively related to TSS ($R = 0.50$, $n = 44$, $P < 0.001$) and turbidity ($R = 0.57$, $n = 44$, $P < 0.001$).

Secchi disk depth was low (11.3 ± 1.8 cm) and showed an increasing trend toward the end of the study, reaching values of 16 cm ($R^2 = 0.25$, $n = 45$, $P < 0.001$) (Fig. 3b). No significant differences between sampling times were observed when considering the untransformed series. However, in agreement with the observed patterns in ΔTSS and Δturbidity, ΔSecchi readings were significant lower in the afternoon (ΔSecchi ANOVA, $P < 0.05$) (Fig. 3b right panel). Secchi disk readings were negatively correlated with TSS ($R = 0.44$, $n = 45$, $P < 0.05$) and nephelometric turbidity ($R = 0.46$, $n = 45$, $P < 0.001$).

Total phosphorus concentrations were varied haphazardly during most of the study period (with pulses in both Ppart and TDP fractions, see below) (Fig. 3c–e). Overall, TP values averaged 629 ± 165 μg P l^{-1} and ranged from 404 to 1,105 μg P l^{-1} (Table 1). The particulate fraction contributed most (78%) to total TP, while the dissolved fraction (TDP) accounted for the remaining 22%. Within the latter fraction, SRP was always very low, representing only about 1.4% of TP. TP, Ppart, and TDP concentrations did not differ between sampling times, and neither did the detrended series ΔTP, ΔPpart, and ΔTDP (Fig. 3c–e). Also, SRP values did not show differences between sampling times. Ppart concentrations were correlated with TSS values ($R = 0.60$, $n = 45$, $P < 0.001$).

TON concentrations were also high, with values varying from 1,515 to 5,586 μg N l^{-1} (Table 1). TON showed fluctuations without a clear pattern during the 15 days of sampling, TDON being the main fraction (~66%). Nitrate concentrations (11 ± 13 μg N l^{-1}) showed several peaks during the 15 days of study; one of them occurring during the pulse of TDP. Nitrite (4 ± 9 μg N l^{-1}) and ammonia (14 ± 12 μg N l^{-1})


a
Water temperature (°C)
20
22
24
26
28
30
a
b
b
-0.8
-0.4
0.0
0.4
0.8
1.2
a
b
a
b
DO (mgl-1)
8
12
a
b
b
-1
0
1
a
b
a
c
pH
8.0
8.5
9.0
9.5
a
b
b
-0.08
-0.04
0.00
0.04
0.08
0.12
0.16
a
b
a
d
TSS (mgL-1)
100
200
300
400
500
-40
-20
0
20
40
60
ab
a
b
e
Turbidity (NTU)
100
200
300
400
0
500
-20
0
20
40
60
a
a
b
f
%AFDW
0
25
50
-3
-2
-1
0
1
2
3
a
b
a
12-02
14-02
16-02
18-02
20-02
22-02
24-02
26-02
Date
8
14
20
Hours
Night
Morning
Afternoon
Day Times

◀**Fig. 2** *Left panels*: time evolution during the study period of: **a** water temperature, **b** dissolved oxygen (DO), **c** pH, **d** total suspended solids (TSS), **e** turbidity, and **f** percentage of ash-free dry weigh (%AFDW). The *arrow* indicates the storm event. *Middle panels*: Box plots of each variable versus sampling times (8, 14, and 20 h). *Right panels*: Box plots of each detrended variable (see text) versus day times (night, morning, afternoon). Treatments labeled with different letters are significantly different

Table 1 Mean values and range of main physical, chemical, and biological parameters, measured during the study period

Physical and chemical parameters	Mean	Range
Water column depth (m)	1.18	1.16–1.22
Temperature (°C)	25	22–29
DO (mg l^{-1})	9.6	7.0–13.6
pH	9.0	8.3–9.2
Conductivity (mS cm^{-1})	2.4	2.2–2.9
Secchi Disk (cm)	11	8–16
TSS (mg l^{-1})	197.6	127.0–456.0
AFDW (mg l^{-1})	66.2	48.0–109.0
%AFDW	35	24–44
Turbidity (NTU)	176	108–402
TP (µg P l^{-1})	629	404–1,105
Ppart (µg P l^{-1})	476	288–641
TDP (µg P l^{-1})	153	24–617
SRP (µg P l^{-1})	10	ND-35
TN (µg N l^{-1})	2,680	1,521–5,591
TON (µg N l^{-1})	2,665	1,515–5,586
TDON (µg N l^{-1})	1,625	650–2,736
N-NO3- (µg N l^{-1})	11	ND-52
N-NO2- (µg N l^{-1})	4	ND-51
N-NH4 + (µg N l^{-1})	14	ND-56
Chl-*a* (µg l^{-1})	309	168–470

concentrations were variable, showing no clear trends over the 15 days. TN and the dissolved inorganic forms (NO_3-N, NO_2-N and NH_4^+-N) did not show any clear daily patterns.

As mentioned above, a storm occurred around 20 h on February 15. The passage of a cold front produced a sudden decrease in air temperature, which was coincident with the observed maximum instantaneous wind speed (54.7 km h^{-1}). This storm produced the only precipitation event (35.4 mm) registered during the study, causing an increase of the lake depth of similar magnitude (i.e., roughly 3 cm, from 1.65 to 1.68 m).

A sudden increase in TSS and turbidity was observed on February 15, which was coincident with the storm aforementioned (see Fig. 2d & e). TSS increased from about 188 mg l^{-1} (recorded at 14 h) to 456 mg l^{-1} (recorded at 20 h). However, by the next morning, the TSS had dropped back to values (192 mg l^{-1}) similar to those recorded before the storm. A similar trend was observed for the ash-free dry weight (AFDW) fraction, as both variables were strongly correlated ($R = 0.86$, $n = 45$, $P < 0.001$) (not shown). Both variables showed increases of almost two fold, being lower for the AFDW fraction (from 66 to 109 mg l^{-1} = 1.7 fold) than for TSS (188 to 456 mg l^{-1} = 2.4 fold), resulting in the lowest %AFDW (24%) recorded during the study period.

Total phosphorus also was increased after the storm on February 15 (from 404 to 697 µg P l^{-1} = 1.7 fold). The immediate increase in TP was almost entirely due to a 1.9 fold increase in the particulate fraction, while TDP and SRP remained momentarily unchanged (Fig. 3c–e, left panels). However, a delayed, more pronounced (up to ~1,000 µg l^{-1}) increase in TP was recorded on February 16. This delayed increase in TP was almost entirely due to TDP, which raised from about 76 to 432 µg P l^{-1}, i.e., 5.7 fold (Fig. 3e, left panels). This pulse of TDP lasted for about two days, and after that, all phosphorus fractions returned to values similar to those recorded before the storm. TP and TDP values during the storm event were significantly different from the rest of the dataset (TP, *t* test $P < 0.001$; TDP, Mann–Whitney rank sum test, $P < 0.001$).

Discussion

Previous studies of Laguna Chascomús demonstrated that incident solar radiation strongly affects the dynamics of seston (TSS), transparency, and particulate phosphorus (Ppart) by controlling the amount of radiant energy available to the plankton community (Torremorell et al., 2009; Lagomarsino et al., 2011). On a seasonal scale, the concentration of TSS closely tracks the sine wave pattern of PAR irradiance, and as a result, the pattern of transparency mirrors that of irradiance (Torremorell et al., 2007; Pérez et al., 2011). On a shorter time scale (weeks), we were able to reproduce these patterns in mesocosm experiments in which the incident solar radiation was manipulated using different

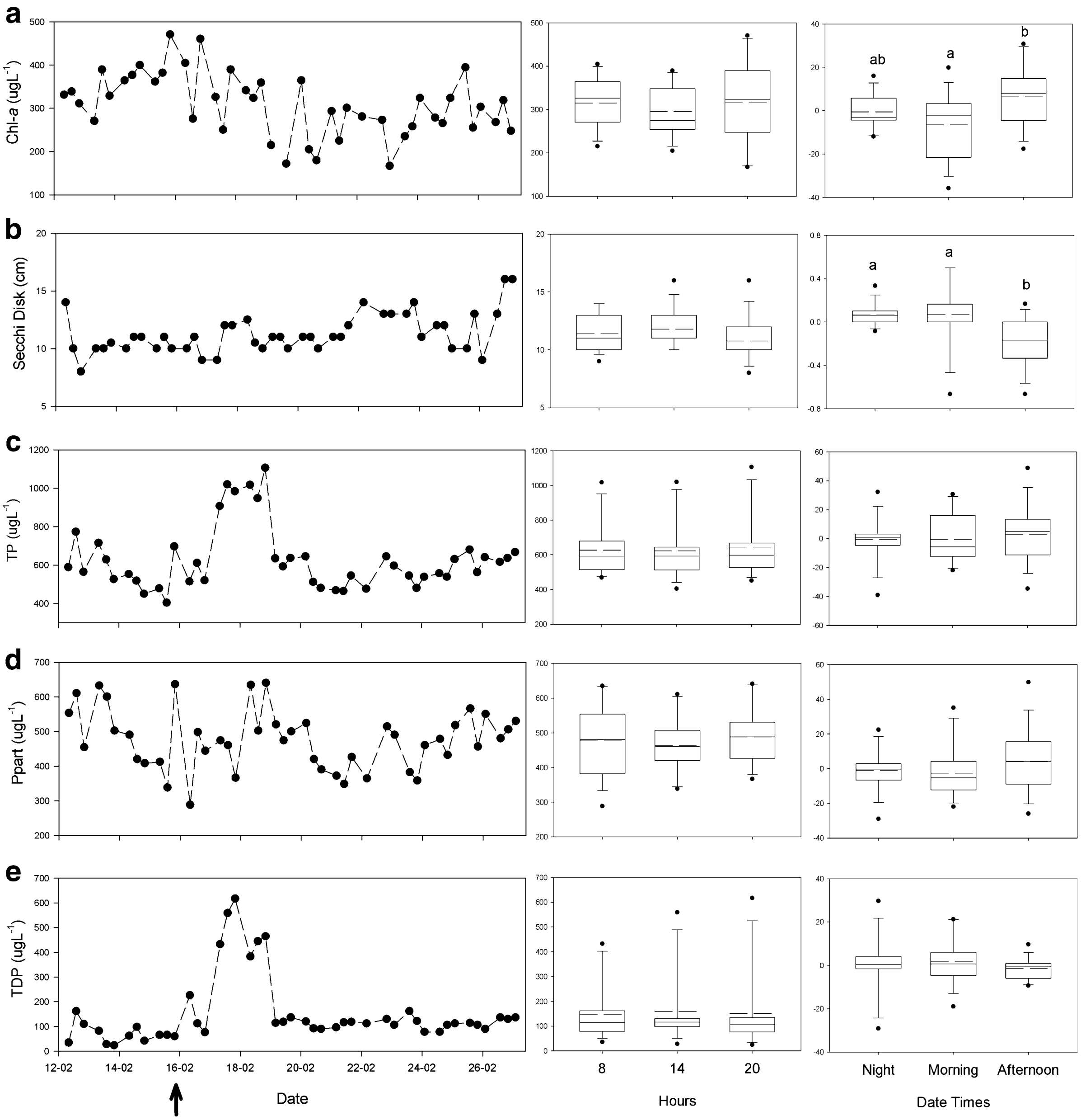


Fig. 3 *Left panels*: time evolution during the study period of: **a** Chlorophyll-*a* (Chl-*a*), **b** secchi disk, **c** total phosphorus (TP), **d** particulate phosphorus (Ppart), and **e** total dissolved phosphorus (TDP). The *arrow* indicates the storm event. *Middle panels*: Box plots of each variable versus sampling times (8, 14, 20 h). *Right panels*: Box plots of each detrended variable (see text) versus day times (night, morning, afternoon). Treatments labeled with different letters are significantly different

degrees of shading (Llames et al., 2009). These studies, however, were based on analysis of data collected weekly or every other week and therefore were unsuitable for detecting daily variability.

In this study, we found that the typical daily bell-shaped pattern of incident irradiance drove the daily patterns of air temperature and wind speed. This daily periodicity in weather variables had several correlates in lake water variables. The untransformed series of water temperature, DO, and pH displayed significant lower values at 8 h. Moreover, the detrended series showed significant higher values during the morning.

As mentioned in the M&M section, the values of the detrended series may be interpreted as the rate of change of the variable of interest. These results suggest that the lowest values of water temperature, DO, and pH observed at 8 h are the result of relatively slow decreases during the night. These trends are relatively more rapidly reverted during the morning, whereas during the afternoon, there are virtually no changes.

The remaining lake water variables did not exhibit significant differences between sampling times when considering the untransformed data series. In most cases, however, we observed that the series were not stationary (i.e., they had a significant trend, either increasing or decreasing, with time), which could preclude the detection of diel patterns. By detrending the series, we were able to detect differences (indicative of daily patterns) in ΔTSS, Δ turbidity, and Δ chlorophyll-*a* (higher during the afternoon), Δ %AFDW (higher during the morning), and ΔSecchi (lower during afternoon).

Laguna Chascomús is a highly productive lake, with values of phytoplankton primary production close to 17 g C m^{-2} day^{-1} in late spring and early summer (Torremorell et al., 2009). Here, we found that the variability in TSS was closely correlated to Chl-*a* levels ($P < 0.001$). Both variables were characterized by the presence of daily patterns, i.e., their rates of change (ΔX) were higher during the afternoon. This pattern may be partly due to intense photosynthesis activity, which may be inferred from the higher Δ DO and Δ pH observed during the morning (and the lower DO and pH values during the night) and partly due by resuspension by winds during the afternoon which was the windiest time of the day. The observed pattern in Δ %AFDW also suggests the interactive effects of the incident radiation and wind. The rapid increase in %AFDW (i.e., higher Δ %AFDW) during the morning may indicate the accumulation of organic material because of photosynthesis, while the subsequent decrease (during the afternoon) is compatible with the resuspension of inorganic particles during the afternoon. The analysis of the wind event provides support for this interpretation. During this event, the increase in organic matter was 43 mg l^{-1}, whereas the increase in the ash fraction was 225 mg l^{-1}.

The high levels of TSS were translated in low Secchi depth during the study period. Water transparency was also related to Chl-*a* levels, but the correlation was weak ($R = 0.33$, $P < 0.05$). This result agrees with previous reporting that, in Laguna Chascomús, changes in water transparency are only weakly related to algal particles, being mostly controlled by a mixture of particles of different natures (autotrophic, heterotrophic, and detrital) (Pérez et al., 2011). The variability in TSS was also reflected in turbidity levels. Considering the whole dataset, we found that differences in TSS explained 89% of the variation in turbidity. During most of the time (11 out of 15 days), turbidity levels showed increases from morning to afternoon. These increases also could be related to the observed patterns in Chl-*a*, as both variables were closely related ($R = 0.57$, $P < 0.001$).

During the 15 days of this study, the values of total phosphorus were consistently high and generally dominated by the particulate fraction, which on average accounted for about 78% of the total phosphorus pool. These findings are in agreement with the available data from previous years, indicating that most part of the water column phosphorus was associated with particulates (Lagomarsino et al., 2011). Although both TP and Ppart showed an important temporal variation over the study period, we found no clear evidences of daily patterns. This contrasts with reports from other shallow lakes. For example, Havens et al. (2007) reported diurnal changes in TP associated with afternoon winds in Lake Okeechobee during summertime. Also, Shinohara & Isobe (2010) documented closely fluctuations in suspended solids and Ppart ($R = 0.96$) with increasing wind speeds during daytime. In Laguna Chascomús, variations in TSS concentration were positively related with Ppart, but in comparison with Shinohara & Isobe (2010), the correlation was weak ($R = 0.6$). This could partly explain the lack of daily patterns in Ppart, associated with the higher TSS values and the higher wind speeds in the afternoon.

The relatively calm weather conditions prevailing during the best part of the study were briefly interrupted by a storm on the evening February 15 that lasted until about 4 a.m. of the following day. Laguna Chascomús responded to this short storm in several ways. First, right after the storm, the lake displayed a sudden increase in TSS and turbidity, pointing out to sediment resuspension by wind-driven turbulence. The amount of the mobilized material from the sediments to the water column was quite high ($\sim$268 mg l^{-1}) but comparable to the values of resuspended material reported for other shallow lakes worldwide (Kristensen et al., 1992; Zhu et al., 2005). This increase in TSS and turbidity was a short-lived perturbation, as both variables returned to pre-storm values within less than one day. It is important to note that wind speeds similar to that recorded during the storm event (~50 km h^{-1}) are infrequent in the study area, occurring less than 40 times per year.

Other effects produced by the storm were the increase in water column depth and the increase in phosphorus concentrations. At 20 h, February 15, soon after the wind started to blow, a modest peak in Ppart was recorded. Although the measured concentration of Ppart was comparable to other values measured during the study, the Δ Ppart observed at this time was the highest recorded during the study period. TDP and SRP fractions did not show increases during the storm event. In contrast, several authors have reported large internal inputs of these dissolved fractions (mainly SRP) to the overlying water column under similar disturbances (Søndergaard et al., 1992; Zhu et al., 2005). The high phytoplankton productivity (Torremorell et al., 2009) together with the high amounts of calcium carbonate particles (Conzonno, 1991; Torremorell et al., 2007) commonly recorded in this lake suggests a relative high turnover rate for SRP, due either to a rapid algal uptake or to adsorption onto suspended calcium carbonate particulates (Murphy et al., 1983) which may be expected at the alkaline pH values typical of the lake.

More significantly, however, the delayed increase in total phosphorus was recorded from 8 h February 17 to 20 h February 18. During this period, total phosphorus concentration was on average ~996 μg P l^{-1}, as compared to pre- and post-peak values that averaged ~573 μg P l^{-1}. This increase in TP was primarily (~90%) due to increased TDP concentration: ~616 versus 102 μg P l^{-1}, and only secondarily (~10) to the particulate fraction ~634 versus 499 μg P l^{-1}. While the phosphorus pulse lasted, the TP concentration remained higher than 900 μg P l^{-1}, as compared to other times, on which it never exceeded 800 μg P l^{-1}. Similarly, TDP remained higher than 380 μg P l^{-1}, as compared to the rest of the study when it never exceeded 230 μg P l^{-1}. The source and mechanism responsible for the increase in phosphorus concentration recorded after the storm are not obvious. Water inputs from the watershed seem unlikely, given that the inflow streams were dry during the study period. In any event, this pulse of dissolved P resulted unstable, and both total and dissolved P concentrations returned to pre-storm values within a couple of days.

Lake Chascomús is a complex turbid system with a large amount of TSS, Chlorophyll-*a*, and turbidity levels. As mentioned above, these variables exhibit seasonal trends in response to weather variables that could partly mask daily patterns. Here, we noticed that TSS and its %AFDW, turbidity levels, Chl-*a*, and water transparency exhibit daily patterns associated with daily patterns of incident solar radiation and afternoon winds speeds.

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References

Adrian, R., C. Reilly & H. Zagarese, 2009. Lakes as sentinels of climate change. Limnology and Oceanography 54: 2283–2297.

APHA, 1992. Standard Methods for the Examination of Water and Wastewater, 18th ed. American Public Health Association, Washington DC.

Bayley, S. E., I. F. Creed, G. Z. Sass & A. S. Wong, 2007. Frequent regime shifts in trophic states in shallow lakes on the Boreal Plain: alternative ''unstable'' states? Journal Limnology and Oceanography 52: 2002–2012.

Beklioglu, M., G. Altinaya & C. O. Tan, 2006. Water level control over submerged macrophyte development in five shallow lakes of Mediterranean Turkey. Archiv für Hydrobiologie 166: 535–556.

Conzonno, V. H., 1991. Determination of seston alkalinity in natural waters. Hydrobiologia 222: 85–87.

Coops, H., M. Beklioglu & T. L. Crisman, 2003. The role of water-level fluctuations in shallow lake ecosystems – workshop conclusions. Hydrobiologia 506–509: 23–27.

Cózar, A., J. A. Gálvez, V. Hull, C. M. García & S. A. Loiselle, 2005. Sediment resuspension by wind in a shallow lake of Esteros del Iberá (Argentina): a model based on turbidimetry. Ecological Modelling 186: 63–76.

Dangavs, N. V., A. M. Blasi & D. O. Merlo, 1996. Descripción sistemática de los parámetros morfométricos considerados en las lagunas pampásicas. Limnobios 1: 35–39.

Genkai-Kato, M. & S. R. Carpenter, 2005. Eutrophication due to phosphorus recycling in relation to lake morphometry, temperature, and macrophytes. Ecology 86: 210–219.

Havens, K. E., K. R. Jin, N. Iricanin & R. T. James, 2007. Phosphorus dynamics at multiple time scales in the pelagic zone of a large shallow lake in Florida, USA. Hydrobiologia 581: 25–42.

Hellström, T., 1991. The effect of resuspension on algal production in a shallow lake. Hydrobiologia 213: 183–190.

Hessen, D. O., 2006. Determinants of seston C:P-ratio in lakes. Freshwater Biology 51: 1560–1569.

Iriondo, M. H. & E. C. Drago, 2004. The headwater hydrographic characteristics of large plains: the Pampa case. Ecohydrology and Hydrobiology 4: 7–16.

James, W. F., E. P. Best & J. W. Barko, 2004. Sediment resuspension and light attenuation in Peoria Lake: can macrophytes improve water quality in this shallow system? Hydrobiologia 515: 193–201.

Janse, J. H., 1997. A model of nutrient dynamics in shallow lakes in relation to multiple stable states. Hydrobiologia 342(343): 1–8.

Kristensen, P., M. Søndergaard & E. Jeppesen, 1992. Resuspension in a shallow hypertrophic lake. Hydrobiologia 228: 101–109.

Lagomarsino, L., G. Pérez, R. Escaray, J. Bustingorry & H. Zagarese, 2011. Weather variables as drivers of seasonal phosphorus dynamics in a shallow hypertrophic lake (Laguna Chascomús, Argentina). Fundamental and Applied Limnology 178: 191–201.

Laprida, C., M. J. Orgeira & N. García Chapori, 2009. El registro de la pequeña edad de hielo en lagunas pampeanas. Revista de la Asociación Geológica Argentina 65: 603–611.

Lopretto, E. & G. Tell, 1995. Ecosistemas de aguas continentales. Metodologías para su uso. Tomo I. Ediciones Sur, La Plata.

Luettich, R. A., D. R. Harleman & L. Somlyody, 1990. Dynamic behavior of suspended sediment concentrations in a shallow lake perturbed by episodic wind events. Limnology and Oceanography 35: 1050–1067.

Llames, M. E., L. Lagomarsino, N. Diovisalvi, P. Fermani, A. M. Torremorell, G. Pérez, F. Unrein, J. Bustingorry, R. Escaray, M. Ferraro & H. E. Zagarese, 2009. The effects of light availability in shallow, turbid waters: a mesocosm study. Journal of Plankton Research 31: 1517–1529.

Miretzky, P., V. Conzonno & A. Fernandez Cirelli, 2000. Hydrochemistry of pampasic ponds in the lower stream bed of Salado River drainage basin, Argentina. Environmental Geology 39: 951–956.

Murphy, T. P., K. J. Hall & I. Yesaki, 1983. Coprecipitation of phosphate with calcite in a naturally eutrophic lake. Limnology and Oceanography 28: 58–69.

Niemistö, J., H. Holmroos, Z. Pekcan-Hekim & J. Horppila, 2008. Interactions between sediment resuspension and sediment quality decrease the TN:TP ratio in a shallow lake. Limnology and Oceanography 53: 2407–2415.

Nõges, P., R. Adrian, O. Anneville, L. Arvola, T. Blenckner, D. G. George, T. Jankowski, M. Järvinen, S. C. Maberly, J. Padisák, D. Straile, K. Teubner & G. Weyhenmeyer, 2010. The impact of variations in the climate on seasonal dynamics of phytoplankton. In George, D. G. (ed.), The Impact of Climate Change on European Lakes, Aquatic Ecology Series 4. Springer, New York: 253–274.

Nõges, T., P. Nõges & R. Laugaste, 2003. Water level as the mediator between climate change and phytoplankton composition in a large shallow temperate lake. Hydrobiologia 506: 257–263.

Pannard, A., M. Bormans & Y. Lagadeuc, 2007. Short-term variability in physical forcing in temperate reservoirs: effects on phytoplankton dynamics and sedimentary fluxes. Freshwater Biology 52: 12–27.

Pérez, G., M. Llames, L. Lagomarsino & H. Zagarese, 2011. Seasonal variability of optical properties in a highly turbid lake (Laguna Chascomús Argentina). Photochemistry and Photobiology 87: 659–670.

Qin, B. Q., W. P. Hu, G. Gao, L. Luo & J. Zhang, 2004. Dynamics of sediment resuspension and the conceptual schema of nutrient release in the large shallow Lake Taihu, China. Chinese Science Bulletin 49: 54–64.

Quirós, R. & E. Drago, 1999. The environmental state of Argentinean lakes: an overview. Lakes and Reservoirs: Research and Management 4: 55–64.

Scheffer, M., S. H. Hosper, M. L. Meijer, B. Moss & E. Jeppesen, 1993. Alternative equilibria in shallow lakes. Trends in Ecological & Evololution 8: 275–279.

Scheffer, M., 1998. Ecology of Shallow Lakes. Chapman & Hall, London.

Scheffer, M. & E. Jeppesen, 2007. Regime shifts in shallow lakes. Ecosystems 10: 1–3.

Schippers, P., H. van de Weerd, J. de Klein, B. de Jong & M. Scheffer, 2006. Impacts of agricultural phosphorus use in catchments on shallow lake water quality: about buffers, time delays and equilibria. Science of the Total Environment 369: 280–294.

Shinohara, R. & M. Isobe, 2010. Daily change in wind-induced sediment resuspension and phosphorus forms in a shallow eutrophic lake. Fundamental and Applied Limnology/Archiv für Hydrobiologie 176: 161–171.

Søndergaard, M., P. Kristensen & E. Jeppesen, 1992. Phosphorus release from resuspended sediment in the shallow and wind exposed Lake Arreso, Denmark. Hydrobiologia 228: 91–99.

Søndergaard, M., E. Jeppesen, T. L. Lauridsen, C. Skov, E. H. Van Nes, R. Roijackers, E. Lammens & R. Portielje, 2007. Lake restoration in Denmark and The Netherlands: successes, failures and long-term effects. Journal of Applied Ecology 44: 1095–1105.

Tammeorg, O., J. Niemistö, T. Möls, R. Laugaste, K. Panksep & K. Kangur, 2013. Wind-induced sediment resuspension as a potential factor sustaining eutrophication in large and shallow Lake Peipsi. Aquatic Sciences 75: 559–570.

Torremorell, A., M. E. Llames, G. L. Pérez, R. Escaray, J. Bustingorry & H. E. Zagarese, 2009. Annual patterns of phytoplankton density and primary production in a large, shallow lake: the central role of light. Freshwater Biology 54: 437–449.

Torremorell, A., J. Bustigorry, R. Escaray & H. E. Zagarese, 2007. Seasonal dynamics of a large, shallow lake, laguna Chascomús: the role of light limitation and other physical variables. Limnologica 37: 100–108.

van Nes, E. H., W. J. Rip & M. Scheffer, 2007. A theory for cyclic shifts between alternative states in shallow lakes. Ecosystems 10: 17–27.

Zhu, G. W., B. Q. Qin & G. Gao, 2005. Direct evidence of phosphorus outbreak release from sediment to overlying water in a large shal-low lake caused by strong wind wave disturbance. Chinese Science Bulletin 50: 577–582.