Storm impacts on alpine lakes: antecedent weather conditions matter more than the event intensity.

Running head: Contrasted storms effects on mountain lakes

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Abstract

Extreme weather events may be just as important as gradual trends for the long-term trajectories of ecosystems. For alpine lakes, which are exposed to both exacerbated atmospheric warming and intense episodic weather events, future conditions might not be appropriately forecast by only climate change trends, i.e., warming, if extreme events have the potential to deflect their thermal and metabolic states from their seasonal ranges.

We used high-frequency monitoring data over three open-water seasons with a one-dimensional hydrodynamic model of the high-altitude Lake Muzelle (France) to show that rainstorms or windstorms, notwithstanding their intensity, did not trigger long-lasting consequences to the lake characteristics when light penetration into the lake was not modified. In contrast, storms associated with high turbidity input from the watershed ("turbid storms") strongly modified the lacustrine hydrodynamics and metabolism for the rest of the open-water season through reduced light penetration. The long-lasting effects of turbid storms were related to the inputs and in-lake persistence of very-light glacial suspensoids from the watershed. The occurrence of the observed turbid storms was not related to the wind or rain intensities during the events. Instead, the turbid storms occurred after dry and atypically warm spells, i.e., meteorological conditions expected to be more frequent in this alpine region in the upcoming decades. Consequently, storm events, notwithstanding their intensity, are expected to strongly imprint the future ecological status of alpine lakes under climate warming.

Introduction

In addition to increases in the average forcing conditions such as global atmospheric warming, climate change is expected to generate shifts in the frequency and magnitude of extreme weather events (i.e., heatwaves, droughts, heavy rainfalls, floods, or windstorms) with great regional variability (IPCC, 2013). Intense episodic weather events could be as important as gradual trends in mechanistically driving the long-term trajectories of ecosystems (Parmesan *et al.*, 2000, van de Pol *et al.*, 2017), but the regional heterogeneity and stochastic nature of extreme weather events introduce greater uncertainties in the prediction of future trajectories. In terrestrial ecology, the effects of both trends and events have been jointly considered to understand the outcomes of climate change (Carrer *et al.*, 2016, Jentsch *et al.*, 2007). In limnology, and more specifically lentic systems, climate change research is still coerced by the search for global and long-term patterns that are consequences of atmospheric warming (Woodward *et al.*, 2016): e.g. increase in lake surface water temperature (Austin & Colman, 2007, O'Reilly *et al.*, 2015, Woolway *et al.*, 2017), shorter ice cover (Magnuson *et al*, 2000), longer stratification length (Kraemer *et al.*, 2015), warming-induced shift in biological assemblages (Yvon-Durocher *et al.*, 2011) or abundances (Kraemer *et al.*, 2017). The contribution of extreme events to the realized and projected modifications to lakes under climate change are still poorly considered (Jones *et al.*, 2009) despite a growing body of evidence of the disproportional role of episodic meteorological disturbances and fluctuations on the physics, biogeochemistry and ecology of lakes (de Eyto *et al.*, 2016, Giling *et al.*, 2017, Jennings *et al.*, 2012, Kasprzak *et al.*, 2017, Klug *et al.*, 2012).

Most previous studies have showcased events of exceptional amplitudes (de Eyto *et al.*, 2016, Kasprzak *et al.*, 2017, Klug *et al.*, 2012) to emphasize the necessity of incorporating episodic disturbances in our long-term understanding of lakes. To exemplify their effects on lakes, authors have mainly opted for an 'impact-related' definition of these extreme events (e.g. van de Pol *et al.*, 2017). In other words, because not all extreme weathers necessarily lead to clear impacts, reported storm events are usually selected under an *ad hoc* definition based on the effects they have on lakes, rather than only for their meteorological characteristics (for instance, see Jennings *et al.*, 2012, Kuha *et al.*, 2016, Vachon & del Giorgio, 2014).

Above-mentioned examples of weather-induced events revealed the considerable variability in the magnitudes, durations and manifestations of the effects a storm generates on a lake. Klug *et al.* (2012) evaluated the consequences of Tropical Cyclone Irene in 2011 on eight North American lakes. They concluded that the magnitude of physical alterations cannot be solely explained by the storm intensity nor the lake-catchment characteristics and was instead function of the interaction between both factors. The amplitude and duration of storm-induced physical disturbances for a set of eight Finnish lakes, which experienced the same storms, were only loosely related to the magnitude of change in weather (Kuha *et al.*, 2016). In fact, storm-triggered physical disturbances can be relatively short-lived even for exceptionally intense events (17 days on average; Jennings et al., 2012 and a week for Irene, Klug *et al*., 2012), while only events with very large return periods are expected to trigger long-term effects on the lake hydrodynamics (Jennings *et al.*, 2012). However, the biogeochemical and ecological effects of storms can persist over longer periods, and usually independently from the duration of the physical disturbances (Jennings *et al.*, 2012). For instance, an exceptional storm in 2011 (centennial return period) on Lake Stechlin triggered changes in algal biomass and composition that lasted over one month (Kasprzak *et al.*, 2017). Water transparency and concentrations in colored dissolved organic matter recovered only after one year due to two successive flood events in Lake Pääjärvi (Jennings *et al.*, 2012). One of the most dramatic examples is Lake Apopka shifting, after a tropical cyclone in 1947, from a clear macrophyte-dominated state to a permanent turbid state (Bachmann *et al*., 1999).

Besides, the physical and biological disturbances induced by storms can largely differ among systems (de Eyto *et al.*, 2016, Jennings *et al.*, 2012). Overall, the effects of rainstorms and windstorms on lakes are detected through partial to total mixing of the water mass (Jennings *et al.*, 2012, Klug *et al.*, 2012, Tsai *et al.*, 2008). Usually, the disruption of thermal stratification comes with a decrease in water transparency that is due to major inputs of terrestrial dissolved or particulate matter (de Eyto *et al.*, 2016, Sadro & Melack, 2012, Vidon *et al.*, 2018), sediment resuspension (Jennings *et al.*, 2012) or lacustrine algal growth (Kasprzak *et al.*, 2017). Biogeochemical effects of storms usually converge towards larger O_2 uptake or the release of CO_2 to the atmosphere; however, these effects are due to different pathways. Decreased O_2 concentrations have been attributed to increasing respiration (de Eyto *et al.*, 2016, Tsai *et al.*, 2008) or light limitation to primary production (Sadro & Melack, 2012), while increased CO_2 could result from increased respiration of allochthonous inputs (Weyhenmeyer *et al.*, 2004), remobilization of hypolimnetic stores (Huotari *et al.*, 2011, Jones *et al.*, 2009) or direct CO_2 inputs from the watershed (Jones *et al.*, 2009, Vachon & del Giorgio, 2014). As a counterexample, the consequences of the exceptional storm over Lake Stechlin in 2011 resulted in a net positive effect on primary production, as upwelling reinjected nutrients into the euphotic zone (Kasprzak *et al*., 2017).

If we are to ultimately include extreme events in lake projection models under climate change, the next step is to address which meteorological processes determine the magnitude, duration and manifestation of storm-driven changes on lakes. Such an approach calls for a meteorological, instead of an impact-related, definition of extreme events (van de Pol *et al.*, 2017). Under such a definition, all extreme weather events on pluri-annual datasets have to be scrutinized if they do or do not trigger consequences at the lake scale.

The physical, chemical and ecological characteristics of high-elevation lakes are highly sensitive to inter-annual climate variability, as much in terms of atmospheric temperatures as of precipitation patterns (Parker *et al*., 2008). Atmospheric warming trends are more emphasized in alpine regions than lowland regions (IPCC, 2013). The direct (lake dynamics) and indirect (mediated by the watershed vegetation for instance) consequences of increasing trend in air temperatures over high-altitude lakes are expected to be large, qualifying them as climate warming “hot-spots” (Rose *et al*., 2009). However, intense weather events are typical climate features of mountain lacustrine ecosystems, and flood events in these areas are triggered by localized summer cold precipitation events (Fouinat *et al.*, 2017, Wilhelm *et al.*, 2012). We evaluated whether summer storms affected the physics and biogeochemistry of a high-altitude lake, quantified the extent and duration of any effects, and assessed whether the impacts of extreme events override the seasonal effects of atmospheric temperature. Significant and persistent impact of summer storms on the temperature, hydrodynamics and biogeochemistry of high-altitude lakes during the ice-free season would imply that forecasts of ecological trajectories of high-altitude lakes under climate change would require an explicit integration of the effects of extreme events within the more general warming trend (IPCC 2013).

Materials & Methods

Study site

Lake Muzelle (44°57.037′N, 6°5.845′E) is a proglacial lake located in the Western Alps in France, in Ecrins National Park. The lake is at an altitude of 2105 m above sea level (asl), has an area of 0.09 km^2, and mean and maximum depths of 15 and 18.3 m. Water flows into the lake by a braided glacial stream and makes its way out through a single overflow. The lake is ice-covered from December to May-June and is stratified from June to September. The 4.2 km^2 catchment area is above the treeline, reaches a maximum elevation of 3465 m asl, and mainly comprises granite and gneiss. The watershed includes a glacially covered area that had a surface area of approximately 0.2 km^2 (4.8% of the watershed) in 2009. The average gradient of the watershed slope is > 40%. The area surrounding the lake is covered by an alpine lawn and used as pasture for sheep during the summer, while the upper watershed is bare rock (Fouinat *et al.*, 2017). The lake is oligotrophic, with total phosphorous concentrations < 5 $\mu gP.L^{-1}$ and dissolved organic carbon concentrations < 1 $mg.L^{-1}$ (Nellier *et al.*, 2015). The Secchi depth is typically > 7 m in the early ice-free season, which allows 1% of the sunlight to reach the hypolimnion. The lake stratifies within a few days after the ice melts, the thermocline is typically between 6 and 8 m and chlorophyll *a* exhibits two peaks, one immediately below the thermocline and the other 2-3 m above the bottom of the lake. Water sampling at the sediment-water interface in 2014 revealed the existence of living algae at these depths (C. Bertrand, pers. comm.), and benthic primary production is the main carbon source of the food web (Perga *et al.*, 2017).

Weather data and thresholds for summer storm events

Meteorological data were provided by a weather station (Campbell Scientific CR10X) located 3.5 km from Lake Muzelle, at Lake Lauvitel at 1530 m asl (data courtesy of D. Dumas, Université Lyon 3, France). The weather station records hourly-averaged solar irradiance, cloud cover, atmospheric temperature, relative humidity, wind speed, rain and snow precipitation. Another weather station (Campbell Scientific CR800) was installed on the shores of Lake Muzelle (2 m above the lake surface) during the summers of 2014 and 2015, and the datasets from the two weather stations were cross-validated for each summer season (see supplementary information SI 1).

We focused on extreme windstorm and rainstorm events occurring during the summer stratification periods of Lake Muzelle from June 21st to September 30th in each of 2013, 2014 and 2015 (Days of Year DOY 172-274). Extreme events are climatologically defined according to a threshold value near the upper (or lower) ends of the range of locally observed values of the variable (usually 5-10%, as reported in Van de Pol *et al.*, 2017). The empirical cumulative distribution of summer precipitation for the three summers recorded at Lake Lauvitel indicated that the frequency of events (including dry days) with daily precipitation of 30 $mm.day^{-1}$ is < 3%, corresponding to an average of 3 events per summer (see SI 1). Thus, rainstorms were defined as events in which daily precipitation surpassed this threshold. Locally for Lake Muzelle, this threshold corresponds to 9 $mm.day^{-1}$ (SI 1). The empirical cumulative distribution of the summer daily average wind speed for the three summers at Lake Lauvitel returned that the frequency of events with daily wind speeds of 3 $m.s^{-1}$ is < 3%, corresponding to an average of 2-3 events per summer (see SI 1). Windstorms were thereby defined as events in which the average wind speeds surpassed this threshold, which is consistent with the values reported in Jennings *et al*. (2012). In Lake Muzelle, the local threshold for windstorms corresponds to 3.6 $m.s^{-1}$ (SI 1). Daily instead of hourly records were used to directly account for duration information.

Physical and metabolic changes in Lake Muzelle

Data collection and curation

In the fall of 2012, Lake Muzelle was equipped with autonomous temperature sensors (Tinytag®) distributed vertically along the water column (at 2, 4, 8 and 18 m depths) and anchored to a submerged buoy at the maximum depth. The water temperature was recorded at 15-min intervals throughout the year. In addition, a multiparameter probe (RBR® XR-420) equipped with a sensor wiper to limit biofouling recorded temperature, turbidity, and dissolved oxygen concentrations (DO) every 30 min at 14 m depth. In the fall of 2013, temperature sensors were replaced by temperature/dissolved oxygen sensors (Minidots®, PME) at 2, 4, 8 and 18 m depths, and data were recorded every 30 min. In June 2015, the sensor line was rearranged. Temperature-oxygen sensors (Minidots®, PME) were placed at 1, 7, and 13 m depths, and new temperature sensors (Tinytag Aquatic 2®) were set at 2, 4, 8 and 16 m depths. Unfortunately, the multiparameter probe failed at the end of June 2015. Sensors were serviced twice each year, in June and at the end of September. During servicing campaigns, a vertical profile with a multiparameter probe (EXO-1, YSI) was performed to provide reference data for the quality assurance/quality control checks. The retrieved data were standardized using DataStandardizer (developed by McBride, Lamont and Shute, University of Waikato, New Zealand, https://www.lernz.co.nz/uploads/data-standardizer-user-guide.pdf) and checked, cleaned and corrected for linear deviation of sensors using B3 software (developed by McBride and Hamilton, http://gleon.org/research/projects/b3-a-qaqc-tool). Subsequent analyses were performed on the hourly averaged time series.

Storm consequences on the physical structure and metabolism of the lake

The storm-driven destabilization of the water column and the recovery time were quantified by the Schmidt stability index (in $J.m^{-2}$; Schmidt, 1928). The maximum heat gain of the lake during summer was computed as the difference of the lake heat content between June 21st and the day of the highest lake surface water temperature. The lake heat content at a specific day was computed as the product of depth integrated water temperatures to the water specific heat (Wetzel & Likens, 2000). Further consequences of the storms were assessed through changes in the deep-water turbidity (whenever data were available) and changes in DO, as standardized to saturated oxygen concentrations (DO-DOsat) to exclude the temperature-controlled changes in oxygen solubility.

Approaches used to estimate lake metabolism (as Net Ecosystem Production, NEP) from continuous free-water measurements of DO rely on the assumption that changes in DO can be attributed to biological processes and physical vertical exchanges of O_2 (Hanson *et al.*, 2008, Staehr *et al.*, 2010). Diel changes in DO are thereby a prerequisite of applications of these models, with decreasing DO at nighttime due to atmospheric outflux and respiration, and higher DO during the day due to irradiance-dependent photosynthesis. However, in high-altitude lakes, the substantial day-night variability in the air and surface water temperatures fosters convective mixing at night and differential cooling (Livingstone & Lotter, 1998, Peter & Sommaruga, 2017). This unaccounted additional flux of DO during the nighttime affects the diel DO budget and thereby limits the relevance of most metabolism computation models for some time periods (Hanson *et al.*, 2008). A prior wavelet analyses of the DO signal at all depths for the three summers confirmed that a diel cycle in DO was rarely observed, thereby restricting the time periods when metabolism could be estimated from continuous free-water measurements of DO (see SI 2). Assessments were conducted using different computational and modelling methods of lake metabolism based on continuous free-water measurements of DO that were gathered in the LakeMetabolizer package (Winslow et al., 2016) on the time periods when diel DO cycles were observed. All methods provided similar estimates, but the discontinuity of the estimates hindered the ability of the methods to pinpoint the potential metabolic effects of storms.

In a second approach, we tried a less accurate but continuous estimate of NEP. Herein, NEP was assumed as the main driver of weekly changes in DO (lateral and vertical DO fluxes were thereby neglected). NEP was approximated as the slope of the linear fit of an 8-day time window of the DO time series. The 8-day window was the shortest period that provided statistically representative NEP estimates that correctly damped the diel oscillations in the linear slope fit. Periods were defined to begin and end immediately before and after the selected storms. Because the lake surface waters were saturated to super-saturated with DO, our approximation was expected to erroneously attribute DO diffusive efflux to respiration, and thereby to under-estimate epilimnetic NEP. In the hypolimnion, vertical fluxes can be neglected but lateral fluxes generated by differential cooling can act as a source of DO. Neglecting lateral fluxes is thereby expected to overestimate hypolimnetic NEP. Whenever possible, NEP estimates from the linear fit were compared to those assessed from the continuous free-water measurements of DO, showing good coherence between the two (SI 2). Estimates obtained through linear fit spanned a narrower range than those estimated by the continuous free-water measurements. Methods comparison confirmed that the linear fit led to lower estimates for epilimnetic NEP than the continuous free-water measurements of DO while the two methods provided more similar values for hypolimnetic NEP (SI2). The linear fit thereby provided a simple way to detect trends and changes in the heterotrophy/autotrophy of the system in response to extreme events (provided they last longer than one week) and also provides a 95% confidence interval to the estimated values.

Modelling the 2015 event

We used a one-dimensional hydrodynamic model (Simstrat, Goudsmit *et al.*, 2002) to disentangle the main processes that led to significant and long-lasting changes in the lake thermal structure. Simstrat is a finite-difference lake model with k-ε turbulence closure that has been used to analyse the thermal structure of many lakes (Fink *et al.*, 2014, Schwefel *et al.*, 2016). The model was calibrated for Lake Muzelle with the temperatures data from 2015 prior to the first storm event of this year (referred to as #9, see results) and independently validated over an early summer storm-free period for the year 2014 (DOY 170-200, Root mean square error RMSE= 0.9°C at z= 2m, and 0.1°C at z= 18 m). Data inputs for meteorological forcing in the model included wind and air temperature data from the Lake Muzelle weather station and solar radiation from the Lake Lauvitel weather station. The influences of the tributary and potential groundwater flow were added in the model as a constant inflow of cold water to the deepest cell of the lake model (i.e., deep cold water underflow). The outflow was removing surface water with discharge adjusted to match the previously estimated residence time. Our objective was not to provide a fully validated model, but to document the mechanisms by which the lake responded to a particular storm event. Because observations showed that event #9 came with a change in the water transparency in addition to the thermal and biogeochemical effects, the effects of the changes in light penetration were simulated with two scenarios. In the first scenario, we simulated a transient storm effect on water transparency using inflows loaded with heavy, fast-sinking particles. In this first case, the Secchi depth dropped from 7 m (typical values recorded in Lake Muzelle) to 0.5 m during the event and rapidly returned to 7 m through an exponential function with a decay timescale of 2 days. The light penetration was related to the Secchi depth (SD) as $k_d = c/SD$, with c ~ 0.14 (Schwefel *et al.*, 2016). In the second case, the drop in the water transparency was set to the same magnitude (from 7 m down to 0.5 m), but the decay time was scaled to the lake water renewal time in the summer (Nellier *et al.*, 2015) to mimic the inputs of small light particles by the riverine water. The use of exponential decay for the change in turbidity was motivated by the turbidity time series observed in 2013. The model outputs were compared to the *in situ* data.

Results

Meteorological conditions of the summers of 2013, 2014 and 2015

The summer of 2014 was colder and wetter than the summers of 2013 and 2015. The average air temperature in the summer of 2014 was 0.9°C and 2.2°C lower than those of 2013 and 2015, respectively (Table 1), while the average daily precipitation was 42% higher. The average wind speeds were comparable. The cumulative air temperatures were similar during the first month of the summers of 2013 and 2014 (Figure 1a), but increased faster during the second half of summer 2013. Precipitation was regularly distributed in 2014 and rare in 2013 (Figure 1b). The first month of the summer of 2015 was both hot and dry, with no rain before mid-July (Figure 1a-b).

Table 1. Average weather conditions in summers 2013-2015 (June 21st to September 30th) and descriptions of detected rainstorms and windstorms. sd = standard deviation.

	Summer 2013	Summer 2014	Summer 2015
Average ± sd air temperature (°C)	13.2 ±3.9	12.3±2.9	14.5 ±4.8
Mean daily precipitation ± sd (mm)	3.3±10.4	4.7±9.9	3.3±8.3
Average wind speed ± sd ($m.s^{-1}$)	1.1±0.6	1.1±0.7	1.2±0.7
Rainstorms: **Dates** and daily precipitation (mm)	**30/7/13**: 51 mm **7-8/8/13**: 55+45 mm **8/9/13**: 54 mm	**30/6/14**: 39 mm **21/7/14**: 36 mm **14/8/14**: 43 mm **27/8/14**: 54 mm	**23/7/15**: 34 mm **14-15/9/15**:43+39 mm
Windstorms: **Dates** and average daily wind speed	**28-29/7/13**: 3.2 + 5.2 $m.s^{-1}$	**29/6/14**: 4.0 $m.s^{-1}$ **10-11/8/14**:3.0 + 5.0 $m.s^{-1}$	**13/9/15**: 3.1 $m.s^{-1}$ **17/9/15**: 5.3 $m.s^{-1}$

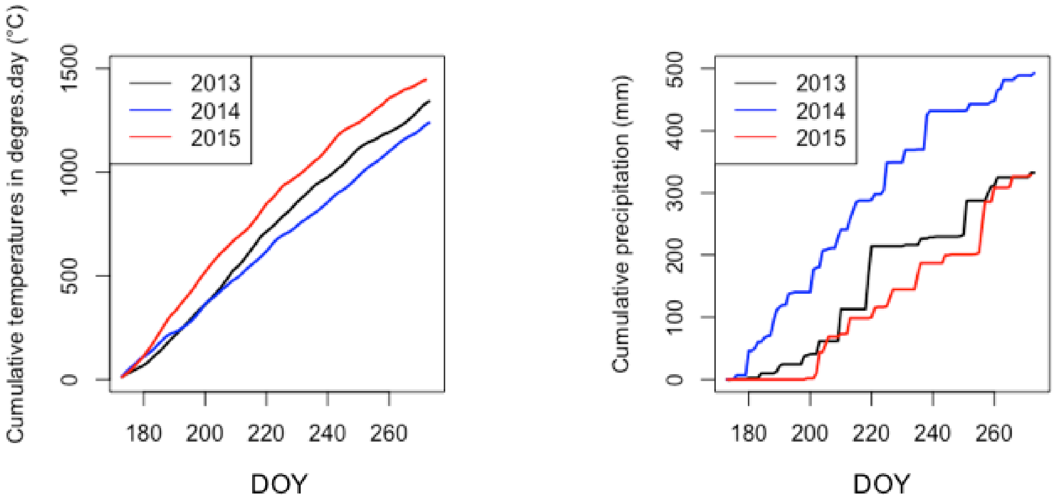
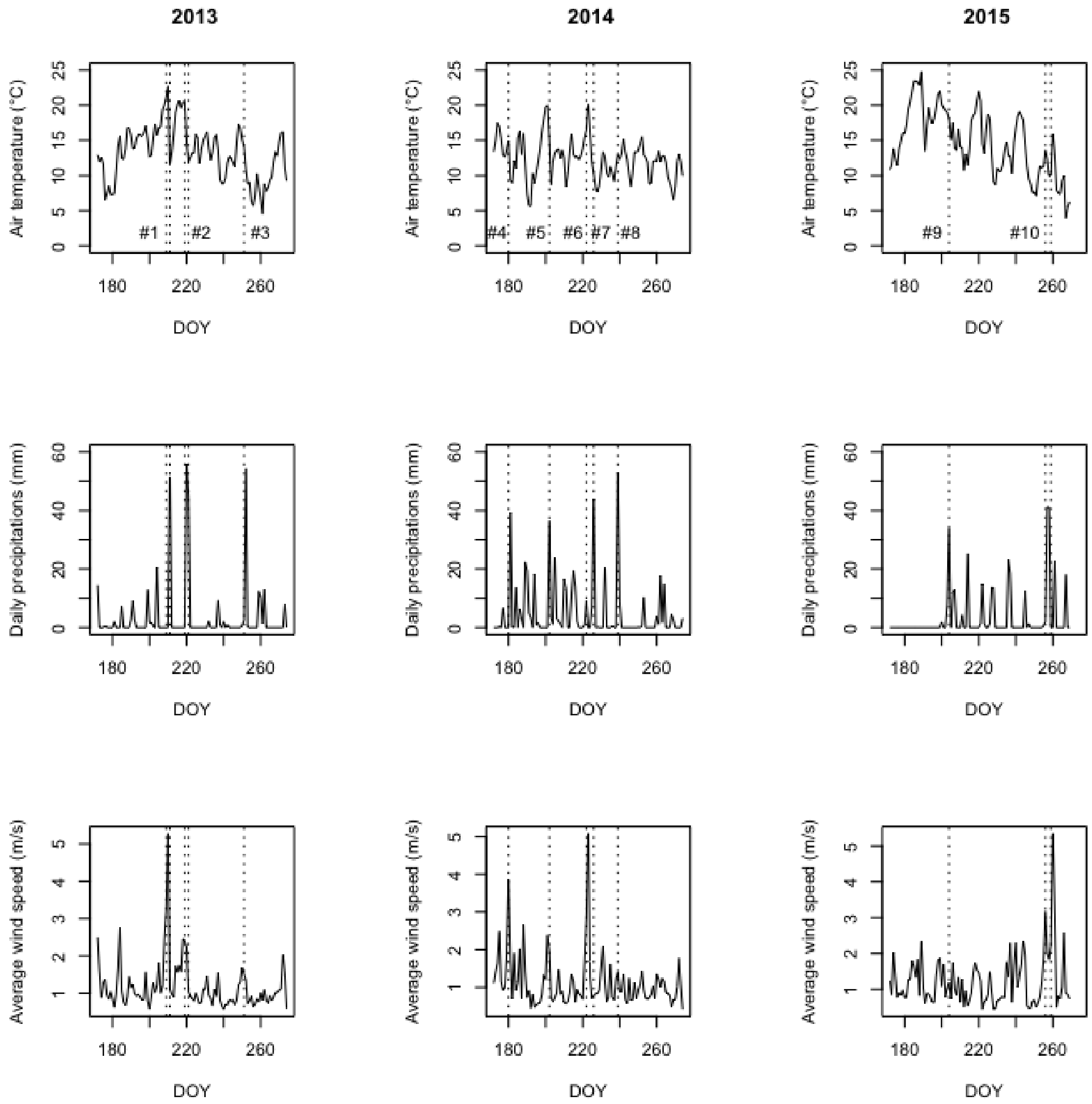


Figure 1. Cumulative temperature (a) and precipitation (b) over the summers of 2013, 2014 and 2015 recorded at the Lauvitel weather station (DOY: days of year).

Based on the previously set climate thresholds, 10 storm events were detected over the three summers. In the summer of 2013, three events were recorded, with a two-day windstorm in late July (28-29/7) that was followed by a rainstorm (30/7). This three-day storm was considered a single event (event #1, DOY 209-211). A two-day rainstorm occurred in early August (event #2, DOY 219-221), with another rainstorm one month later (event #3, DOY 251). All three events in 2013 had very high precipitation (> 50 $mm.day^{-1}$). Storms were the most frequent in the summer of 2014, and the first windstorm was followed by a rainstorm in late June (event #4, DOY 180-181), three rainstorms (21/7, 14/8 and 27/8, events #5-7, DOY 202, 222-223 and 226) and one windstorm (10/8, event #8, DOY 239; Figure 2). In 2015, only two events were recorded, with a rainstorm (precipitations = 32 mm, the lowest in intensity of all detected rainstorms) on 22/7 (event #9, DOY 204), and a large 4-day wind and rainstorm event (13-17/9, event #10, DOY 256-259).



313

314 ***Figure 2***

315 ***Daily average air temperature, total precipitation and average wind speed for the summers***
316 ***(June 21st to Sep 30th) of 2013, 2014 and 2015 at Lake Muzelle. The dotted lines indicate the***
317 ***detected rainstorms and windstorms (with intensities > 97% of events), and each event was***
318 ***identified by an event number (from #1 to #10).***

Physical and chemical lake structures

General seasonal trends

Over the three-year observation period, the lake was at an early stage of thermal stratification at the beginning of the summer (21/6 or DOY 172, Figure 3). The background turbidity was < 5 FTU (Formazin Turbidity Units), which was consistent with the high transparency of the waters. By the end of August, the temperature warmed to 10-15°C above the thermocline, which typically stabilized below 8 m. The diel variability in the water temperature reached 2-3°C in the surface layers. In 2014, the deepest water layer warmed linearly but only by 2°C during the summer. In contrast, in 2013 and 2015, this deep warming trend reversed after specific storm events (#2 for 2013 and #9 for 2015). The Schmidt stability index increased from 0 on the first day of summer to 50-150 $J.m^{-2}$ in September. The surface temperatures and stabilities were higher in the summers of 2013 and 2015 than in 2014, consistently with the observed ranking in air temperatures (Figure 3). Counter-intuitively, the heat gain in the lake during the summer was higher in 2014 ($2.6\ 10^9$ J) than in both 2013 ($2.2\ 10^9$ J) and 2015 ($1.8\ 10^9$ J) despite the lower air temperatures of the summer of 2014.

The surface waters were at equilibrium or supersaturated in oxygen throughout the summer of 2014 and 2015 (no data for 2013) (Figure 3). The deeper waters (below 8 m) were first under-saturated with oxygen immediately after the spring turnover of 2013 and 2014, attesting that the water mixing does not necessarily last long enough to renew the deep oxygen after hypoxia conditions set in under the winter ice each year. However, the oxygen concentrations continued to increase during stratification in the first month of summer. By mid-late July, hypolimnetic waters were close to equilibrium or even supersaturated in oxygen. Deep DO began to decrease from mid- to late summer and returned to under-saturated conditions, but the timing when the DO trend reversed varied among the years (late July in 2015 to late August in 2014, Figure 3).

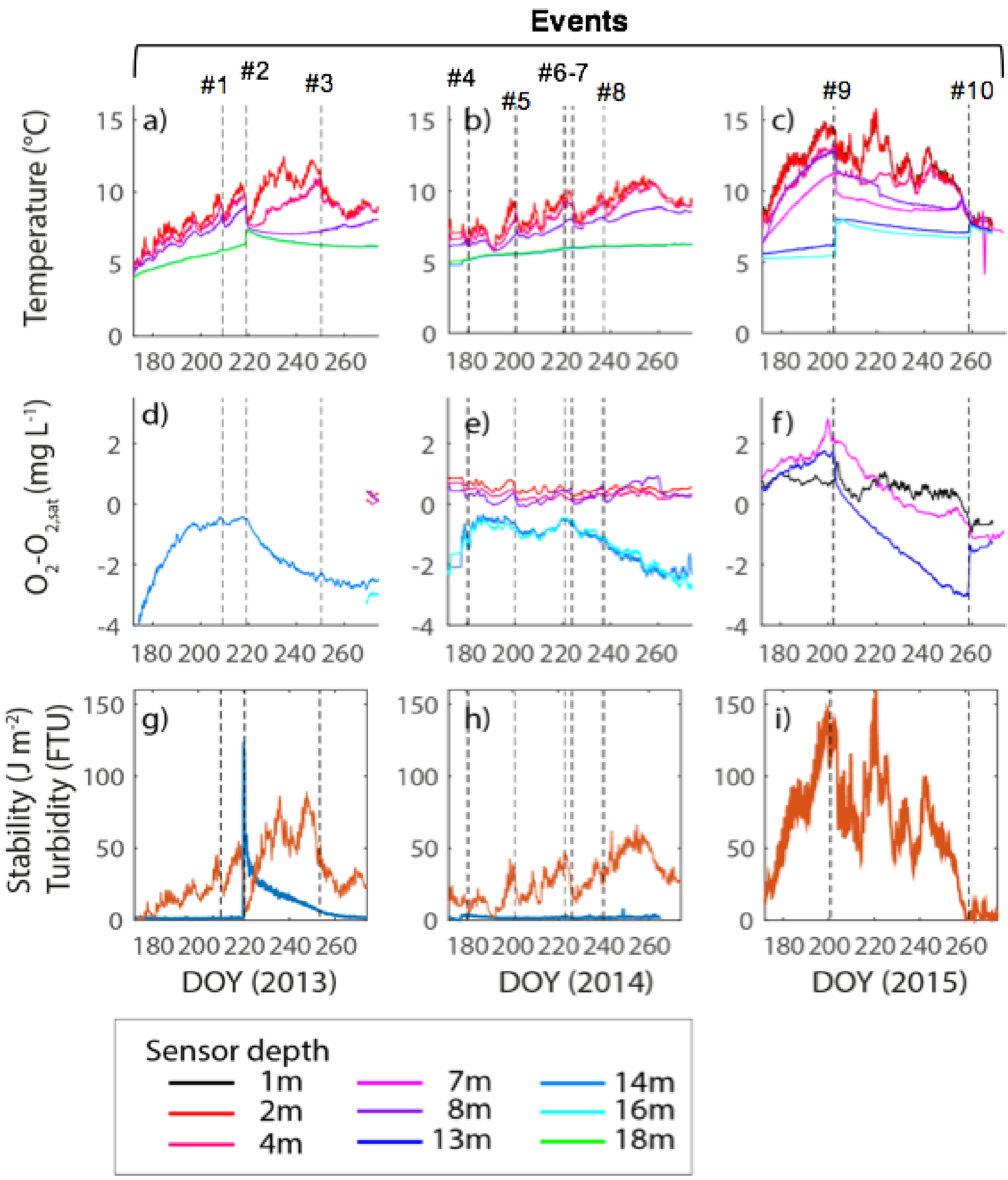


Figure 3. Changes in water temperatures at different depths in the summers of 2013 (a), 2014 (b) and 2015 (c), changes in DO (relative to DO at saturation) in the summers of 2013 (d), 2014 (e) and 2015 (f), changes in water mass stability (orange line) and turbidity (blue line) in the summers of 2013 (g), 2014 (h) and 2015 (i). The dotted vertical lines indicate the events.

The metabolic rates at all depths and years ranged between -0.1 and 0.5 $mgO_2.L^{-1}.d^{-1}$ (Figure 4), and were consistent with those estimated at Lake Emerald, a comparable high-altitude lake in the U.S. (Sadro & Melack, 2012; -5 to 5 $\mu molO_2.L^{-1}.d^{-1}$). Epilimnetic waters (0-6 m) in 2014 and 2015 were close to metabolic neutrality throughout the reported time periods (no estimates available in 2013), and no significant changes over time were evident (Figure 4). Deeper waters were highly autotrophic in the early summer, which was consistent with the increase in DO observed during the first part of summer and the high transparency (Figure 3). The metabolism in the deep water then exhibited a general trend to neutrality during the season, with a final shift to heterotrophy at different times each year (from mid-July –DOY 200– in 2015, early August –DOY 220– in 2013, to late August in 2014 –DOY 250– Figure 4).

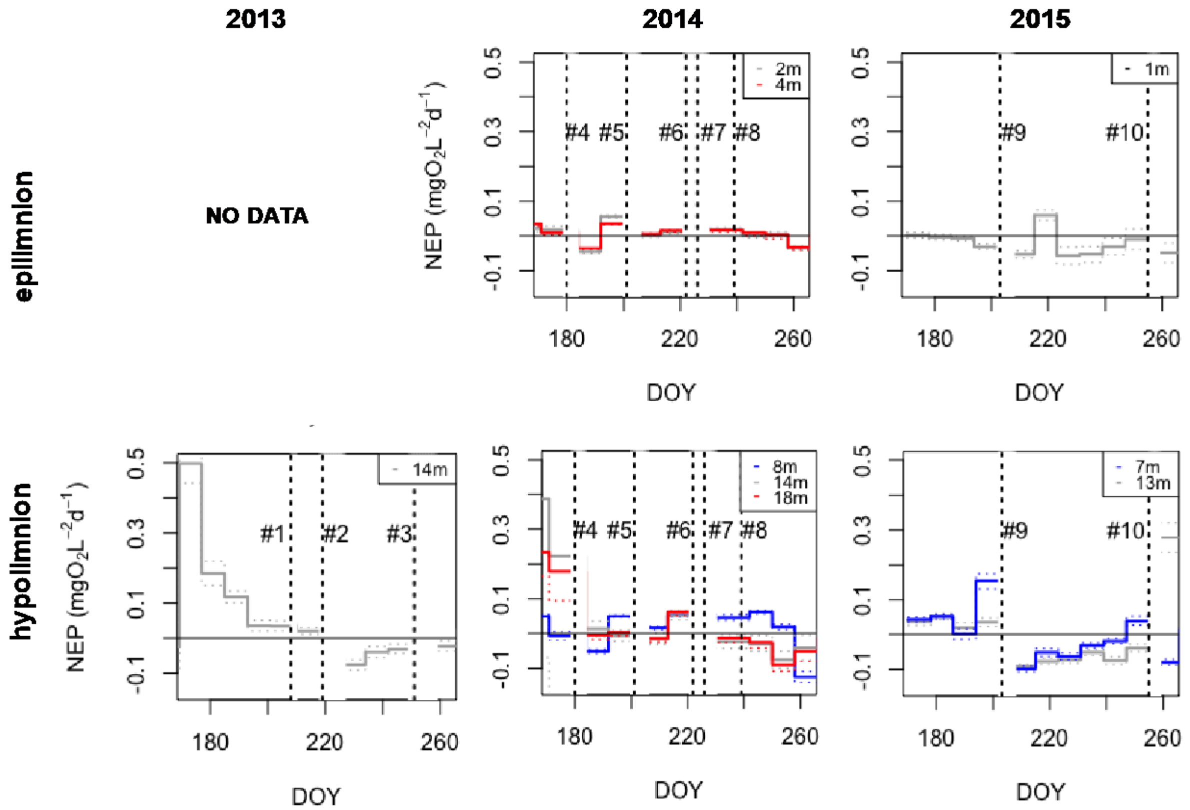


Figure 4. Computed weekly net ecosystem production (mean ± 95% confidence interval of the estimates) for the epilimnetic (b, d) and hypolimnetic (a, c, e) layers of Lake Muzelle during the summers of 2013 (a), 2014 (b, c) and 2015 (d, e). The dotted vertical lines indicate the events.

Storm physical effects

All identified storm events induced at least transient changes in the thermal structure of the lake. Seven of the 10 events (#1, #3, #4-8) generated partial mixing of the surface waters, at most down to the thermocline (8-m depth). These seven storm-driven partial mixing manifested also as minimums in the Schmidt stability index during these times (Figure 3). For the seven storm events, the hypolimnetic turbidity remained unchanged (no data for 2015; Figure 3). The physical disturbance lasted for only a few days, and the thermal structure and thereby stability recovered within one week. The effects of the seven storms did not depend on the type of storm (rain or wind). Because the surface waters were already in O_2 equilibrium with the atmosphere, the partial surface mixing did not modify the O_2 concentrations of the waters or the surface metabolic rates. Hypolimnetic waters were not affected by these seven storms (Figure 4). Although the storms were more frequent and of higher intensity in 2014 than in the other years, and water column was less stable, the magnitudes and durations of the effects were not stronger in 2014 than those during the previous and following summers.

Event #10 occurred late in the season when the Schmidt stability had already dropped below 10 $J.m^{-2}$ and surface waters had already mixed down to > 8 m. The lake was already on its way to fall turnover and event #10 likely hastened fall turnover by a few days. As Lake Muzelle was not stratified before event #10, we do not consider event #10 as a summer storm.

Two of the events (#2 and #9), both of which were rainstorms and windstorms, resulted in a mixing of the water column at all depths (Figure 3). The lake was fully mixed after event #2 in 2013 when the Schmidt stability index dropped from 50 to < 10 $J.m^{-2}$. In 2015, the lake stability was stronger than in the other summers (Figure 3). Although event #9 did not completely mix the water column, the effect was strong enough to reduce the vertical difference in the surface to bottom temperature from 9 to 5°C and the Schmidt stability index by a factor of 3 (from 150 to 50 $J.m^{-2}$, Figure 3). Of the 10 storm events, the daily precipitation was the highest during event #2 (100 mm) and lowest for event #9 (32 mm; Figure 2). Despite the differences in rain intensity, the two storms had the common feature of large changes in water turbidity. The 2013 storm induced a rapid spike in turbidity (from 2 to 226 FTU within one hour) followed by an exponential decrease over the subsequent two months, but remained higher than its original values at the end of September (Figure 3). The turbidity sensor was down during the summer of 2015, but a picture was taken 10 days after event #9 and confirmed that event #9 induced long-lasting turbidity similar to event #2 in 2013 (Figure 5). For such reasons, we refer to storms

#2 and #9 as "turbid storms" (i.e. storms that generated high lake turbidity) in contrast to "clear storms" for events #1, #3, and #4 to #8, as those did not induce changes in lake turbidity (Figure 3).

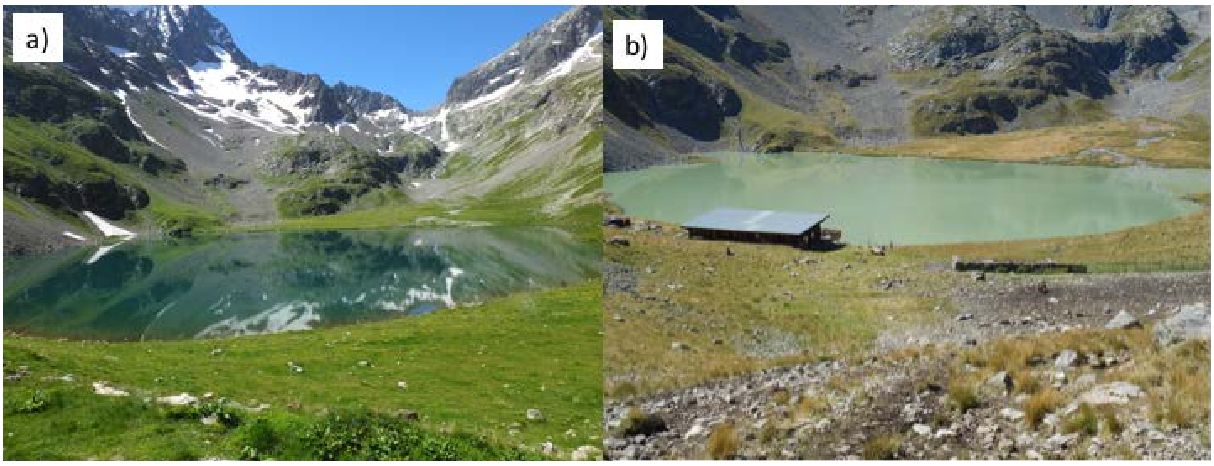


Figure 5. Pictures of Lake Muzelle taken on June 20, 2015, one month before storm event #9 (a) and on August 2, 2015, 10 days after storm event #9 (b).

The lake re-stratified immediately after the turbid storms but the vertical thermal structure was different than before the event (Figure 3). The surface waters (down to 2-4 m depth) returned to temperatures similar to those before the storms within one week and then increased steadily (Figure 3). The deepest waters, which warmed by 1-4°C due to the partial mixing with the near-surface waters, exhibited changes in dynamics and switched from a slow warming trend to a slow cooling trend after the storm. After the turbid storms and during the following month, the oxygen concentrations at depth shifted prematurely from slight undersaturation (2013) or supersaturation (2015) to a marked undersaturation, while this trend occurred 50 days later in 2014 (Figure 3). Consistently, the intermediate and deep-water layers (> 7 m deep) shifted consistently from net autotrophy (significantly positive values of NEP) to net heterotrophy (significantly negative values of NEP) after the turbid storms, and these changes extended beyond the subsequent weather events (Figure 4).

The model simulations pinpointed the key role of the change in turbidity in the duration of the physical disturbance resulting from event #9 in 2015 (Figure 6). The hydrodynamic model with a fast decay timescale (2 days, but the results were similar for no change in turbidity) failed in predicting the thermal structure (Fig. 6a) and stability (Fig. 6b) of the lake, after event #9. In contrast, the 120-day decay timescale could adequately reproduce the temporal evolution in the thermal structure (Fig 6a) and stability (Fig 6b) over the two months following the turbid storm, including the exacerbated heating of the surface temperatures (Fig. 6c “surface layer”), cooling of the bottom waters (Figure 6c “bottom layer”), and increased water stability (Figure 6d), leading to an extension of the time of lake stratification in the fall by > 1 week. The same modelling approach was used to test for a clear storm (event #5, DOY 202 year 2014). The 2-day decay timescale in light absorption following the storm better reproduced the post-storm thermal structure than the 120-day decay time scale (temperature RMSE= 1.4°C and 2.5°C for a 2-day and 120-day decays respectively at z= 2m, SI 3).

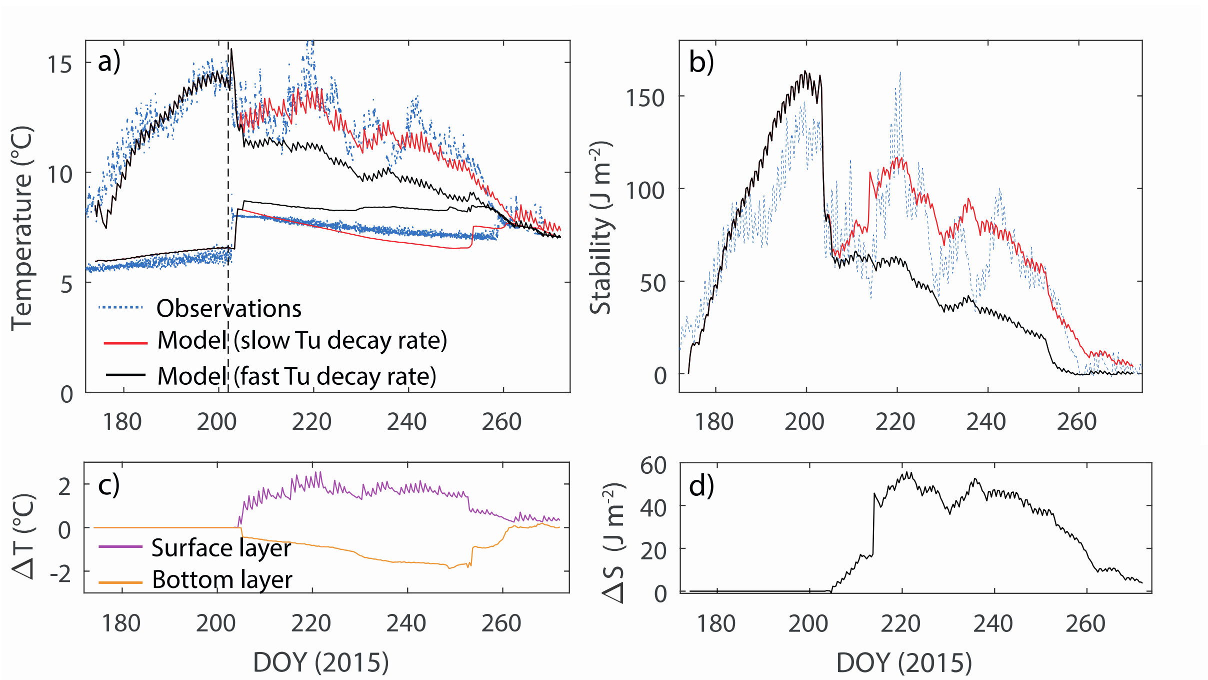


Figure 6. Modelled versus observed changes in surface and bottom water temperatures (a) and water column stability (b) during the summer of 2015. The blue dotted lines represent

observation data, the red and black lines represent the modelled outputs that considered inputs of respectively slow-sinking and fast-sinking particles. (c) Temperature difference between the two models (slow minus fast turbidity decay, near the surface (pink) and near the bottom(orange)). d) Schmidt stability difference between the two models (slow minus fast turbidity decay).

Discussion

Both the occurrence and intensity of storms on Lake Muzelle varied among years, but the magnitudes and durations of their consequences on the physics and biogeochemistry of the lake were not related to the meteorological characteristics of the storms themselves. Events not associated with changes in lake turbidity (i.e. clear storms) resulted in short-term surface mixing, with no further consequences on seasonal patterns of the variables we measured or estimated. For example, although wind energy is particularly efficient at triggering basin-scale internal waves in stratified systems (Bouffard & Lemmin, 2013) and increasing fluxes of gases and nutrients through the thermocline, the typical morphology of mountain lakes often limits the effects of wind intensity and duration and thus wind-driven destratification in the summer (Catalan *et al.*, 2002). Wind speeds >6 $m.s^{-1}$ would have been required to provide enough kinetic energy to durably modify the thermal structure and thermocline depth (SI 4), whereas wind speeds were <5.4 $m.s^{-1}$ even in the windiest days at Lake Muzelle. However, other processes, such as rain-induced river inflow or strong surface cooling, can contribute to mixing and may weaken background stratification (as in event #10).

Although the lake surface waters mixed during and after these clear storms, the duration of mixing was very limited and stability was restored within one week. The modelling approach confirmed that in the absence of a long-lasting change in the light environment of the lake, the thermal and hydrodynamical consequences of the storms, notwithstanding their intensity, remain transient. Data from the summer of 2014 (when rainstorms were the most frequent, and the DO was measured at both the surface and depth) do not provide evidence of any detectable impact of superficial mixing on DO. The surface waters were already well mixed and in equilibrium with the atmosphere, with a neutral balance of a likely low metabolism. In clearwater oligotrophic lakes, the metabolic rates are highest in metalimnetic instead of epilimnetic waters (Giling *et al.*, 2017b). Deep primary production is a typical feature of high-altitude clearwater lakes in the summer (Catalan *et al.*, 2002, Tilzer, 1973) and has been attributed to UV avoidance by algae in high-altitude environments (Sommaruga, 2001, Sommaruga *et al.*, 1997) or to greater nutrient availability below the thermocline (Saros *et al.*, 2005). Indeed, the fact that DO approaches or exceeds supersaturation in the hypolimnion in the early summer, when the lake is already stratified (Figure 3), confirms hypolimnetic autotrophy. Consequently, water mixing confined to surface waters is less likely to generate changes in metabolic rates. The absence of any clear storm-driven modifications of metabolism further suggests that runoff does not generate significant pulses of nutrients, nor of dissolved organic carbon, from this high-mineral watershed with organic-poor soils (Xenopoulos *et al.*, 2003).

In contrast, the rainstorms that were coupled with turbid events (turbid storms of August 2013 and July 2015) had dramatic and long-lasting consequences on the physics and biogeochemistry of the lake. The turbid storms resulted in a full destabilization of the water column with a partial homogenization of water temperatures and DO. Assuming that the increased turbidity was distributed along the whole water column (the turbidity sensor was set at 14 m depth but Figure 5b suggests so), light extinction prevented the water from warming below 2-4 m in both summers, while the dissipation of sunlight energy concentrated at the surface exacerbated the superficial warming (surface layer on Fig. 6c), as in typical turbid young proglacial lakes (Peter

& Sommaruga, 2017). As a result, the depth-temperature gradient became steeper (Figure 6a), and the water masses reached a stability that was 200% higher than expected for clear lake conditions (Figure 6d). As confirmed by the modelling approach, the observed thermal changes are linked to the elevated turbidity that prevented shortwave radiation from penetrating to the deep layer. The cooling trend suggested an external contribution from the groundwater, or more likely from cold riverine water from the glacial inflow, that plunged to the deep water with heat loss that could no longer be balanced by the energy input from the penetration of deep shortwave radiation (bottom layer on Figure 6c). Light extinction shifted the hypolimnetic waters from net autotrophy to net heterotrophy after both turbid storms, as already speculated by Sadro & Melack (2012) while investigating storm-induced shifts in the thermal structure and metabolism of Emerald Lake, a high-altitude lake in the US Sierra Nevada Mountains.

Turbid storms were distinguished from the clear storms by not only the magnitude of their consequences but also the durations of the effects. The disturbances in the vertical thermal and biogeochemical structures of the lake persisted until the fall mixing event, i.e., half the length of the stratified period. The effects of storms on light transmission or DOC in lakes can be more prolonged than the effects on water stability (Jennings *et al.*, 2012). Our modelling approach pinpoints the persistence of slow-sedimenting particles as a mechanism for the long duration of the turbid storm-driven effects. The slow turbidity decrease after the 2013 turbid storm indicates that runoff brought fine-sized particles of very low, if not null, sedimentation rates, which, along with the grey colour of the water after the 2015 turbid storm (Figure 5), strongly points to glacial flour. The watershed of Lake Muzelle is dominated by glacial erosion, and a sedimentological study of Lake Muzelle cores confirmed that the watershed exports fine glacial sediment to the lake (Fouinat *et al.*, 2017). The magnitude and duration of the storm-driven effects on the lake are thereby linked to the mobilization of glacial mineral suspensoids with high reflectance (see Sommaruga, 2015) from the watershed. Because the water renewal for

Lake Muzelle is approximately 3 months in summer (Nellier *et al.*, 2015), the theoretical time required for the restoration of water transparency after this turbid event is longer than the average duration of the stratification and growth season in this mountain lake. The persistence of these glacial mineral suspensoids also explains why Lake Muzelle was warmer at the surface in 2015 but stored less heat during the summer of 2015, despite the much higher air temperatures. Within a matter of hours, the turbid storms shifted the lake-atmosphere coupling, suggesting that persistent storm-induced changes in water clarity could be at least as important as rising air temperatures in determining how the lake responds to climate change (Rose *et al.*, 2016).

Beyond the observed changes in lake metabolism, such an abrupt transition between a clear and turbid state undoubtedly will influence the lake biodiversity and food web. Fine-sized glacial particles can impair the filtering apparatus of filter-feeding zooplankton, while light extinction decreases primary production, with further consequences to phytoplankton species compositions (Sommaruga, 2015). Lake Muzelle is sparsely populated by pelagic zooplankton even in years with high phytoplankton biomass (Perga *et al.*, 2017). The dominant carbon source for the entire food web is benthic primary production (Perga *et al.*, 2017). Persistent light extinction is expected to at least partially shut down the dominant carbon source, thereby limiting the already short completion of the life cycle for many of the lake species. The organic carbon brought by glacial melt could contribute to the amplification of heterotrophy by stimulating microbial respiration, although water cooling might decrease the overall metabolic rates. Thus, the question of how, if at all, glacial organic matter can subsidize the lake food web is an important question. In the two observed cases, oxygen depletion did not reach the level of hypoxic conditions. Nevertheless, the drastic changes in the overall lake environmental conditions indicate long-lasting modifications of the lake food web in the future.

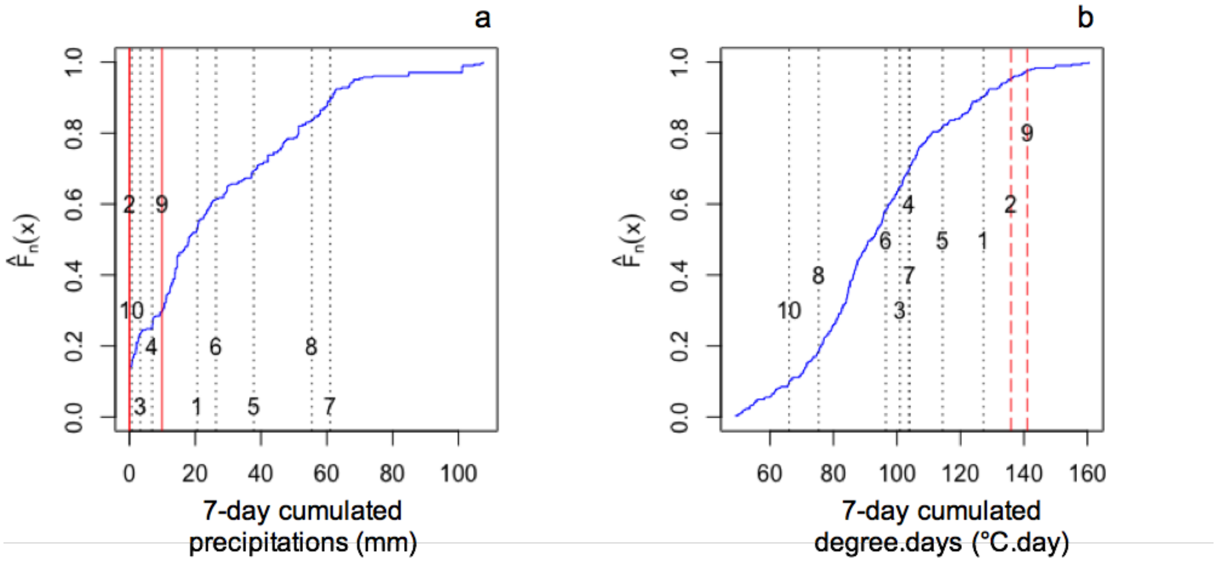


Figure 7: Empirical cumulative distribution of 7-day cumulated precipitations (a) and degree.days (b) for summers 2013, 2014 and 2015 at lake Muzelle. Dotted lines locate meteorological conditions in the week preceding each storm event (which numbers are specified). Clear- and turbid storms are respectively figured with black and red dotted lines.

The classification of a storm as clear or turbid, due to runoff of glacial flour, was not related to the intensity of the events: clear storms occurred at the lowest and highest air temperatures and the two turbid storms represented the lowest and highest storm precipitations (Table 1, Figure 2). Instead, turbid storms appeared in both 2013 and 2015 when a rainstorm occurred after a relatively dry and warm week (Figure 7). Turbid runoff, due to the mobilization of glacial flour, appeared to be influenced by antecedent weather conditions instead of the event characteristics themselves. The roles played by antecedent conditions on the runoff consequences of rainfall have been underlined by Woo (2012) and exemplified in a high arctic catchment (Favaro & Lamoureux, 2014). Therein, sediment mobilization was tied to soil moisture and thereby weather conditions over the two preceding weeks. Herein, the short-term fluctuations in the glacier erosion dynamics might be the mechanism by which antecedent weather conditions determine if a storm will result in the run-off of glacial flour. The production of glacial flour results from glacial abrasion and accumulation at the base of the glacier and is highly variable along the season (Collins, 1989). Instantaneous erosion rates by glacial abrasion increases with the squared velocity at which the glacier is sliding (Herman *et al.*, 2015). For temperate glaciers such as the Muzelle Glacier, the ice-sliding velocity responds to daily variations of air temperature, with velocities that are significantly higher during warmer days (Bartholomew *et al.*, 2012). Atypical warm spells, as those observed before the two turbid storms, are expected to promote high production and accumulation of fine sediment at the glacier bed, which is flushed out at the first rainfall (Collins, 1989).

Although the process linking storms run-off of glacial turbidity to warm spells deserves further validation, the main message of our study is that for Lake Muzelle, drought and heat promote stronger and longer physical and biogeochemical consequences for the lake of summer rainstorms. For the Ecrins region (where Lake Muzelle is located), downscaling of the Action de Recherche Petite Echelle Grand Echelle (ARPEGE) model ($2XCO_2$ scenario) suggested a decrease in summer rainfall and warmer air temperature by the end of the century, with less frequent and potentially more intense rainstorms (Jomelli *et al.*, 2009). Warmer and dryer summers, even combined to less frequent rainstorms, could then promote turbid storms. Thus, the probability of Lake Muzelle annually shifting from a clear to turbid state could also increase, as long as the Muzelle Glacier lies on the watershed. Turbid storms modify the light climate of the lake and change the rule by which the lake responds to atmospheric trend forcings, with large and long-lasting consequences to heat distribution and storage, stability and stratification length, metabolism and potentially the ecology of Lake Muzelle. Under such a scenario, summer storms, despite being less frequent, could significantly change the trajectory of the lake ecology.

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