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Cumulative intensity heatwave index as an assessment tool for climate change effects on shallow lakes

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ABSTRACT

Cumulative intensity heatwave index as an assessment tool for climate change effects on shallow lakes.

Although lakes represent only 0.26% of the total freshwater on Earth, they provide essential environmental services, such as public water supply and irrigation. Water temperature, which drives the lake's physical, chemical, and biological processes, is a parameter typically used for lake management plans. To explore the effects of climate change on Lake Mangueira, a subtropical coastal shallow lake, we assessed the cumulative intensity index, which links heatwave duration to mean intensity. The Air2Water model was calibrated using time-series of observed daily air temperature data and water surface temperature data obtained via remote sensing. Based on climate projections obtained from 26 global climate models, the Air2Water model was used to generate water temperature time-series for a historical period and future scenarios, including SSP1-2.6, SSP2-4.5, and SSP5-8.5. We found that at least 75% of the projections indicated lake heatwaves with a cumulative intensity exceeding 50 °C days under the SSP5-8.5 scenario, compared to 18 °C days in the historical period. Even in the least severe future scenario (SSP1-2.6), 75% of the projected average cumulative intensities were equal to or exceeded every value from the historical period. These findings highlight a concerning shift in the thermal dynamics of Lake Mangueira. The lake is expected to experience more intense and/or longer-lasting heatwaves that have the potential to significantly affect its aquatic communities. The cumulative intensity index can therefore be used to monitor extreme events in these ecosystems, which will help to properly manage them.

KEY WORDS: aquatic ecosystems, lake heatwaves, limnology

RESUMO

Índice de intensidade cumulativa de ondas de calor como ferramenta de avaliação dos efeitos da mudança climática em lagos rasos.

Embora os lagos representem apenas 0.26% do total de água doce na Terra, a sociedade utiliza-os para importantes serviços ambientais, como abastecimento público e irrigação. Para manter esses serviços, um dos parâmetros tipicamente utilizados no gerenciamento de lagos é a temperatura da água, que regula seus processos físicos, químicos e biológicos. Para explorar os efeitos das mudanças climáticas na Lagoa Mangueira, uma lagoa rasa costeira subtropical, foi avaliada *a ocorrência de ondas de calor com dados de temperatura superficial da água e do índice de intensidade cumulativa, que associa a duração das ondas de calor à sua respectiva intensidade média. O modelo de estimativa de temperatura da água Air2Water foi calibrado com uma série temporal de dados diários de temperatura do ar e com dados de temperatura superficial da água obtidos via sensoriamento remoto. A partir de projeções climáticas de 26 modelos climáticos globais, o modelo Air2Water foi utilizado para gerar séries temporais de temperatura da água no período histórico e nos cenários futuros SSP1-2.6, SSP2-4.5, e SSP5-8.5. Verificamos que pelo menos 75% das projeções indicaram ondas de calor lacustres com uma intensidade cumulativa maior que 50 °C dia no cenário SSP5-8.5, em comparação a 18 °C dia do período histórico. Mesmo no cenário futuro menos crítico (SSP1-2.6), 75% dos valores médios projetados de intensidade cumulativa igualaram ou excederam os valores do período histórico. Esses resultados indicam uma mudança particularmente preocupante na dinâmica térmica da Lagoa Mangueira, que estará sujeita a ondas de calor mais intensas e/ou de maior duração, implicando em efeitos potencialmente graves sobre suas comunidades aquáticas. O índice de intensidade cumulativa pode assim ser usado para avaliar eventos extremos nesses ecossistemas, objetivando gerenciá-los adequadamente.*

PALAVRAS-CHAVE: ecossistemas aquáticos, limnologia, ondas de calor lacustres.

INTRODUCTION

Lake systems are associated with important environmental services, such as public water supply and irrigation (Woolway et al., 2021b), even though these ecosystems represent only 0.26% of the total freshwater available on Earth (Collischonn & Dornelles, 2015). These limited water bodies face increasing pressure from human activity (Barbosa et al., 2019) and must be properly managed and monitored to preserve the critical services they provide.

Monitoring lake systems is becoming increasingly necessary due to climate change driven by global warming (Schlegel & Smit, 2018). Among lake systems, subtropical coastal shallow lakes (SCSL) have lower thermal inertia than deeper lakes, which makes them more susceptible to short-term climate extremes (Wieliczko et al., 2021). Water temperature, which drives physical, chemical, and biological processes in these ecosystems, is a parameter typically used to monitor SCSL (Cavalcanti et al., 2016).

Water temperature data measured *in situ* is difficult to obtain, although they provide crucial information for monitoring lake systems (Tavares et al., 2019). Remote sensing techniques have been proposed to overcome this scarcity of data, offering broader spatial and temporal coverage, that is typically unattainable through *in situ* methods, which are generally costly and complex to operate (Handcock et al., 2012). Physically-based models are also used to estimate water temperature, such as Air2Water, a very useful tool in climate change studies applied to SCSL (Piccolroaz et al., 2013).

In addition to monitoring the thermal dynamics of SCSL based on water temperature data, global climate models (GCM) can be used to predict future climates. When these methods are combined, the accuracy and reliability of their climate projections increase (Brêda et al., 2020). GCMs are subject to the emission of greenhouse gases into the atmosphere (Tejadas et al., 2016), from which the Intergovernmental Panel on Climate Change (IPCC) has proposed different Shared Socioeconomic Pathways (SSPs). The SSPs are associated with the projected interconnected impacts between biodiversity and the quality of life of human systems, requiring society to adapt in different ways through actions to mitigate these impacts and their systemic effects on ecosystems (IPCC, 2022).

Heatwave indexes, which were initially created for atmospheric systems and later applied to aquatic ecosystems can be used to measure the potential impacts of changing water temperature on the aquatic communities in SCSL (Hobday et al., 2016). In this study, we apply the cumulative intensity heatwave index, that expresses the duration and average intensity of these extreme events. Thus, the objectives of this study are to i) determine the cumulative intensity index of projected lake heatwaves for Lake Mangueira, a SCSL in the extreme south of Brazil, and ii) discuss the associated ecological impacts.

METHODOLOGY

Study area

Lake Mangueira (Fig. 1) is situated on the southern coast of Rio Grande do Sul (RS), Brazil, near the border of Uruguay. Lake Mangueira is characterized as a subtropical coastal shallow lake (SCSL), and it can also be classified as a continuous warm polymictic with no seasonal ice cover, that only stratifies for short periods of a few hours at most (Lewis Jr, 1983). The lake serves as a source of freshwater for the local rice crop, and it is part of the Taim Hydrological System, which includes the federally protected Taim Ecological Station.

Another characteristic that defines the Lake Mangueira as a SCSL is its location, from 32°20′ to 33°00′ S and 52°20′ to 52°45′ W, a subtropical region with a Cfa climate based on the Köppen Climate Classification (Tavares et al., 2019). The Lake Mangueira is considered to be shallow because of its mean depth of 2.6 m, and it reaches a maximum depth of 6.0 m in the central region. Lake Mangueira has a length of 90 km, a surface area of 820 km², and a width ranging from 3 to 10 km (Wieliczko et al., 2021). The gauging station from which the daily air temperature data were collected (detailed in the next section) is situated on a narrow strip of land to the west of Lake Mangueira (Fig. 1).

Water temperature modeling

The modeling process, which estimates a variable of interest based on other variables that are easier to obtain, varies according to the application. In this study, the variable of interest is the water temperature of lake systems, which can be estimated by the Air2Water model from air temperature data, more readily available than water temperature data (Tavares et al., 2019). The Air2Water model estimates the lake surface water temperature (LSWT) based on a simplified net heat flux representation (Eqs. 1 and 2), and its parameters are calibrated through the stochastic optimization method to which it is coupled (Toffolon et al., 2014). In Table 1, the physical meaning of each parameter of the Air2Water model is presented in more detail.

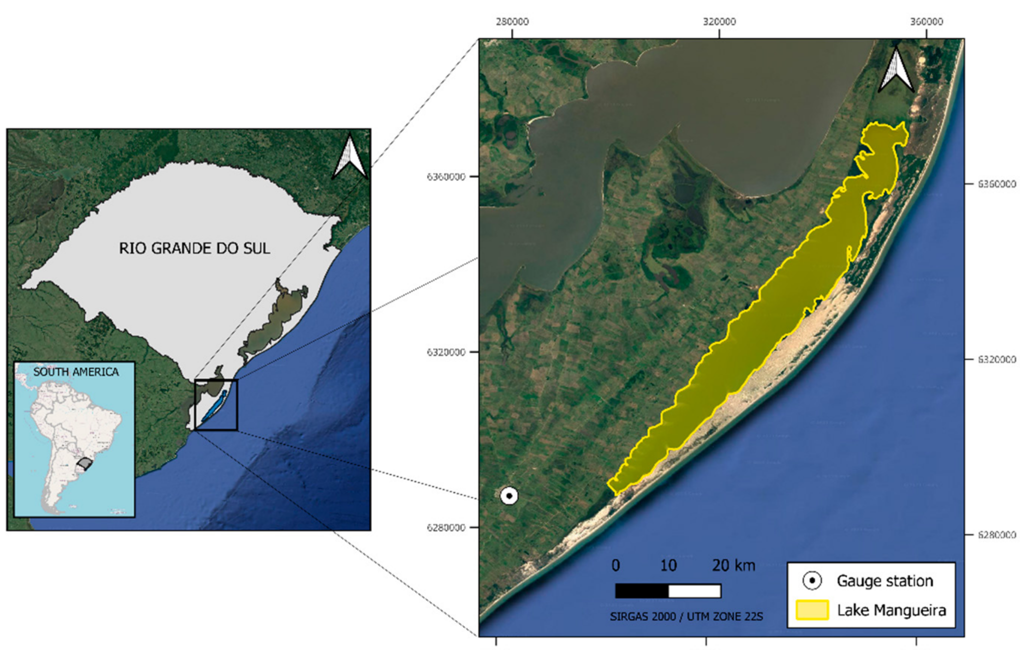


Figure 1. Location of the Lake Mangueira/RS and the weather station in Santa Vitória do Palmar/RS, both in the Extreme South of Brazil. *Localização da Lagoa Mangueira/RS e da estação meteorológica em Santa Vitória do Palmar/RS, ambas no Extremo Sul do Brasil.*

$$\frac{dT_w}{dt} = \frac{1}{\delta}\left\{a_1 + a_2\,T_a - \,a_3\,Tw + \,a_5\,cos\,\left[2\pi\,\left(\frac{t}{ty} - \,a_6\right)\right]\right\} \quad \text{(Equation 1)}$$

$$\begin{cases} \delta = \,exp\,\left(-\frac{T_w - T_h}{a_4}\right) & for\;T_w \geq \,T_h \\ \delta = \,exp\,\left(-\frac{T_h - T_w}{a_7}\right) + exp\,\left(-\frac{T_w}{a_8}\right) & for\;T_w < \,T_h \end{cases} \quad \text{(Equation 2)}$$

Where:

T_w = water temperature of the lake's surface layer (°C)
T_a = air temperature near the lake's surface layer (°C)
T_h = hypolimnion temperature (°C)
a_1 to a_8 = model parameters
t = time in adopted units
t_y = duration of a year in adopted units
δ = function of the difference between surface temperature and temperature T_h (of the hypolimnion).

The Air2Water model associates air temperature with the water temperature of the epilimnion, because this water layer exchanges heat with the air, and the air temperature is its only input variable. Thus, the main regulator of the thermal dynamics of lake systems is air temperature in the Air2Water model (Piccolroaz et al., 2013), which has already been applied to lakes around the globe (Piccolroaz et al., 2020), including lakes on the Tibetan Plateau (Guo et al., 2022), in China (Wang et al., 2024), and in the Northern Hemisphere (Toffolon et al., 2014).

Air2Water model adjustment

Particle swarm optimization (PSO) was used to adjust the parameters of the Air2Water model. In PSO, each particle in the swarm represents a candidate solution that shares information in search of the global optimum (Kennedy & Eberhart, 1995). The number of particles can vary according to the adjustment needs of the model, which considers computational costs and the maintenance of performance measures. In this study, 1000 particles were used in the Air2Water model adjustment process which maintained the performance of using the standard number of 2 000 particles (Saldanha-Ferrari et al., 2024a). The randomness component in the Air2Water model adjustment process, which is mentioned above, is associated with the uniformly distributed random numbers of the PSO method formulation to which it is coupled.

The time-series of daily air temperature data used to adjust the Air2Water model was obtained from the Santa Vitória do Palmar gauging station (Fig. 1), which has records dating back to 1961. In addition to the daily air temperature data, water temperature data covering a period of at least 1

Table 1. Physical meaning of the parameters of the full Air2Water model version. Adapted from Toffolon et al. (2014). *Significado físico dos parâmetros da versão completa do modelo Air2Water. Adaptada de Toffolon et al. (2014).*

Parameter (unit)	Physical meaning
a_1 (°C/d)	Residual difference between air temperature and lake surface temperature
a_2 (d^{-1})	Associated with the air temperature and indirectly the difference between this and the lake surface temperature
a_3 (d^{-1})	Associated with the lake surface temperature and indirectly the difference between this and the air temperature
a_4 (°C)	Direct thermal stratification strength, for water surface temperatures equal to or greater than that of the hypolimnion
a_5 (°C/d)	Amplitude of the externally imposed sinusoidal term
a_6 (-)	Phase of the externally imposed sinusoidal term
a_7 (°C)	Inverse thermal stratification strength, for water surface temperatures lower than that of the hypolimnion
a_8 (°C)	Reduced heat flow during the ice cover period

year is required to adjust the Air2Water model (Piccolroaz et al., 2013). This study used more than 20 years of daily water surface temperature data, obtained through remote sensing using the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Land Surface Temperature/Emissivity Daily Version 6.1 (MOD11A1v061) data. The specific procedures for obtaining water surface temperature data from the MOD11A1v061 are presented in the study by Saldanha-Ferrari et al. (2024b), and their general characteristics are listed in Table 2.

The Air2Water model adjustment was developed with the calibration and validation procedures. For each period, the accuracy of the Air2Water model in estimating the water temperature was measured by using two performance measures: the Nash-Sutcliffe efficiency coefficient (NSE) and the root mean square error (RMSE). After running the full 8-parameter version of Air2Water model, the NSE obtained was equal to 0.96, and the RMSE was equal to 0.85 °C, which validated the model's applicability to the study area and verified the results from another study on Lake Mangueira (Saldanha-Ferrari et al., 2024b).

Table 2. Product characteristics MOD11A1v061. Adapted from Wan et al. (2021). *Características do produto MOD11A1v061. Adaptada de Wan et al. (2021).*

Characteristic	Description
Collection	Terra MODIS
Time coverage	Since 02/24/2000
Time resolution	Daily
Spatial coverage	Global
Spatial resolution (pixel size)	1 km
Number of layers (bands)	12

Water temperature under climate changes

Air temperature data obtained from a set of 26 global climate models (GCMs) served as the input for the Air2Water model, which is widely used in studies projecting future climate (Piccolroaz et al., 2013). The time-series of daily air temperature data obtained from the GCMs and the time-series of daily water temperature estimated by the Air2Water model were associated with a historical period (January 1995 to December 2014) and a future period (January 2081 to December 2100). The future period was established using three different scenarios: SSP1-2.6, SSP2-4.5 and SSP5-8.5 (least severe, moderate and most severe, respectively). The SSPs are scenarios of average air temperature warming (IPCC, 2022), having an identification number related to the respective projection of solar radiation incident on the Earth's surface by the end of the century (Table 3).

A linear scaling method was used to remove the bias from the daily air temperature data for each GCM used in this study, listed in Table 4. This type of approach adjusts daily values based on the difference between mean monthly observed and simulated data and has good results in correcting raw temperature data (Fang et al., 2015). The time-series with corrected daily air temperatures were used as inputs for the adjusted Air2Water model, which resulted in outputs of time-series of daily water temperature for Lake Mangueira for the historical period and future scenarios. The obtained time-series were then used to determine the lake heatwave indexes.

Table 3. Solar radiation levels, average global increase in air temperature and projected challenges for Shared Socioeconomic Pathways (SSP). *Adapted from IPCC (2022). Níveis de radiação solar, aumento médio global na temperatura do ar e desafios projetados para as Trajetórias Socioeconômicas Compartilhadas (do inglês, SSP). Adaptada de IPCC (2022).*

SSP	Solar radiation (W/m²)	Average global increase in air temperature	Challenges
1	2.6	Between 1.5°C and 2°C	Low for adaptation and mitigation
2	4.5	Between 2°C and 3°C	Medium for adaptation and mitigation
5	8.5	Between 4°C and 5°C	Low for adaptation and high for mitigation

Table 4. Name (with hyperlink) and spatial resolution of the global climate models (GCMs) used in the study. *Nome (com hyperlink) e resolução espacial dos modelos climáticos globais (MCGs) utilizados no estudo.*

Name	Spatial resolution (km)
ACCESS-CM2	125
ACCESS-ESM1-5	125
AWI-CM-1-1-MR	93.5
EC-Earth3	70
EC-Earth3-Veg	70
EC-Earth3-Veg-LR	112.5
IITM-ESM	187.5
IPSL-CM6A-LR	250
MIROC6	140
MPI-ESM1-2-HR	93.5
MPI-ESM1-2-LR	187.5
MRI-ESM2-0	112.5
NESM3	187.5
BCC-CSM2-MR	112.5
CanESM5	280
CESM2-WACCM	100
CMCC-CM2-SR5	100
CMCC-ESM2	100
FGOALS-g3	200
GFDL-ESM4	100
INM-CM4-8	150
INM-CM5	150
KIOST-ESM	187.5
NorESM2-LM	250
NorESM2-MM	100
TaiESM1	100

Lake heatwave cumulative intensity index

A lake heatwave is defined as an atypically warm event that lasts at least 5 days, and has a daily water temperature higher than the 90^{th} percentile of a historical time-series used as a climatological reference. Using this methodology, it is possible, to detect heatwaves in the cooler months without underestimating them in the time-series. In this sense, the effects of these extreme events on aquatic communities can be observed beyond intra-annual seasonal variation (Hobday et al., 2016).

The heatwave index calculated in this study was the cumulative intensity, defined as the integral of daily water temperature differences relative to climatology, and it is expressed as $i_{\text{cumulative}}$ (Eq. 3).

$$i_{\text{cumulative}} = \int_{t_s}^{t_e-1} [T(t) - T_{clim}(j)]\, dt \qquad \text{(Equation 3)}$$

Where:

$i_{\text{cumulative}}$ = cumulative intensity index (°C days);
t_s = date on which the lake heatwave begins (day)
t_e = date on which the lake heatwave ends (day)
$T(t)$ = water surface temperature of the daily time-series at time t (°C)
$T_{clim}(j)$ = climatological mean calculated over a historical period on day j of the year (°C)

This integral counts the day the heatwave starts (ts) and the day before it ends, excluding the day the heatwave ends (te), which has a water temperature below the 90th percentile (Hobday et al., 2016). The cumulative intensity index can be adapted directly for any aquatic ecosystem in which a daily water temperature time-series is available for a historical period and future scenario, which makes it possible to compare the magnitude of heatwaves in locations with different temperature variability. In this context, the cumulative intensity heatwave index is an important tool for measuring the impacts of these extreme events on Lake Mangueira.

Cumulative intensity index values were determined based on the lake heatwaves in the historical period (1995 to 2014) and the future scenarios (2081 to 2100) from each GCM. The historical period was the reference for obtaining the daily time-series with the climatological mean and the 90th percentile, used to identify the lake heatwave over time and calculate the cumulative intensity, respectively. Initially, lake heatwaves projected by the CESM2-WACCM GCM were illustrated, whose average value of cumulative intensity was closest to the median of the average values over the historical period among the set of 26 GCMs. The Community Earth System Model Version 2 (CESM2) simulations contribute to Coupled Model Intercomparison Project phase 6 (Danabasoglu et al., 2020), which is used to develop the Whole Atmosphere Community Climate Model (WACCM), a comprehensive numerical model that spans a range of altitudes from the Earth's surface to the thermosphere (NCAR/NSF, 2025).

After representing only four lake heatwaves using values estimated from the CESM2-WACCM GCM, the respective average values of cumulative intensity between the 523 lake heatwave events in the historical period and future scenarios were represented. The representation chosen for the average values of cumulative intensity among the lake heatwaves estimated from CESM2-WACCM was the boxplot, which was also used to represent the average values of cumulative intensity for each of the 26 GCMs, for the historical period and future scenarios. For all boxplots, the cumulative intensity values were first plotted for the historical period and the SSP1-2.6 and SSP2-4.5 scenarios, and then for the historical period and the SSP5-8.5 scenario.

RESULTS AND DISCUSSION

Cumulative intensity index based on the CESM2-WACCM GCM

The results based on the data from the CESM2-WACCM GCM showed 52 lake heatwaves in the historical period, and 4 of them were represented graphically (Fig. 2). During each heatwave, the lake surface water temperature (LSWT) time-series varied in relation to their respective climatology, which implies differing values of cumulative intensity index. A lake heatwave of minimal duration (5 days) that is associated with a low average intensity will inevitably have a low cumulative intensity index (Fig. 2a). On the other hand, a longer lake heatwave with

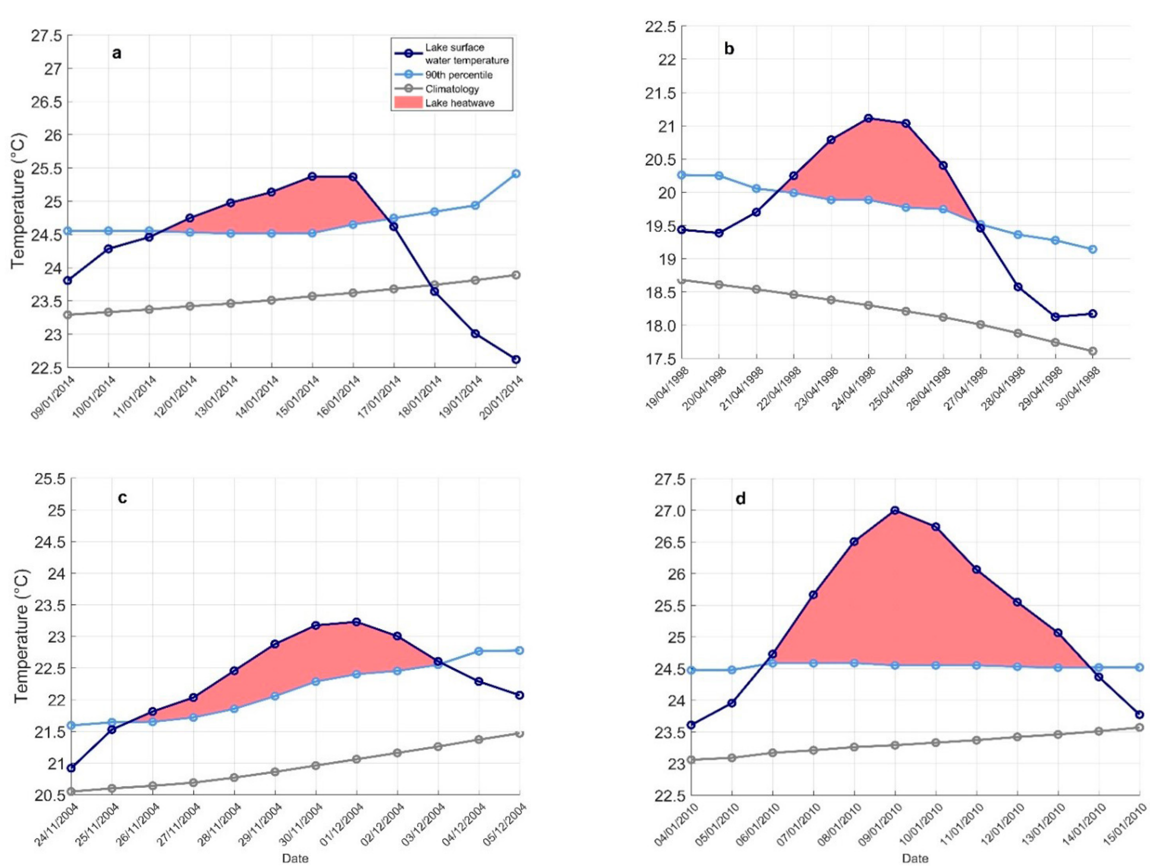


Figure 2. Time-series of water surface temperature of Lake Mangueira, and its respective 90th percentile and climatology estimated in the historical period from CESM2-WACCM GCM for lake heatwave events with values of low (a), moderate (b and c) and high (d) cumulative intensity. *Série temporal de temperatura superficial da água da Lagoa Mangueira, seus respectivos percentil 90 e climatologia estimados no período histórico a partir do CESM2-WACCM para ondas de calor lacustres com baixos (a), moderados (b e c) e altos (d) valores de intensidade cumulativa.*

a higher average intensity results in substantially higher cumulative intensity index values (Fig. 2d). Moderate cumulative intensity index values are associated with short lake heatwaves (Fig. 2c), lake heatwaves with low values of average intensity (Fig 2d), or heatwaves with a combination of moderate duration and average intensity.

Lake heatwave events with high cumulative intensity (e.g. Fig. 2d) are associated with an increase in LSWT at magnitude that exposes aquatic organisms to unprecedented extreme thermal conditions. This increase in water surface temperature is in line with the predicted increase in global average temperatures (Schlegel & Smit, 2018), and may have consequences such as the increased mortality of sensitive species, changes in species distribution/composition, and, ultimately, a loss of aquatic biodiversity (Till et al., 2019).

It is important to note that the upper distribution limits of the 52 heatwave events estimated by CESM2-WACCM GCM for the historical period did not exceed 50 °C days of cumulative intensity (Fig. 3a). By contrast, the upper distribution limits of the projected cumulative intensity values for future scenario SSP2-4.5 exceeds the threshold of 100 °C days. In addition, the median of the distribution of future scenario SSP2-4.5 (30 °C days) was higher than 75% of the cumulative intensity values from the historical period.

The median of scenario SSP5-8.5 was higher than the upper limit of the historical period, which suggests that 50% of the future heatwaves at Lake Mangueira will have a cumulative intensity equal to or greater than about 90 °C days (Fig. 3b). Furthermore, at least 25% of the lake heatwaves in this future scenario have a cumulative intensity higher than 300 °C days, based on the third quartile mark next to this threshold. In the most critical of the SSP5-8.5 scenario projections, Lake Mangueira is subject to heatwaves with cumulative intensities that exceed 600 °C days.

Cumulative intensity index based on GCMs

Boxplots of the average values of cumulative intensity for each of the 26 GCMs indicate that the thermal dynamics of Lake Mangueira will be substantially altered in the future scenarios SSP1-2.6 and SSP2-4.5 (Fig. 4a). There is a notable change in the average cumulative intensity values between even the least severe future scenario (SSP1-2.6) and the historical period. This finding is supported by approximately 75% of the projections associated with the SSP1-2.6 scenario, which have average cumulative intensities equal to or greater than all values for the historical period. In future scenario SSP2-4.5, 75% of the heatwaves at Lake Mangueira have average cumulative intensities above 30 °C days.

Projected lake heatwaves for Lake Mangueira using all 26 GCMs suggest average cumulative intensities for the SSP5-8.5 scenario that are notably higher than the historical period (Fig. 4b). At least 75% of the lake heatwaves have cumulative

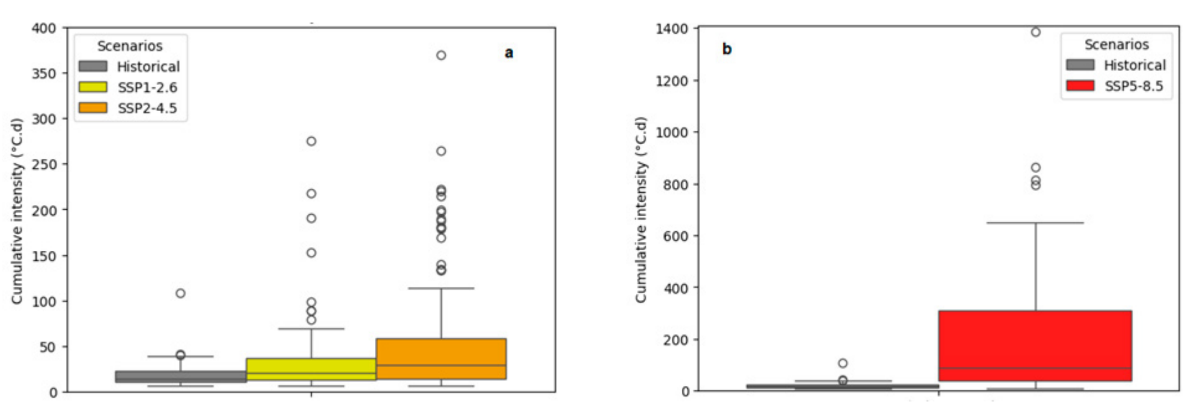
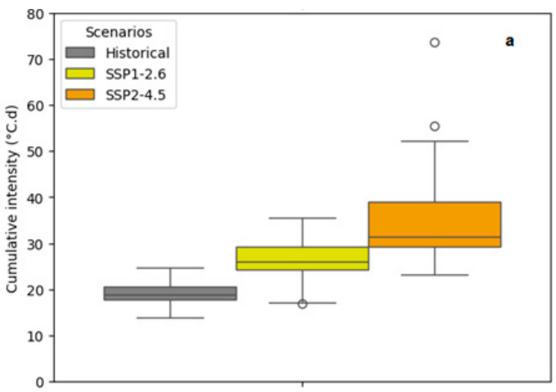


Figure 3. Cumulative intensity of lake heatwaves for Lake Mangueira from CESM2-WACCM GCM in the historical period and SSP1-2.6 and SSP2-4.5 scenarios (a), and in the historical period and the SSP5-8.5 scenario (b). The open circles are outliers. *Intensidade cumulativa de ondas de calor lacustres para a Lagoa Mangueira a partir do CESM2-WACCM no período histórico e nos cenários SSP1-2,6 e SSP2-4,5 (a), e no período histórico e no cenário SSP5-8,5 (b). Os círculos abertos são dados atípicos.*



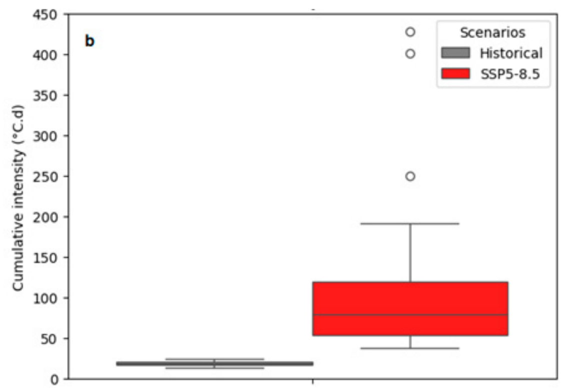


Figure 4. Average values of cumulative intensity of lake heatwaves for Lake Mangueira from each of the 26 GCMs in the historical period and the SSP1-2.6 and SSP2-4.5 scenarios (a), and in the historical period and the SSP5-8.5 scenario (b). The open circles are outliers. *Valores médios de intensidade cumulativa de ondas de calor lacustres na Lagoa Mangueira a partir de cada um dos 26 modelos climáticos globais no período histórico e nos cenários SSP1-2,6 e SSP2-4.5 (a), e no período histórico e no cenário SSP5-8,5 (b). Os círculos abertos são dados atípicos.*

intensities higher than 50 °C days in the SSP5-8.5 scenario, based on the first quartile of its distribution compared to 18 °C days in the historical period. In addition, the upper limit of the distribution of average cumulative intensities is almost 200 °C days in the SSP5-8.5 future scenario, which suggests a particularly concerning shift in the thermal dynamics of Lake Mangueira.

The elevated cumulative intensity values obtained for the projected lake heatwaves at Lake Mangueira indicate longer-lasting events and/or increasing water temperatures. These projections align with the trend of rising air temperatures by the end of this century (IPCC, 2018), and they are highly related with the upward trend in the average projected duration of lake heatwaves (Saldanha-Ferrari et al., 2024b). One indication of a significant departure from the thermal conditions that shaped the aquatic environment in the past (Woolway et al., 2021a) is a change in the dissolved oxygen concentration in a lake, which could threaten essential lake ecosystem services and its biodiversity (Jane et al., 2021).

Ecological implications

High temperatures affect aquatic organisms in many ways, including increased mortality, habitat loss and changes in food webs. For example, warmer water can affect fish growth, reproduction and behavior. Some fish move to cooler water, and others move to deeper water. Some species may lose breeding grounds as temperatures rise. These changes can lead to population decline, an increased risk of species extinction, and food web rearrangements (Pörtner et. al., 2022).

Although the impacts of climate change are widespread, they are not uniform, and accumulating evidence suggests that responses to climate change vary as a function of relative vulnerability based on differences in exposure, sensitivity, and adaptive capacity (Kovach et al., 2019). Some organisms can cope with changes to their environment changing their behavior or morphology. Behavioural responses to rising temperatures may manifest before changes at the population or species level, such as distribution shifts or population decline (Beever et al., 2017).

Morphological changes are often associated with changes in body size (Eastman et al., 2012; Ozgul et al., 2010). The metabolic rates of ectotherms are sensitive to temperature (Gardner et al., 2011), so warmer temperatures may result in faster growth rates and ultimately smaller body sizes (Atkinson, 1994). Growth rate, in turn, is related to the chemical composition of the organism and their C:N:P stoichiometry in particular, because high growth rates require a disproportionate investment in biosynthetic cell structures, which are rich in N and P (Elser et al., 1996; Woods et al., 2003). These effects are particularly concerning in tropical/subtropical lakes, such as Lake Mangueira, where the historical plankton composition is mainly nano-/microplankton (Crossetti et al., 2013; Crossetti et al., 2018; Rosa et al., 2017; Rosa et al, 2021), because of the implications for upper trophic levels.

Phenology refers to the seasonal timing of recurring biological events, which is a key indicator of species' responses to climate change (Staudinger et al., 2019). Phenological shifts in aquatic habitats are less well documented than in terrestrial systems. One documented trend is the rapid response of phytoplankton to rising temperatures. Changes in the timing of phytoplankton blooms (Wasmund et al., 2019) can create mismatches among consumers and alter food web structure (Post, 2017). Furthermore, the effects of phenological shifts on species with multiple life stages are complex, and shifts that are beneficial to one life stage may be detrimental to another (Campbell et al., 2019). Thus, asynchronous phenological shifts have the potential to disrupt the functioning, persistence and resilience of population dynamics, ecosystems and ecosystem services (Asch et al., 2019; Staudinger et al., 2019).

Finally, climate change is causing large-scale changes to the distribution and abundance of species, which results in the restructuring of terrestrial and aquatic ecosystems (Lenoir & Svenning, 2015; Pacifici et al., 2017). Factors such as microclimates, complex topography, and land use changes must be taken into account to accurately predict changes in organisms and ecosystems (Guo et al., 2018; Sirami et al., 2017). The projections presented in this study confirm the vulnerability of Lake Mangueira to extreme events due to climate change and its morphometry (Wieliczko et al., 2021).

The effects of lake heatwaves can also be observed in other parameters, such as oxygen levels, which directly affect the distribution of aquatic species. These effects occur on short timescales due to the rapid metabolic response of aquatic organism to rising water temperatures (Cavalcanti et al., 2016). Aquatic species and populations respond to rising temperatures through changes in morphology, behavior, phenology, and geographic range shifts. These changes are mediated by evolutionary responses and, when combined with the direct impacts of climate change on ecosystems, including more extreme events, accentuate widespread changes to productivity, nutrient cycling, species interactions, vulnerability to biological invasions, and other emergent properties (Weiskopf et al., 2020). These impacts may alter the benefits and services that ecosystems provide to society.

CONCLUSION

This study assesses the effects of climate change on the water temperature of Lake Mangueira, an ecosystem that is vulnerable to extreme events such as heatwaves. Using a large ensemble of global climate models and an adjusted lake surface water temperature model, important shifts in the state of Lake Mangueira were verified using the cumulative intensity index. This heatwave index can be used as a control and monitoring tool for lakes, because water temperature, the variable used to calculate the index, drives multiple processes in these ecosystems.

The cumulative intensity values obtained from the CESM2-WACCM GCM show that at least half of the cumulative intensity projections for the SSP2-4.5 future scenario exceed 75% of the historical lake heatwave index. The shift in the thermal dynamics of Lake Mangueira worsens in the most severe future scenario (SSP5-8.5), where half of the cumulative intensity projections exceed every cumulative intensity value from the historical period and also exceed the 90 °C days threshold.

The cumulative intensity values from an ensemble of 26 GCMs show that at least 75% of the projections indicate lake heatwaves with average cumulative intensities higher than 50 °C days in the SSP5-8.5 scenario, compared to 18 °C days during the historical period. Even in the least severe future scenario (SSP1-2.6), 75% of the projected average cumulative intensities equal or exceed every value from the historical period.

The cumulative intensity values obtained from the GCMs highlight the vulnerability of subtropical coastal shallow lakes, such as Lake Mangueira, to climatic extremes. Our results indicate that Lake Mangueira will be exposed to more intense and/or longer-lasting heatwaves, which may have serious consequences for the aquatic communities in the lake. The increased risk of negative impacts on this ecosystem underscores the importance of studying heatwave indexes, such as cumulative intensity, to reduce long-term ecological costs, and the vulnerability of human communities to the environmental services associated with lake systems. Long-term in situ and/or remote sensing studies are needed to assess the true impact of global climate change on lake ecosystems. Studies that highlight the resilience of aquatic ecosystems to climate change can contribute to the conservation and management of these environments.

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AUTHOR CONTRIBUTIONS

C.H.S.F.: data modelling, programming and analysis, writing - original draft and graphic preparation; J.M.B.: data modelling and programming; M.H.T.: Data modelling; D.d.M.M.: project supervision; L.H.R.R.: discussion of results, project supervision, and writing - proofreading and editing.

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