

Global reconstruction of twentieth century lake surface water temperature reveals different warming trends depending on the climatic zone

Article

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1 Title

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3 warming trends depending on the climatic zone

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22 Abstract

23 Lake surface water temperatures (LSWTs) are sensitive to climate change, but previous
24 studies have typically focused on temperatures from only the last few decades. Thus, while
25 there is good appreciation of LSWT warming in recent decades, our understanding of longer-
26 term temperature change is comparatively limited. In this study, we use a mechanistically
27 based open-source model (*air2water*), driven by air temperature from a state-of-the-art global
28 atmospheric reanalysis (ERA-20C) and calibrated with satellite-derived LSWT observations
29 (ARC-Lake v3), to investigate the long-term change in LSWT worldwide. The predictive
30 ability of the model is tested across 606 lakes, with ninety-one percent of the lakes showing a
31 daily Root Mean Square Error smaller than 1.5 °C. Model performance was better at mid-
32 latitudes and decreased toward the equator. The results illustrated highly variable mean
33 annual LSWT trends during the 20th century and across climatic regions. Substantial warming
34 is evident after ~1980 and the most responsive lakes to climate change are located in the
35 temperate regions.

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42 project. Satellite lake temperature data are available at <http://www.laketemp.net>. The lake
43 model used is available to download from <https://github.com/spiccolroaz/air2water>.

45 **Introduction**

46 Global climate change is increasingly evident from a wide variety of observations (Hulme
47 2016; Roe et al. 2017; Rogora et al. 2018). Surface air temperature measurements show a
48 rapid increase in global temperature during the 20th century (IPCC 2013), and climate models
49 project continued warming in the future (Cubasch et al. 2001; Meehl et al. 2007). Numerous
50 studies have also shown widespread increases in lake surface water temperature (LSWT)
51 (Schneider and Hook 2010; O'Reilly et al. 2015; Woolway et al. 2017a; Ptak et al. 2018).
52 Such increases are of great importance to aquatic ecology, as changes in lake temperature
53 influence a myriad of physical and ecological processes, including mixing patterns,
54 phenology, and the structure of biotic communities (Adrian et al. 2009; Kraemer et al. 2015;
55 Piccolroaz et al. 2015; Thackeray et al. 2016). Understanding lake thermal responses to
56 climate is therefore critical for predicting biotic change and for anticipating the repercussions
57 of climatic variability on lakes and their associated ecosystems.

58 While there is sufficient evidence to demonstrate that lakes have warmed in recent
59 decades, our understanding of longer-term temperature change (e.g., extending back before
60 the second half of the 20th Century) is comparatively limited. Global LSWT studies have
61 relied heavily on thermal infrared imagery from spaceborne satellites and, as such, are
62 restricted to the period since the early 1980's (Schneider and Hook 2010; O'Reilly et al.
63 2015). Other observational methods include paleolimnological temperature proxies (Tierney
64 et al. 2010; Lehnherr et al. 2018) and in-situ measurements (Verburg et al. 2003; Austin and
65 Colman 2008; Kainz et al. 2017; Woolway et al. 2017a; Matulla et al. 2018). However, the
66 lakes investigated using these methods are relatively few in number. The lack of a global 20th
67 century baseline temperature against which recent lake warming can be referenced limits
68 quantitative understanding of LSWT trends observed in recent decades within the context of
69 longer-term variability. For example, several lakes around the world have demonstrated a
70 response to the recent warming 'hiatus' (1998-2012) (Medhaug et al., 2017), and LSWT
71 trends evaluated during the hiatus period may underestimate longer-term warming (Winslow
72 et al. 2018). In addition, analysing the relationship between large-scale teleconnection
73 patterns and fluctuations of LSWT trends found in some regions (Livingstone and Dokulil,
74 2001; Blenckner et al. 2007; Katz et al., 2011; Salmaso 2012; Ptak et al. 2018) may provide
75 new insights if a long-term global map of LSWT dynamics would be available. The extent to
76 which lake warming has occurred at a global scale during the last century, and how those
77 patterns vary across lakes worldwide, requires further investigation.

78 Due to the scarcity of in-situ observations, quantifying LSWT change worldwide
79 during the 20th century requires a modelling approach. Trying to make reliable predictions of
80 how LSWT has evolved due to climatic change is difficult. LSWT responds to complex
81 thermodynamic fluxes (Henderson-Sellers 1986; Woolway et al. 2015), hence its precise
82 quantification using process-based numerical models requires detailed over-lake
83 meteorological data (e.g., wind speed, humidity, cloud cover) as inputs (Bruce et al. 2018).
84 In-situ meteorological information of such fine detail is not frequently available above lakes
85 worldwide and over long-time periods and meteorological gridded products are typically
86 associated with coarse spatial resolution and larger uncertainties when extending back prior
87 to the second half of the 20th Century. To overcome this limitation, previous studies have
88 used simple regressive/statistical models (Webb 1974; McCombie 1959; Sharma et al. 2008).

89 These require as input only air temperature, a variable that is more often available and
90 commonly more reliable than other meteorological variables (Gleckler et al. 2008). However,
91 regression models are typically not able to address some fundamental physics and their use is
92 controversial when applied with air temperature ranges beyond the limits of the time series
93 used for model calibration (Piccolroaz et al., 2018), as would be expected under climate
94 change.

95 To overcome the limitations of the aforementioned traditional modelling approaches,
96 Piccolroaz et al. (2013) developed the *air2water* model, a hybrid model (Toffolon and
97 Piccolroaz 2015) which combines a physically based derivation of the governing lake
98 thermodynamic equations with a statistical calibration of model parameters. The model was
99 developed to retain the simplicity of regression models, such as the limited number of
100 required input variables, while preserving the robustness of deterministic models. *air2water*
101 has been shown to provide similar performance, in terms of simulating LSWT, to process-
102 based models (Toffolon et al. 2014; Piccolroaz 2016), and to be an effective tool to
103 investigate LSWT responses to historic and future climate change (Piccolroaz et al. 2015;
104 Piccolroaz et al. 2016; Wood et al. 2016; Czernecki and Ptak 2018; Piccolroaz et al. 2018;
105 Piccolroaz and Toffolon 2018) also when applied to lakes with different morphological
106 characteristics from around the world (Toffolon et al. 2014; Prats and Danis 2019).

107 Producing reliable projections of LSWT using only air temperature globally would be
108 a major advantage for many scientific purposes and practical applications. For this reason, in
109 this contribution we use *air2water* forced by a state-of-the-art global air temperature
110 reanalysis product (ERA-20C) to simulate long-term LSWT change in 606 lakes worldwide
111 during the 20th century. Besides showing the potential of this model for global-scale climate
112 change impact studies on lakes, we use the reconstructed LSWT time series to investigate
113 how lakes situated across climatic gradients have responded to climate change since 1900.
114 Also, while previous studies have focussed on LSWT variations during summer (Jul-Sep)
115 (Austin and Colman 2007; Schneider and Hook 2010; O'Reilly et al. 2015) we focus, in this
116 study, on annually-averaged LSWTs, thus gaining a different, and potentially more insightful,
117 perspective of LSWT change. With this study we aim at contributing to research on the lake
118 thermal dynamics and trends through providing the first global reconstruction of LSWT
119 during the 20th century.

120

121 **2. Materials and methods**

122 *2.1. Study sites and characteristics* - The lakes investigated in this study ($n = 606$)
123 were selected based on the availability of satellite-derived LSWT observations (see below).
124 The study sites vary in their geographic and morphological characteristics. They range in
125 altitude between -216 m above sea level and 4,753 m above sea level, in latitude between
126 54.55 °S and 74.48 °N, in surface area between 49.06 km² and 81,844 km², and in mean
127 depth between 0.1 m and 738.7 m (Table S1).

128

129 *2.2. The air2water model* - To simulate LSWT in each lake, we used the *air2water*
130 model (Piccolroaz et al. 2013), an open-source model that simulates LSWT relying solely on
131 surface air temperature observations as reasonable proxy for the overall external forcing. It is
132 a zero-dimensional heat budget model to the well-mixed surface volume of the lake,

133 accounting for all the heat flux components at the lake-atmosphere interface (shortwave
134 radiation, longwave radiation, and diffusive terms) mathematically simplified to obtain a
135 simple ordinary differential equation. The added value of *air2water* compared to purely
136 regressive models is the explicit inclusion of the effect of vertical thermal stratification on
137 lake thermal dynamics through a simple, yet effective, empirical relationship. In this respect,
138 the model showed good ability also to simulate the seasonal evolution of the well-mixed layer
139 thickness (Toffolon et al. 2014; Piccolroaz et al. 2015). A detailed description of the model is
140 available in Text S1 in the Supplementary material.

141 The six model parameters of *air2water* (see Text S1) were calibrated by optimizing a
142 metric of model performance via an automatic optimization procedure (Particle Swarm
143 Optimization, Kennedy and Eberhart 1995), using only air temperature as input and observed
144 LSWT as reference. In this way, the model is data-driven (Solomatine et al. 2009), while
145 being physically based, allowing for distilling information about the behaviour of the system
146 into the values of the parameters. The model equation was solved numerically by using the
147 Crank-Nicolson numerical scheme with a daily time step.

148
149 *2.3. Surface air temperature* - We downloaded the air temperatures needed to drive
150 *air2water* from the European Centre for Medium Range Weather Forecasts' (ECMWF)
151 ERA-20C reanalysis product, which provides air temperature at 2-m height above surface at a
152 daily time step and at a grid resolution of 1° (European Centre for Medium-Range Weather
153 Forecasts, 2014). Time series data were extracted for the grid point situated closest to the
154 centre of each lake, defined as the location of maximum distance to land, calculated using the
155 distance-to-land dataset of Carrea et al. (2015). When the surface elevation of the ERA-20C
156 grid was not equivalent to the elevation of the lake, surface air temperature was corrected to
157 over-lake values using appropriate lapse rates (Γ). Γ is variable within short time periods
158 (Rolland 2003), due to, among other things, synoptic circulations (Pagès and Miró 2010) and
159 changing cloud cover (Minder et al. 2010), and therefore in this study we followed the
160 method of Gao et al. (2012). We evaluated site-specific Γ by calculating the difference
161 between temperatures at two pressure levels covering the maximum elevation range of a grid
162 (such as 850 hPa and 925 hPa) and divided through the differences in the corresponding
163 geopotential heights (i.e., the geopotential $\text{m}^2 \text{s}^{-2}$ divided by the gravitational acceleration
164 9.81 m s^{-2}).

165
166 *2.4. Satellite-derived lake surface temperature data* – The parameters of the *air2water*
167 model were calibrated against satellite-derived lake surface water temperature data from the
168 ARC-Lake v3 dataset (MacCallum and Merchant 2012), available at
169 <http://www.laketemp.net>. Daily lake-mean time-series were obtained from the spatially-
170 resolved satellite data by averaging across the lake area. Lake-mean surface temperatures
171 were used in order to average across the intra-lake heterogeneity of LSWT responses to
172 climate change (Woolway and Merchant 2018; Zhong et al. 2018). We used fifteen years
173 (1996-2010) of data to calibrate the model. Such a calibration period was shown by
174 Piccolroaz (2016) and Piccolroaz et al. (2018) to be sufficient to generate accurate predictions
175 of LSWT using *air2water*, also when the time series is affected by large gaps (as is common

176 in satellite-derived lake surface temperature due to the presence of clouds). The entire
177 satellite-data period was used to make the derived model parameters as robust as possible.

178

179 *2.5. Statistical methods and analysis* – The accuracy of *air2water* in simulating
180 LSWT was evaluated by calculating the Root Mean Square Error (also used as performance
181 metric for model calibration):

182

$$183 \quad RMSE = \sqrt{\frac{\sum_{i=1}^N (\hat{T}_{w,i} - T_{w,i})^2}{N}}, \quad (4)$$

184

185 and the Nash Sutcliffe Efficiency Index (Nash and Sutcliffe 1970):

186

$$187 \quad NSE = 1 - \frac{\sum_{i=1}^N (\hat{T}_{w,i} - T_{w,i})^2}{\sum_{i=1}^N (\hat{T}_{w,i} - \bar{T}_w)^2}, \quad (5)$$

188

189 where $\hat{T}_{w,i}$ and $T_{w,i}$ are the daily observed and simulated LSWT at time i , \bar{T}_w is the mean of
190 observed temperature, and N is the length of the observational record. The NSE is a
191 normalized metric that provides an evaluation of model performance relative to the variability
192 of the observed time series. This metric ranges from $-\infty$ to 1: a value of 1 corresponds to a
193 perfect match between measured and simulated values, and a value of 0 indicates that the
194 model prediction is as accurate as using the mean of the observations. In this study, we define
195 the lakes that are reasonably well modelled by *air2water* as those with a NSE of greater than
196 0.8.

197

198 The statistical metrics above were compared across climatic zones, as identified by
199 the Köppen climate classification (Köppen and Geiger 1930; Köppen 1990), which provides
200 an efficient way to describe climatic conditions defined by multiple variables and their
201 seasonalities. Here, we used the Köppen climate classification for a long-term average
202 climate (1901-2010), using the same criteria as Kottek et al. (2006) and Chen and Chen
203 (2013). The Köppen classification uses monthly temperature and precipitation data averaged
204 over the 1901-2010 period, on a 0.5° longitude x 0.5° latitude grid. For a fuller account, refer
205 to Chen and Chen (2013). The Köppen climate classification of each lake is given in Table
206 S1. The main characteristics of the Köppen climate zones are described in Table S2.

206

207 The long-term variations of air temperature and LSWT were analysed in terms of
208 annually-averaged temperature anomalies relative to the reference period 1951-1980. For
209 each lake, thermal reactivity to changes in air temperature was quantified as the slope of the
210 regression line (without intercept) between annually-averaged air temperature anomalies (x-
211 axis) and LSWT anomalies (y-axis) over the 1900 to 2010 period (excluding the reference
212 period 1951-1980).

212

213 **3. Results**

214

215 3.1. *Model performance* – The results of using *air2water* to simulate the seasonal
216 cycle of LSWT is illustrated in Figure 1. We compared the time series of observed and
217 simulated LSWT for five selected case-study lakes (Lake Malombe, Lake Assad, Lake
218 Garda, Lake Tahoe, Har-Hu Lake), one from each of the major Köppen climate classification
219 zones. The calculated daily RMSE of each case-study lake was below 1 °C, and the NSE was
220 above 0.9. Inspection of these time series suggests that the model is able to capture several
221 aspects of the inter-annual variability in LSWT, such as the timing of warming and cooling,
222 and year-to-year differences in the summer maximum and winter minimum. In addition,
223 *air2water* is able to simulate the presence and timing of ice cover (where applicable) and the
224 annual range in LSWT (Fig. S1).

225 To extend the evaluation of the ability of *air2water* to simulate LSWT worldwide we
226 show, in Figure 2, the calculated daily RMSE and NSE for all lakes, inherently characterized
227 by considerably different annual LSWT cycles (see Fig. S2). The calculated RMSE between
228 modelled and observed daily LSWTs across the study sites varied between 0.41 °C and 2.32
229 °C, with an average value among all the lakes equal to 1.10 °C. The RMSE values were less
230 than or equal to 1.00 °C in 38% of the lakes studied, and less than or equal to 1.50 °C in 91%
231 of cases. The computed NSE also varied among lakes, ranging between -0.05 and 0.99, with
232 an average value among all the lakes of 0.90. A NSE larger than 0.95 was calculated in 74%
233 of lakes, while a value larger than 0.90 was calculated in 84% of lakes. Cases of NSE close to
234 0 were restricted to equatorial lakes, while it rapidly increased to a value close to 1 towards
235 approximately 15° latitude (North and South, Figs 2b and d). As further commented in the
236 Discussion, such low values of this performance metric were primarily linked with the
237 thermal characteristics inherent to these lakes, which are characterized by small variance of
238 observations (see Fig. S2b), rather than with substantial model deficiencies. This is also
239 suggested by the absence of any strong relationship between latitude and the calculated
240 RMSE, which shows relatively small values throughout the range of considered latitudes
241 (Fig. 2c), except for a slight decrease in model performance at higher latitude, in particular
242 northward of 50°N.

243 Although latitude can be assumed as a first proxy for mean climatic conditions, we
244 reinforced this analysis by evaluating the two metrics of model performance among the more
245 representative Köppen climate classification zones (Fig. 3). The RMSE in lakes situated
246 within a ‘Tropical’ climate was 0.87 °C ($n = 80$), compared to 1.08 °C ($n = 51$) in lakes
247 situated within a ‘Dry’ climate, 1.02 °C ($n = 143$) in lakes situated within a ‘Mild temperate’
248 climate, 1.21 °C ($n = 313$) in lakes situated within a ‘Snow’ climate, and 1.05 °C ($n = 19$) in
249 lakes situated within a ‘Polar’ climate. The RMSE was comparable among the five climatic
250 zones, although slightly smaller values were obtained for ‘Tropical’ and ‘Polar’ regions.
251 Conversely, the comparison of the calculated NSE among the Köppen climate classification
252 zones demonstrate clearly that, relative to this metric, model performance was lower in
253 tropical lakes, compared to any other climate zone. In particular, we calculated an average
254 NSE of: Tropical = 0.55, Dry = 0.95, Mild temperate = 0.94, Snow = 0.96, Polar = 0.92.
255 However, some lakes situated within the ‘Mild Temperate’ ($n = 7$) and ‘Dry’ ($n = 1$) Köppen
256 climate zones also experienced poor model fit ($NSE < 0.5$), but these were situated at low
257 latitude. Specifically, these lakes were clustered in Central-Eastern Africa (Fig. 2b),

258 essentially in a ‘Mild Temperate’ Köppen climate zone of the type *Cfb*, a subtropical oceanic
259 climate that can be found in mountainous locations of some tropical countries (Fig. 3b).

260

261 3.2. *Global 20th century temperature evolution*- Figure 4a and b show the modelled
262 LSWT variations (annually-averaged temperature anomalies) of the studied lakes along with
263 the corresponding air temperatures variations, grouped by Köppen climate zones and
264 separated between Northern and Southern Hemisphere, from 1900-2010. The analysis was
265 carried out only on lakes with a NSE higher than 0.8 ($n = 540$). The results indicate that lake
266 surface temperatures have varied considerably from 1900 to 2010, with substantial
267 differences between lakes in the Northern ($n = 479$) and Southern Hemisphere ($n = 61$) and
268 across Köppen climate zones. For example, while in both Hemispheres a clear warming
269 occurred since the 1980s, different trends emerged during the first half of the century (e.g.,
270 prior to 1950). A previous pronounced warming period, during the so called Early Twentieth
271 Century Warming (ETCW) (see e.g., Hegerl et al. 2018), involved all but Tropical lakes in
272 the Northern Hemisphere and particularly lakes in the ‘Snow’ Köppen climate zone (see also
273 the Discussion for further details). On the contrary, lakes in the Southern Hemisphere were
274 characterized by slower but continuous warming after the 1920s. A synthesis of the warming
275 trends in the two hemispheres and across Köppen climate zones is provided in the
276 Supplementary material (Table S3) for overlapping subperiods of 30 years.

277 Such distinct LSWT dynamics clearly reflect different air temperature trends, but
278 LSWTs were substantially modulated by the lakes’ thermal reactivity, which is different
279 depending on the Köppen climate zones (Fig. 4c; see also Table S3). In all lakes, the thermal
280 reactivity to changes in air temperature quantified through the regression fit described in
281 Section 2.5 was statistically significant ($p < 0.01$). Results are summarized in Figure 4c,
282 grouped by climate zones. On average the annually-averaged thermal reactivity, was higher
283 (i.e., more responsive lakes) for the ‘Mild Temperate’ zone (median value of 0.55), and lower
284 (i.e., more resilient lakes) for the ‘Snow’ and ‘Polar’ zones (median value of 0.17 and 0.18,
285 respectively; see also Fig. S3). Lakes in the ‘Tropical’ and ‘Dry’ climate regions had
286 intermediate values (median value of 0.48 and 0.36, respectively). The effects on LSWT
287 response to air temperature trends are clear. In the Northern Hemisphere, after the 1990s air
288 temperature in the ‘Polar’ and ‘Snow’ regions warmed more than in the other climate regions,
289 but LSWT did not respond considerably as an annual average. Conversely, lakes in the ‘Mild
290 Temperate’ region experienced a significant warming, almost four times more intense than in
291 the ‘Polar’ and ‘Snow’ regions (on average 0.48°C vs. 0.12°C , relative to the reference period
292 1951-1980; see also Table S3 for an overview of the different air temperature and LSWT
293 warming trends across Köppen climate zones).

294 The low thermal reactivity observed in lakes that freeze in winter (particularly in the
295 ‘Polar’ and ‘Snow’ regions) are, at least partially, ascribable to the insulating effect of the
296 ice-cover, which inhibits heat exchange at the lake-atmosphere interface. As expected, the
297 same slope of the regression line between annually-averaged air temperature anomalies and
298 LSWT anomalies evaluated considering only the ice-free period indicated clearly higher
299 thermal reactivity in all but ‘Tropical’ lakes (since these lakes do not freeze), and particularly
300 in lakes located in the ‘Snow’ and ‘Polar’ regions (Fig. S4). This is coherent with previous
301 studies that suggested that deep and cold lakes exhibit an amplified response of LSWT to

302 changes in air temperature in summer (Piccolroaz et al. 2015; Zhong et al. 2016; Woolway
303 and Merchant 2017). Despite this amplification effect expected for deep lakes in the ‘Snow’,
304 ‘Polar’ and cold ‘Dry’ regions, however, on an annual basis the lakes located in the ‘Mild
305 Temperate’ region are confirmed to be the most thermally responsive.

306

307 **4. Discussion**

308 Many earlier studies have used models to simulate LSWT change, but these have typically
309 focused on individual lakes (Hadley et al. 2014; Piccolroaz et al. 2018), or a large number of
310 lakes within a confined region (Hondzo and Stefan 1993; Read et al. 2014; Winslow et al.
311 2017a; Woolway et al. 2017a; Czernecki and Ptak 2018; Prats and Danis 2019). In addition, a
312 large proportion of previous studies have used models that require a number of
313 meteorological variables. Prior to this investigation, no known studies have simulated LSWT
314 responses to climate change in lakes worldwide by using surface air temperature as the only
315 climatic driver.

316 For many of the 606 studied lakes, *air2water* was able to predict accurately LSWT
317 during the satellite-period. One of the most relevant features of the *air2water* simulations was
318 that the model was able to reproduce accurately inter-annual fluctuations of LSWT. This is
319 particularly remarkable considering that air temperature from reanalysis at grid resolution of
320 1° was used in the model calibration. The *air2water* model performed best, as evaluated by
321 NSE, in non-tropical lakes. In general, a decrease in model performance can be observed
322 towards the equator. However, we must note that this is predominantly a result of the
323 minimal seasonal variability of LSWT in these lakes and is inherent in the definition of NSE.
324 Specifically, lakes at low latitudes (i.e., lower than 15° North and South) typically experience
325 a seasonal range of < 5 °C compared to > 25 °C in some temperate lakes (Fig. S2). Thus, the
326 same RMSE between observed and modelled LSWT has a greater impact on model accuracy,
327 in terms of NSE, in near-equatorial lakes. However, we notice that the worst model
328 performance was bounded between 15 °S and 15 °N, while in the remainder of the tropical
329 region it was comparable to that of lakes located in the other climatic regions. In this regard,
330 among the 66 lakes excluded from the analysis because associated to NSE values lower than
331 0.8, the 92% was between 15 °S and 15 °N and the 83% belonged to the ‘Tropical’ region.

332 Besides the clear predictive value of this simple tool, *air2water* has also some
333 limitations. Surface air temperature is closely related to some of the heat fluxes controlling
334 the net surface energy budget in lakes, such as surface radiation, which is typically a
335 dominant heating term at the lake surface (Schmid and Köster 2016). This allows LSWT to
336 be modelled as a function of air temperature alone in some lakes (Livingstone and Lotter
337 1998). However, other variables such as humidity and wind speed, can influence greatly the
338 lake surface energy budget and thus LSWT (Edinger et al. 1968). For example, tropical lakes
339 experience higher latent heat loss, compared to lakes situated in other climate zones, as a
340 result of the Clausius-Clapeyron relationship whereby the air-water humidity difference, to
341 which the latent heat flux is proportional, increases with decreasing latitude (Woolway et al.
342 2018). In addition, abundant precipitation can contribute to the heat budget of these lakes
343 (Rooney et al. 2018), and the atmospheric boundary layer is typically unstable (Woolway et
344 al. 2017b) resulting in enhancement of near-surface wind speed and greater turbulent heat
345 loss. Some of these contributions are, at least partially, accounted for in the seasonal term

346 included in the *air2water* model, although they do not explicitly appear in the model
347 equations (see Text S1 and Fig. S6 in the Supplementary material)

348 Modelled LSWT also demonstrate a slight decrease of model performance towards
349 higher latitude, in particular in lakes situated in northern Siberia and northern North America.
350 This could indeed be an artefact in the LSWT data used in the model calibration, such that
351 these lakes are typically ice-covered for a large part of the year, thus reducing the number of
352 observational points available for calibration. Additionally, a physically-based ice module has
353 not yet been implemented in the *air2water* model, possibly affecting its performance when
354 applied to lakes that freeze in winter, although the current version of the model has showed
355 good performance also in these cases (Toffolon et al. 2014; Piccolroaz et al. 2015; Czernecki
356 and Ptak 2018; Piccolroaz and Toffolon 2018). Finally, we should notice that also
357 hydrological (e.g., groundwater and snow-melting inflows) and anthropogenic (e.g., sewage
358 inflows, cooling/heating systems) factors may affect model performance in some lakes,
359 which are only implicitly included in the formulation of the model.

360 Given the relatively short duration of the satellite-period, independent model
361 validation was renounced in favour of a more robust calibration of parameters (model validity
362 has been widely demonstrated in several previous applications). This allowed us to
363 reconstruct the global 20th century LSWT evolution with a certain degree of confidence for
364 the first time, contributing to improved understanding of recent and past evolution of lake
365 thermal dynamics worldwide. The LSWT hindcast period covered also the ETCW
366 pronounced warming period, which mainly involved lakes in the Northern Hemisphere (Fig.
367 4a). The ETCW period has been attributed to a combination of external forcing and internal
368 decadal variability, and it is visible also in other global temperature datasets such as
369 HadCRUT4 (see e.g., Hegerl et al. 2018). It was particularly prominent over high latitudes of
370 the Northern Hemisphere, and encompassed exceptional events as for example the Greenland
371 warming in the 1920s-1930s (Chylek et al. 2006) and the ‘Dust Bowl’ drought and heat
372 waves in North America in the 1930s (Cowan et al. 2017). The effects on LSWT are
373 appreciable from some of the few long-term time series covering this period (Magee and Wu,
374 2017; Potemkina et al. 2017), although due to data scarcity they received little attention. The
375 results presented here provide first evidence and quantification of a systematic warming of
376 high latitude lakes in the Northern Hemisphere during the ETCW, which for lakes in the
377 ‘Snow’ climate region was more than twice the recent warming (anomalies relative to the
378 reference period 1951-1980 of 0.31°C in the 1920-1940 vs. 0.12°C in the 1990-2010). We
379 stress that the magnitude of such warming is inherently dependent on the accuracy of the
380 reanalysis product used in the analysis, which, despite the well-recognized good reliability of
381 the ERA-20C dataset, may further improve in the future. In this regard, we should notice that
382 the ERA-20C dataset is affected by changes in the observing system, especially in regions of
383 sparse coverage as for example the Southern Hemisphere or during periods such as around
384 World War II due to non-standard observing practice during wartime (Poli et al., 2016).

385 The present analysis focused on annually-averaged temperatures, offering a change of
386 paradigm compared to the recent tendency towards focusing on long-term changes in summer
387 LSWT (Schneider and Hook 2010; O’Reilly et al. 2015; Sharma et al. 2015). Although
388 summer-averaged LSWT have undoubtedly been pivotal in our understanding and for
389 evaluating the direction of warming globally, they cannot be assumed as representative of the

390 overall thermal response of lakes, due to the existence of substantial seasonal variations in
391 LSWT warming rates (Winslow et al. 2017b; Woolway et al. 2017a; Toffolon et al., 2020)
392 primarily modulated by stratification dynamics (Piccolroaz et al. 2015; Zhong et al. 2016).
393 Specifically, lakes thermal reactivity to changes in air temperature is much higher in summer
394 due to strong thermal stratification, thus lower thermal inertia (Piccolroaz et al. 2015). This
395 is exemplified by the larger values of the thermal reactivity illustrated by Schmid et al. (2014)
396 considering equilibrium LSWT (a proxy for summer lake temperature), compared to our
397 results based on annual averages (Figure 4c).

398 Analysing annual averages in this study allowed us to obtain an integrated overview
399 of lakes thermal dynamics overcoming the seasonal-specific validity of previous global
400 trends. We claim that this is a first step towards extending our understanding of lakes thermal
401 behaviours to all seasons. In fact, not only the intensity but also the timing of air temperature
402 variations crucially affects the extent to which lake surface temperature changes (Piccolroaz
403 et al. 2015; Zhong et al. 2016). In this regard, we note that the lakes thermal sensitivity
404 evaluated in this analysis (Fig. 4c) should be intended as an average value for the study
405 period, while locally it may undergo changes depending on specific air temperature variations
406 throughout the season, possibly modulated also by the insulating effect of the ice cover in
407 lakes that freeze in winter. In addition, morphological factors such as mean depth are known
408 to affect lakes thermal inertia (Toffolon et al. 2014), explaining part of the variability of the
409 computed lakes thermal sensitivity within the same climatic group (Fig. 4c). However, this
410 did not prevent from identifying marked differences across the climatic zones (Fig. S5), with
411 lakes in the ‘Mild Temperate’ region being the most responsive to air temperature changes,
412 but adds another element to be carefully considered in future analyses.

413

414 **5. Conclusions**

415 In this study we presented the first reconstruction of the global 20th century LSWT evolution
416 and contributed to improved understanding of the impact of climate change on lake thermal
417 dynamics worldwide. To this end, we used a simple, but mechanistically based model,
418 *air2water*, which relies on air temperature as the only climate input. In terms of RMSE
419 between observed and modelled daily temperatures, *air2water* was able to simulate the
420 surface temperature of many lakes to within 1.5 °C, similar to the performance achieved by
421 other, more computationally expensive models, which require additional meteorological input
422 data (Stefan et al. 1998; Peeters et al. 2002; Thiery et al. 2014; Zhong et al. 2016; Prats and
423 Danis 2019).

424 The results illustrated highly variable LSWT trends during the 20th century and across
425 climatic regions, with lakes located in the temperate regions being the most thermally
426 responsive. Substantial warming was evident after ~1980 in both hemispheres, while a
427 previous pronounced warming period was found in the Northern Hemisphere providing first
428 evidence of a systematic warming of high latitude lakes during the so called Early Twentieth
429 Century Warming period (1920-1940).

430 The modelled annually-averaged LSWT and the corresponding air temperature data
431 are made available in the Supplementary material for all lakes (limited to lakes with
432 NSE>0.8; Tables S4 and S5), along with their linear trends calculated separately for the
433 Northern and Southern Hemispheres and for the Köppen climate major groups for

434 overlapping subperiods of 30 years (Table S3). The aim is to offer a global 20th century
435 baseline, against which observed and projected lake warming and future applications based
436 on new reanalysis products can be referenced.

437
438

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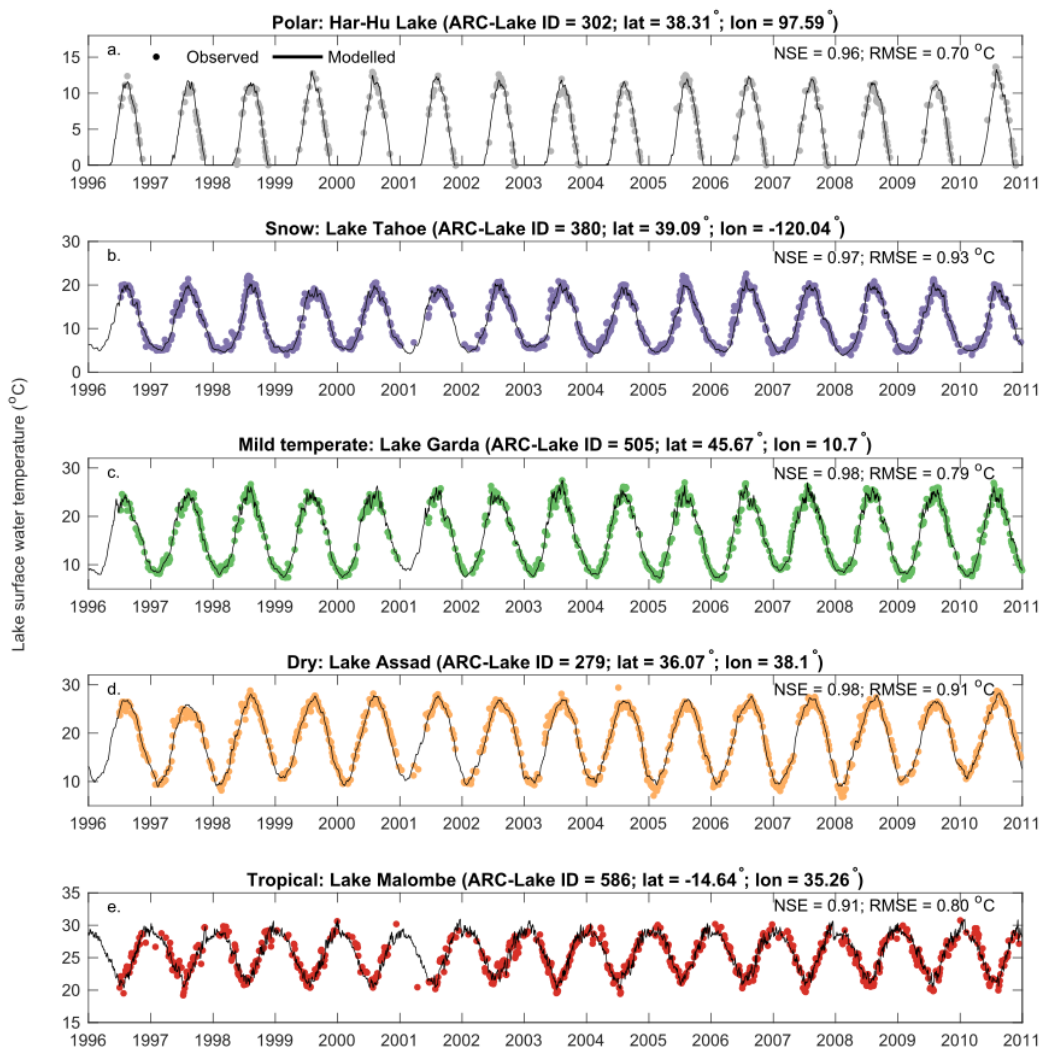
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676 **Figures Legends**

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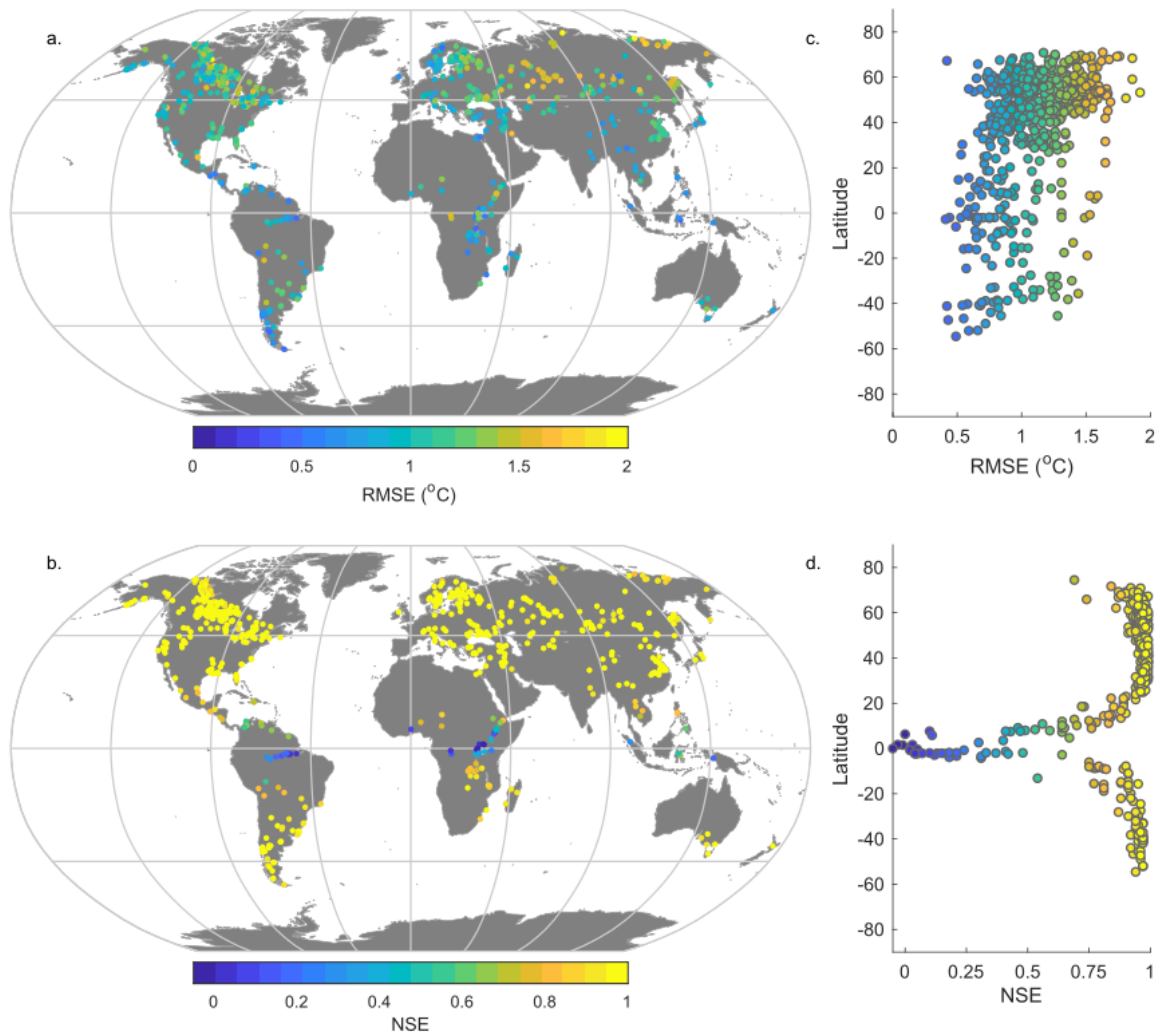
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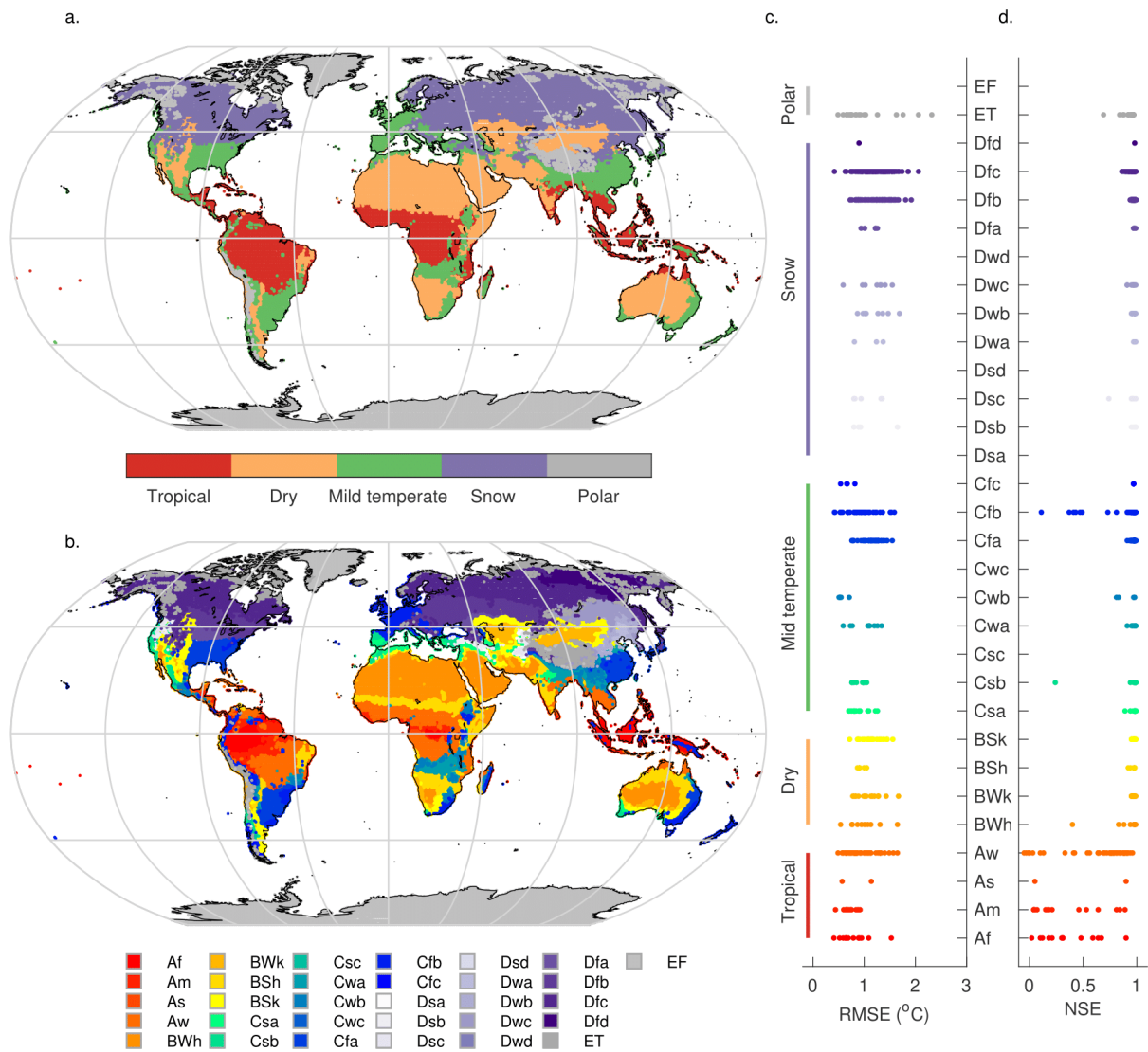
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Figure 1. Comparison of modelled (solid line) lake surface water temperatures with satellite-derived (points) temperature observations for (a) Har-Hu Lake (China), (b) Lake Tahoe (United States), (c) Lake Garda (Italy), (d) Lake Assad (Syria), (e) Lake Malombe (Malawi). Shown are the calculated NSE and RMSE between the observed and simulated daily LSWT.

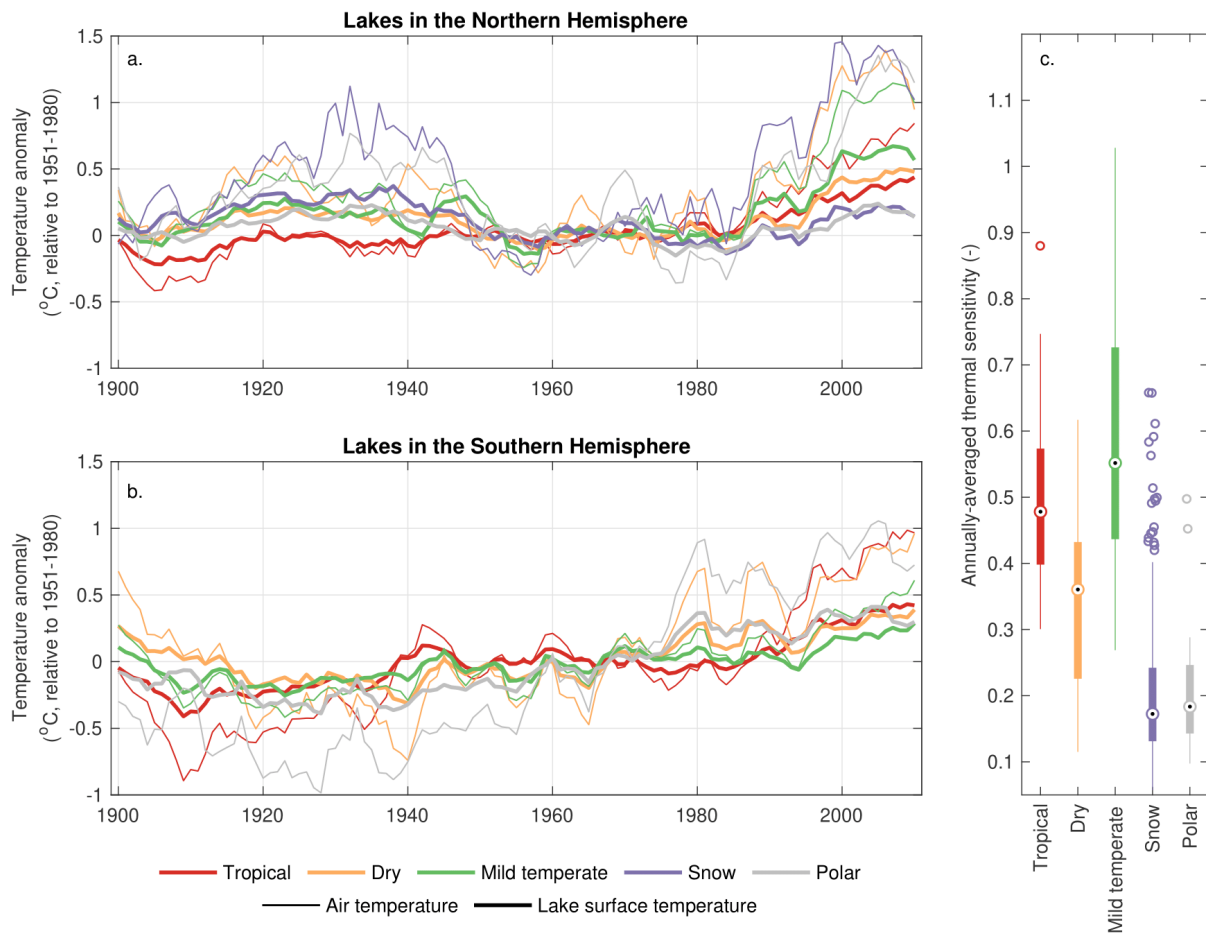


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 684 **Figure 2.** Global patterns in the computed performance of *air2water*, evaluated via (a)
 685 RMSE and (b) NSE between the observed and simulated daily LSWT. The relationship
 686 between latitude and (c) RMSE and (d) NSE are also shown.



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Figure 3. Relationship between the performance of *air2water* and the Köppen climate classification, showing both (a) the major climate types and (b) the climate sub-types. Model performance is evaluated by (c) RMSE and (d) NSE between the observed and simulated daily LSWT.



692
 693 **Figure 4.** Long-term LSWT variations for each major Köppen climate zone for the period
 694 1900-2010 shown for (a) lakes in the Northern Hemisphere and (b) lakes in the Southern
 695 Hemisphere. Only lakes with a NSE higher than 0.8 were included in this long-term analysis.
 696 A five-year moving average is applied to the lake and air temperature data. Also shown is
 697 lakes thermal sensitivity, defined as the slopes of the regression line between annually-
 698 averaged air temperature anomalies and LSWT anomalies over the 1900 to 2010 period,
 699 grouped by climatic region (c).