

1 **Title**

2 Global reconstruction of 20<sup>th</sup> century lake surface water temperature reveals different  
3 warming trends depending on the climatic zone

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21  
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 20<sup>th</sup> 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.

36  
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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 20<sup>th</sup> 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 20<sup>th</sup> 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 20<sup>th</sup>  
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 20<sup>th</sup> 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 20<sup>th</sup> 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 20<sup>th</sup> 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 20<sup>th</sup> 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 km<sup>2</sup> and 81,844 km<sup>2</sup>, 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 ( $\Gamma$ ).  $\Gamma$  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  $\Gamma$  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  $9.81 \text{ m s}^{-2}$ ).

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  $0.5^\circ$  longitude x  $0.5^\circ$  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 20<sup>th</sup> 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  $0.48^{\circ}\text{C}$  vs.  $0.12^{\circ}\text{C}$ , 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 20<sup>th</sup> 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 20<sup>th</sup> 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 20<sup>th</sup> 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 20<sup>th</sup> 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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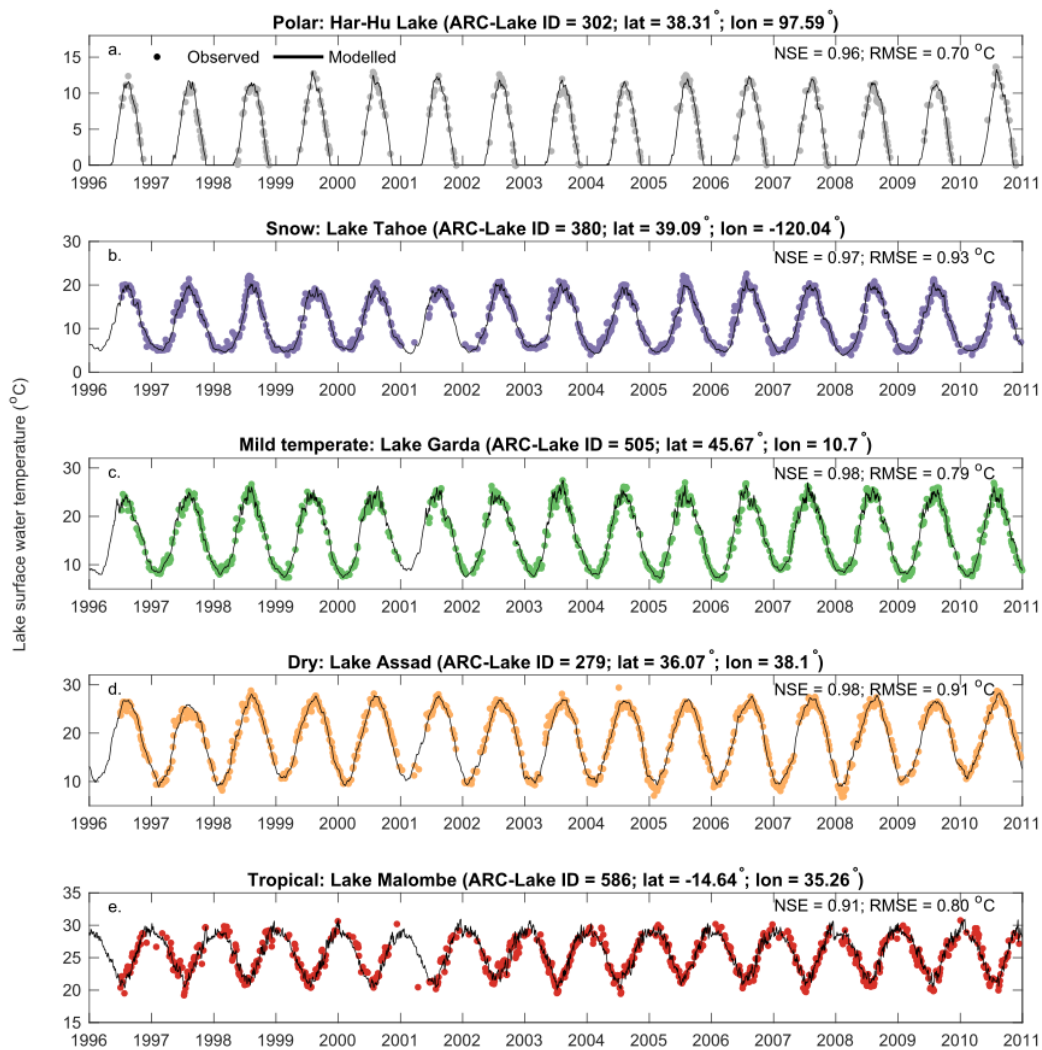
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676 **Figures Legends**

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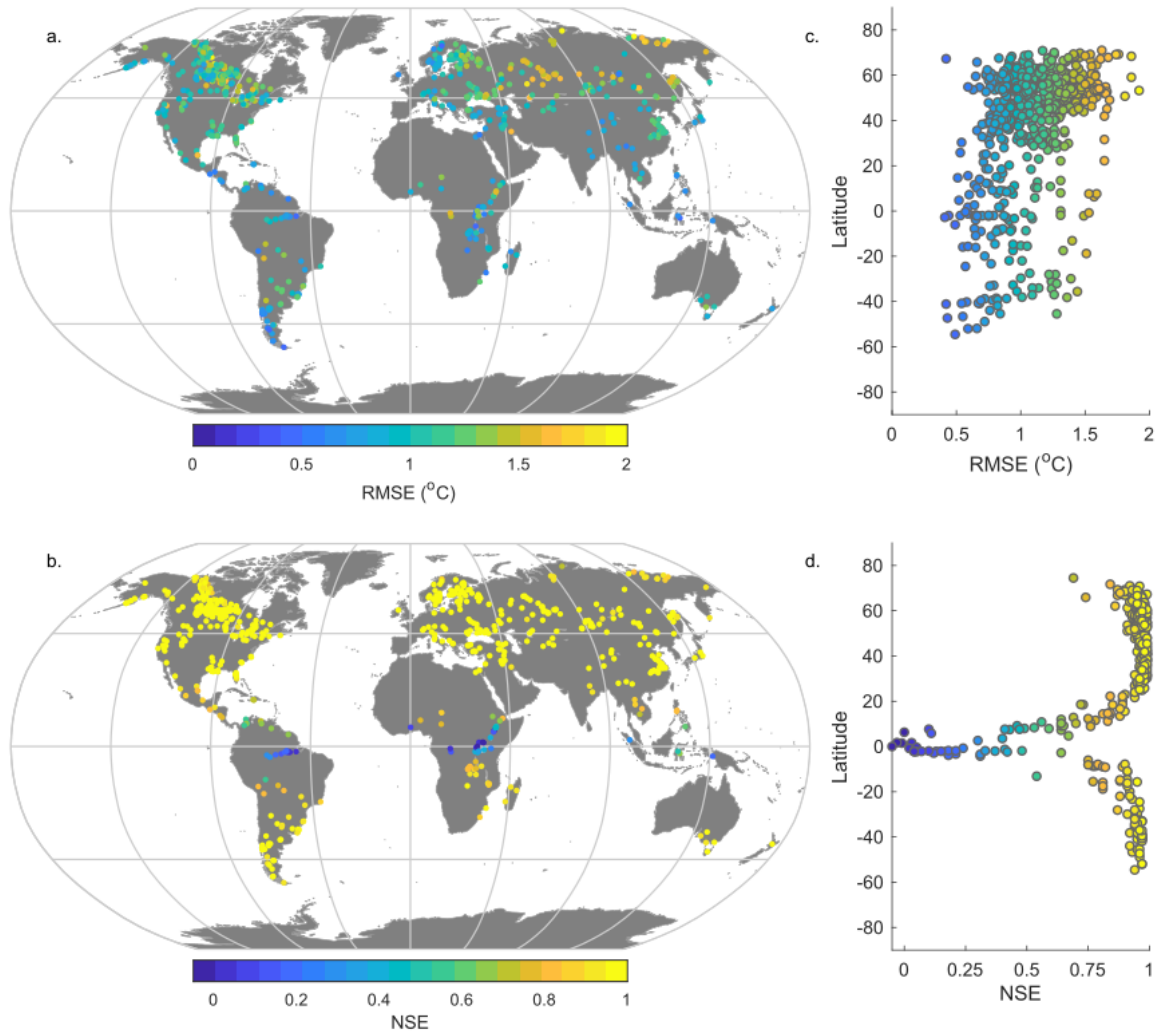
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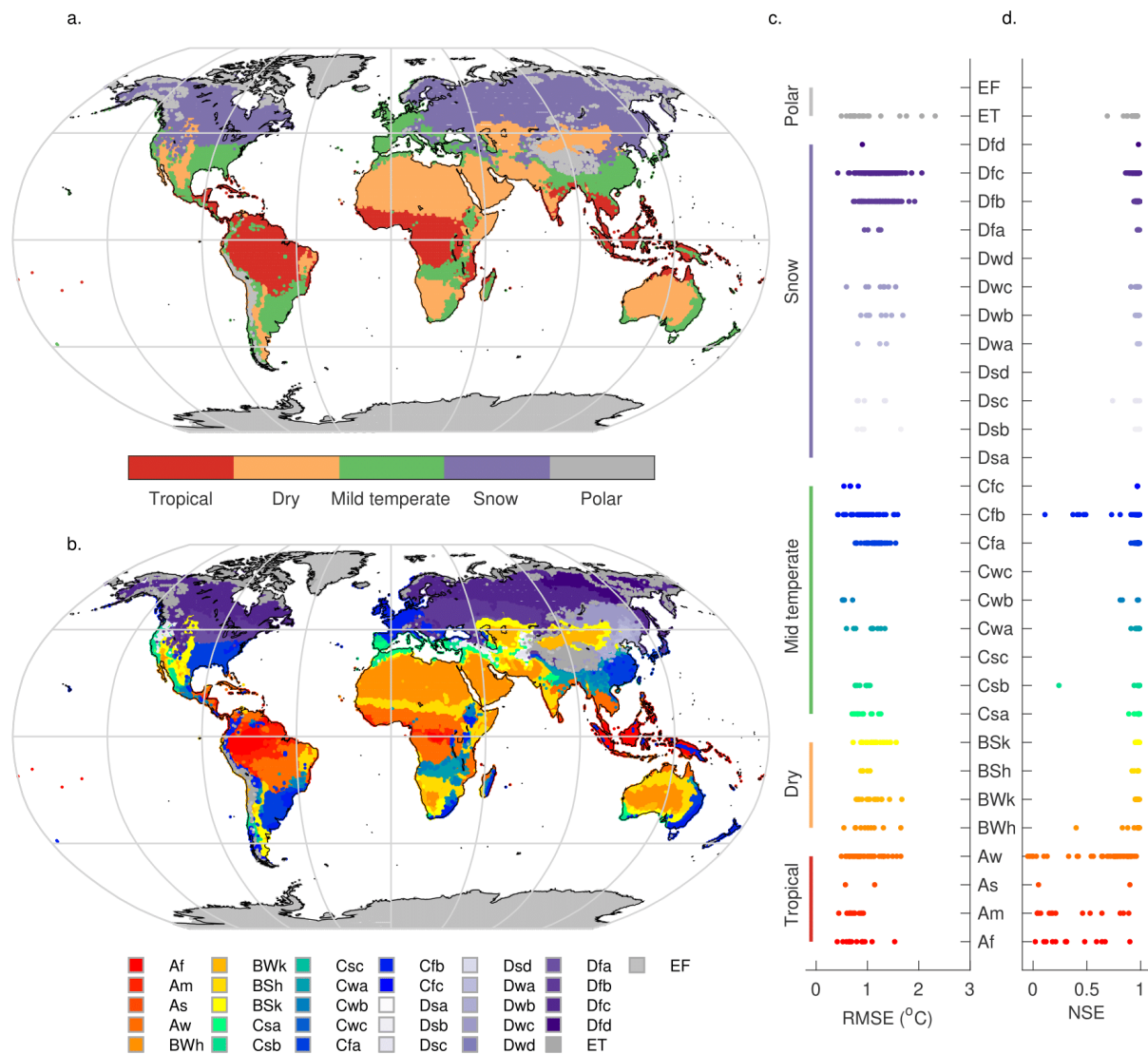
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**Figure 1.** Comparison of modelled (solid line) lake surface water temperatures with satellite-derived (points) temperature observations for (a) Har-Hu Lake (China), (b) Lake Tahoe (United States), (c) Lake Garda (Italy), (d) Lake Assad (Syria),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



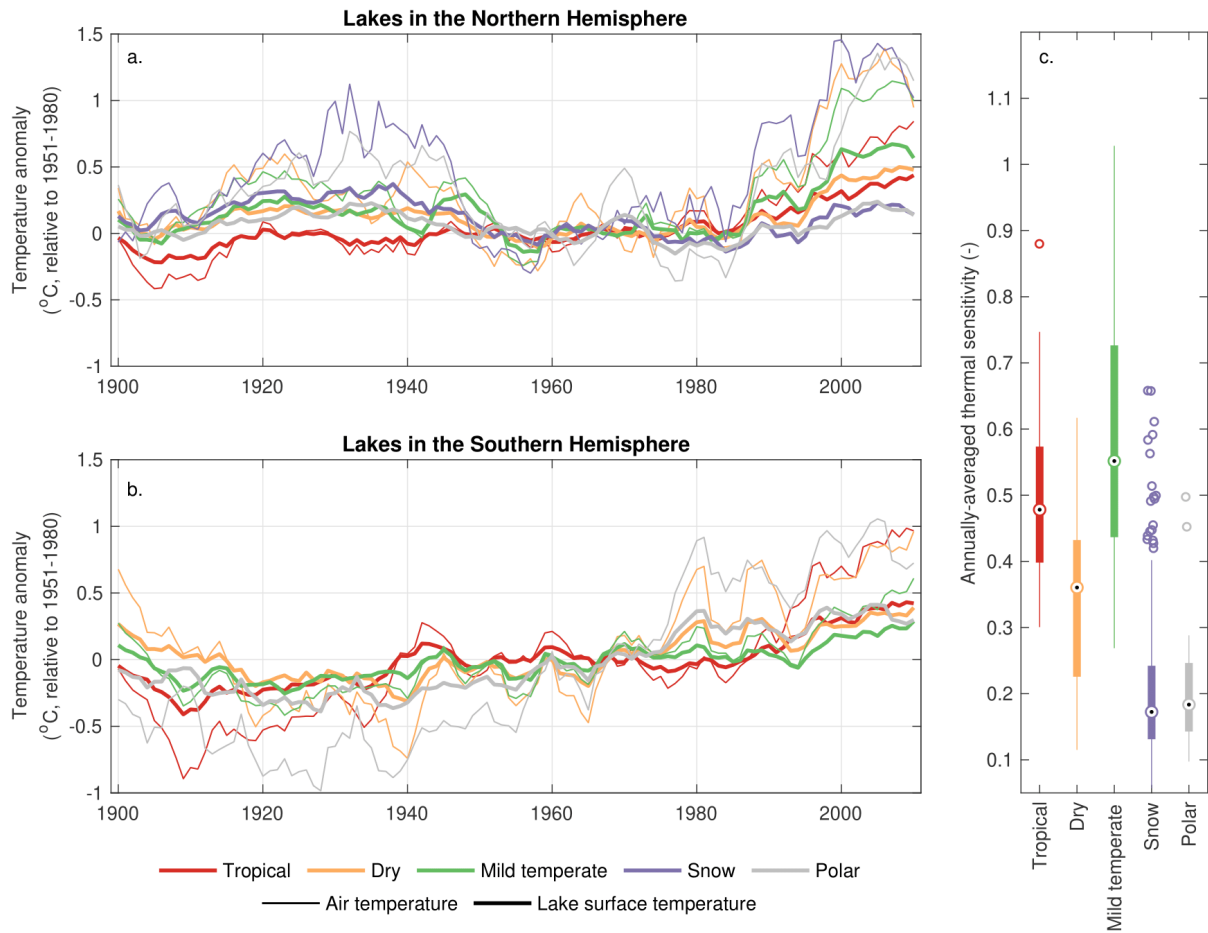
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**Figure 2.** Global patterns in the computed performance of *air2water*, evaluated via (a) RMSE and (b) NSE between the observed and simulated daily LSWT. The relationship between latitude and (c) RMSE and (d) NSE are also shown.



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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.



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 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).