Supplementary information for

The vulnerability of lakes to climate change along an altitudinal gradient

Love Råman Vinnå[1], Iselin Medhaug[2], Martin Schmid[1], Damien Bouffard[1]

[1] Eawag, Swiss Federal Institute of Aquatic Science and Technology, Surface Waters – Research and Management, Kastanienbaum, Switzerland.

[2] Institute for Atmospheric and Climate Science, ETH Zürich, 8092 Zürich, Switzerland.

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Supplementary Table 1 displays linear regression statistics of heat fluxes from Figure 2.

Supplementary Tables 2 and 3 list model parameters and meteorological station details.

Supplementary Figure 1 shows the GCM-RCM model chains used.

Supplementary Figure 2 displays atmospheric forcing and trends, see Fig. 1 a)-f) in main manuscript for the most influential variables.

Supplementary Figure 3 shows future surface and deep water warming and trends.

Supplementary Figure 4 displays modelled and observed cloud fraction used in model forcing.

Supplementary Figure 5 displays Simstrat lake model performance.

Supplementary Figure 6 shows ranges of simulated changes in lake thermal properties for all climate models.

Supplementary Table 1. Lake heat flux change regression coefficients (y = P1*x + P2, colored lines Figure 2) with 95% confidence intervals for the altitude-dependence of trends obtained from regression analysis of annual means (1982 to 2099). Heat fluxes consist of uptake (H_A) and emission (H_W) of infrared longwave radiation, evaporation/condensation (H_E), sensible heat flux (H_C) and uptake of surface downward solar radiation (H_S). Heat fluxes are positive from the atmosphere to the lake. Regression statistics include sum of squares (SSE), R-square (R^2), degrees of freedom (Df), adjusted R-square (AR^2), and root mean squared error (RMSE).

		P1	P2	SSE	R^2	Df	AR^2	RMSE
Ha	RCP2.6	1.24e-03 ±2.40e-04	2.52e-01 ±2.09e-01	2.73	0.81	27	0.80	0.32
	RCP4.5	1.94e-03 ±4.18e-04	5.46e-01 ±3.65e-01	8.28	0.77	27	0.76	0.55
	RCP8.5	3.33e-03 ±6.47e-04	9.07e-01 ±5.65e-01	19.82	0.81	27	0.80	0.86
Hc	RCP2.6	-4.01e-05 ±2.32e-05	9.52e-02 ±2.03e-02	0.03	0.32	27	0.29	0.03
	RCP4.5	-8.47e-05 ±4.00e-05	1.97e-01 ±3.49e-02	0.08	0.41	27	0.39	0.05
	RCP8.5	-1.49e-04 ±8.05e-05	4.00e-01 ±7.03e-02	0.31	0.35	27	0.32	0.11
Hs	RCP2.6	3.49e-04 ±9.55e-05	-2.20e-01 ±8.34e-02	0.43	0.68	27	0.66	0.13
	RCP4.5	6.80e-04 ±1.76e-04	-3.54e-01 ±1.53e-01	1.46	0.70	27	0.69	0.23
	RCP8.5	1.11e-03 ±2.63e-04	-4.52e-01 ±2.30e-01	3.28	0.74	27	0.73	0.35
Hw	RCP2.6	-1.63e-03 ±3.36e-04	-4.52e-03 ±2.93e-01	5.34	0.79	27	0.78	0.44
	RCP4.5	-2.64e-03 ±5.85e-04	-1.02e-01 ±5.10e-01	16.19	0.76	27	0.75	0.77
	RCP8.5	-4.46e-03 ±8.81e-04	-2.04e-01 ±7.69e-01	36.78	0.80	27	0.79	1.17
He	RCP2.6	-7.49e-05 ±5.52e-05	-6.07e-02 ±4.82e-02	0.14	0.22	27	0.19	0.07
	RCP4.5	-1.37e-04 ±1.05e-04	-1.70e-01 ±9.19e-02	0.52	0.21	27	0.18	0.14
	RCP8.5	-2.40e-04 ±1.95e-04	-3.51e-01 ±1.71e-01	1.81	0.19	27	0.16	0.26

Supplementary Table 2. Meteorological stations operated by MeteoSwiss, from which data were retrieved for the calibration period and the downscaled climate scenarios. Additional station information is available at MeteoSwiss (https://www.meteoswiss.admin.ch/). The table also lists derived clearness indices for complete cloud cover k_{cld} and clear skies k_{clr} for each station.

Station	Name	Altitude (m a.s.l.)	k_{clr}	k_{cld}
LUG	Lugano	273	0.75	0.45
OTL	Locarno	367	0.85	0.30
ALT	Altdorf	438	0.80	0.35
GUT	Güttingen	440	0.80	0.40
LUZ	Luzern	454	0.80	0.35
PUY	Pully	456	0.85	0.45
NEU	Neuchâtel	485	0.85	0.35
GLA	Glarus	517	0.75	0.35
SMA	Zürich	556	0.90	0.25
INT	Interlaken	577	0.80	0.40
CHD	Château-d'Oex	1028	0.90	0.35
ROB	Poschiavo	1078	0.75	0.40
ABO	Adelboden	1322	0.80	0.35
DAV	Davos	1594	0.90	0.50
SAM	Samedan	1709	0.90	0.40
SIA	Segl-Maria	1804	0.95	0.30

Supplementary Table 3. Lake model Simstrat parameters, constants and performance after calibration with annual forcing for each lake (Table 1) in ascending order according to altitude. Performance is visualized in Supplementary Figure 5 and explicitly displayed here as sum of squares (SSE), correlation coefficient (R), Number of Residuals (N. Res.) and root mean square difference (RMSD). The last two columns list calibration period dates which are limited by available data. Constants and default parameters not calibrated are given in sub-tables below.

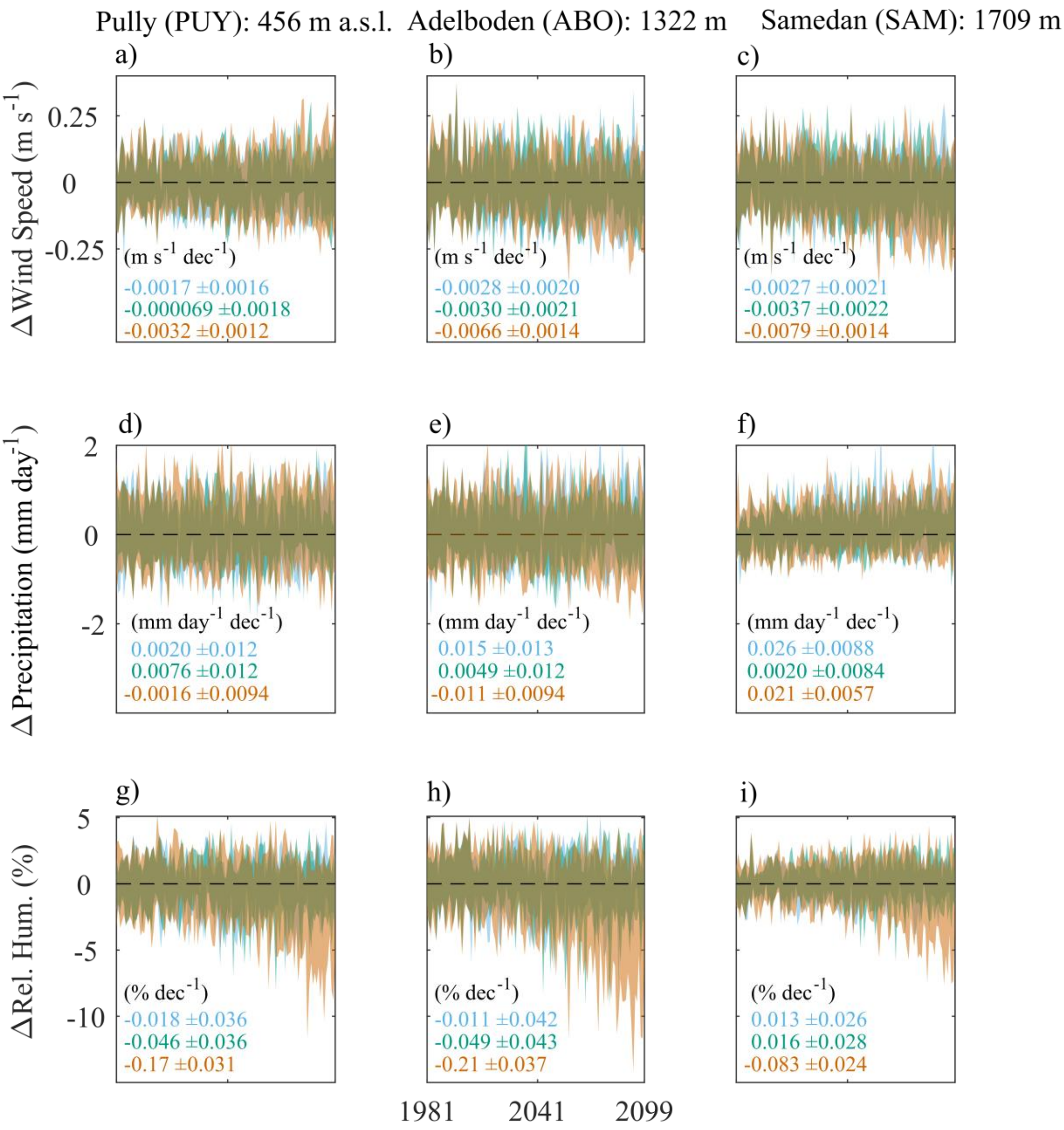
#Altitude	**Parameter**						**Best Fit Results**				**Calibration**	
	α	*α_s*	*α_w*	*f_wind*	*p_radin*	*p_albedo*	SSE	R	N. Res.	RMSD (°C)	Start	Stop
1	0.029	-	-	1.00	0.89	-	1558	0.97	923	0.81	1981	1992
2	0.0092	-	-	1.44	0.89	-	5013	0.98	4724	1.03	1981	2019
3	-	0.043	0.002	1.44	0.92	-	5301	0.98	6659	0.89	1982	2012
4	-	0.21	0.0099	1.38	0.90	0.21	8986	0.98	10737	0.91	1981	2011
5	0.058	-	-	0.64	0.98	0.89	12894	0.94	3761	1.85	1981	2019
6	-	0.044	0.00063	2.04	0.94	2.00	4530	0.97	4755	0.98	1981	2014
7	0.017	-	-	2.03	0.97	1.81	3715	0.97	1177	1.78	1999	2010
8	0.07	-	-	1.33	0.98	1.11	6606	0.98	6965	0.97	1981	2019
9	0.048	-	-	1.38	0.90	0.85	5926	0.96	4501	1.15	1981	2019
10	0.0053	-	-	0.92	0.97	2.00	1406	0.99	943	1.22	1981	2019
11	0.00092	-	-	2.42	0.98	0.48	4205	0.94	1295	1.80	1993	2019
12	0.0051	-	-	1.72	1.06	0.76	1658	0.96	708	1.53	1981	2019
13	0.0026	-	-	2.48	1.06	0.51	3113	0.98	3594	0.93	1981	2019
14	0.0034	-	-	1.00	0.86	1.46	110	0.98	82	1.16	1981	2019
15	0.022	-	-	1.546	0.84	-	13	0.60	21	0.78	1999	2004
16	0.46	-	-	0.80	0.90	0.22	92	0.97	127	0.85	1981	2019
17	0.0058	-	-	1.02	0.92	-	0	0.97	19	0.07	1981	2019
18	0.0064	-	-	1.07	0.94	1.08	3749	0.99	4872	0.88	1981	2019
19	0.0027	-	-	0.49	0.86	0.98	8697	0.96	3749	1.52	1981	2019
20	0.050	-	-	2,43	0,92	1,33	4214	0,95	3072	1,17	1981	2015
21	0.0066	-	-	1.42	0.87	1.90	142	0.94	62	1.51	1981	2019
22	0.032	-	-	1.18	0.89	0.90	2903	0.93	1205	1.55	2006	2017
23	0.012	-	-	0.83	0.89	2.00	54	0.99	99	0.74	2009	2019
24	Default	-	-	Default	Default	Default	-	-	0	-	-	-
25	Default	-	-	Default	Default	Default	-	-	0	-	-	-
26	0.076	-	-	1.02	0.88	0.70	87	0.97	163	0.73	2012	2013
27	0.0062	-	-	1.08	0.87	0.99	484	0.97	939	0.72	2005	2008
28	0.005	-	-	1.75	0.95	2.00	2074	0.97	3859	0.73	2014	2019
29	0.018	-	-	0.97	0.96	1.27	76	0.99	750	0.32	2015	2017

Constants	
lat	lake dependent
p_air	lake dependent annual mean
q_nn	1.1
cd	0.002
hgeo	Lake dependent
k_min	$1*10^{-9}$
Sesonal *α* shift at max(N^2)	0.0002 s^{-2}
freez temp.	0 °C
snow temp.	2 °C

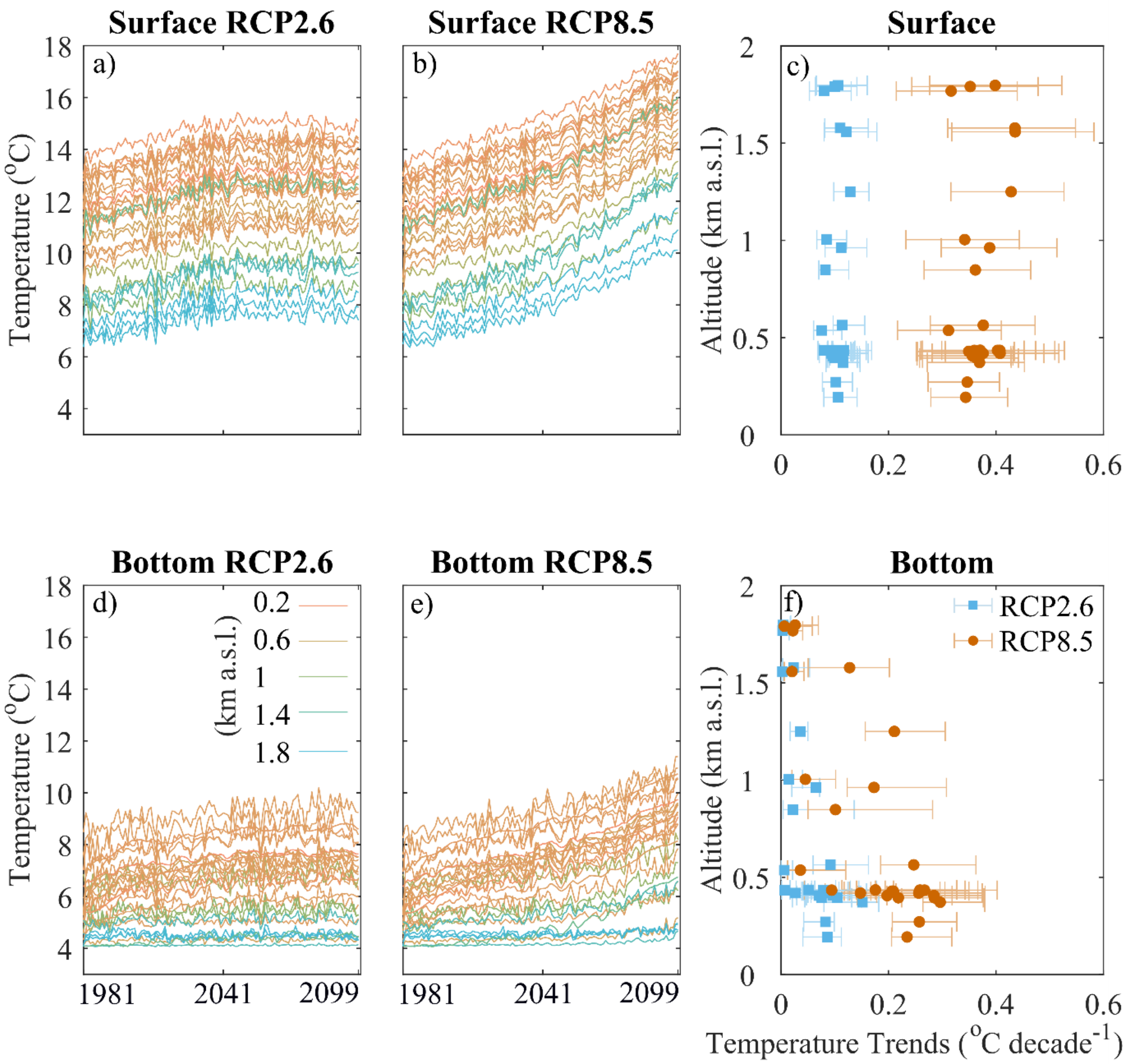
Default Parameters	
α	0.001
f_wind	1.0
p_radin	1.0
p_albedo	1.0
β_sol	0.35

GCM	init	RCM	RCP8.5		RCP4.5		RCP2.6	
			0.11°	0.44°	0.11°	0.44°	0.11°	0.44°
ICHEC-EC-EARTH	r1i1p1	KNMI-RACMO22E		x				
	r3i1p1	DMI-HIRHAM5	x		x		x	
	r12i1p1	CLMcom-CCLM5-0-6		x				
		SMHI-RCA4	x		x		x	
MOHC-HadGEM2-ES	r1i1p1	CLMcom-CCLM4-8-17	x					
		CLMcom-CCLM5-0-6		x				
		KNMI-RACMO22E		x		x		x
		SMHI-RCA4		x		x		x
MPI-M-MPI-ESM-LR	r1i1p1	CLMcom-CCLM5-0-6		x				
		SMHI-RCA4		x		x		x
MIROC-MIROC5	r1i1p1	CLMcom-CCLM5-0-6		x				
		SMHI-RCA4		x		x		x
CCCma-CanESM2	r1i1p1	SMHI-RCA4		x				
CSIRO-QCCCE-CSIRO-Mk3-6-0	r1i1p1	SMHI-RCA4		x				
IPSL-IPSL-CM5A-MR	r1i1p1	SMHI-RCA4	x					
NCC-NorESM1-M	r1i1p1	SMHI-RCA4		x		x		x
NOAA-GFDL-GFDL-ESM2M	r1i1p1	SMHI-RCA4		x				

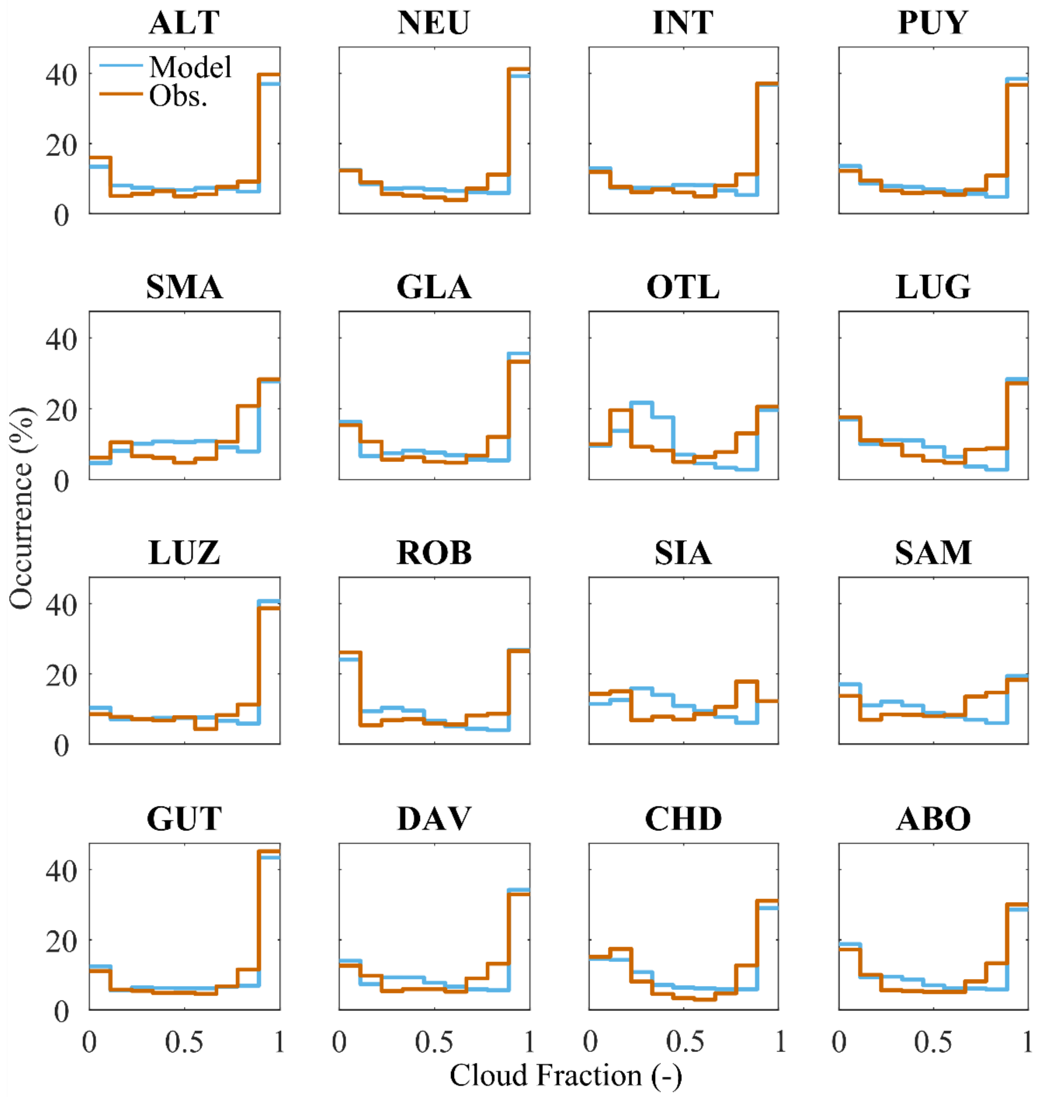
Supplementary Figure 1. Global and regional climate model chains (GCM-RCM) and RCM model resolution is used for the scenarios RCP8.5, RCP4.5 and RCP2.6. “init” indicates which initialization from the CMIP5 historical GCM simulation is used to force the RCM.



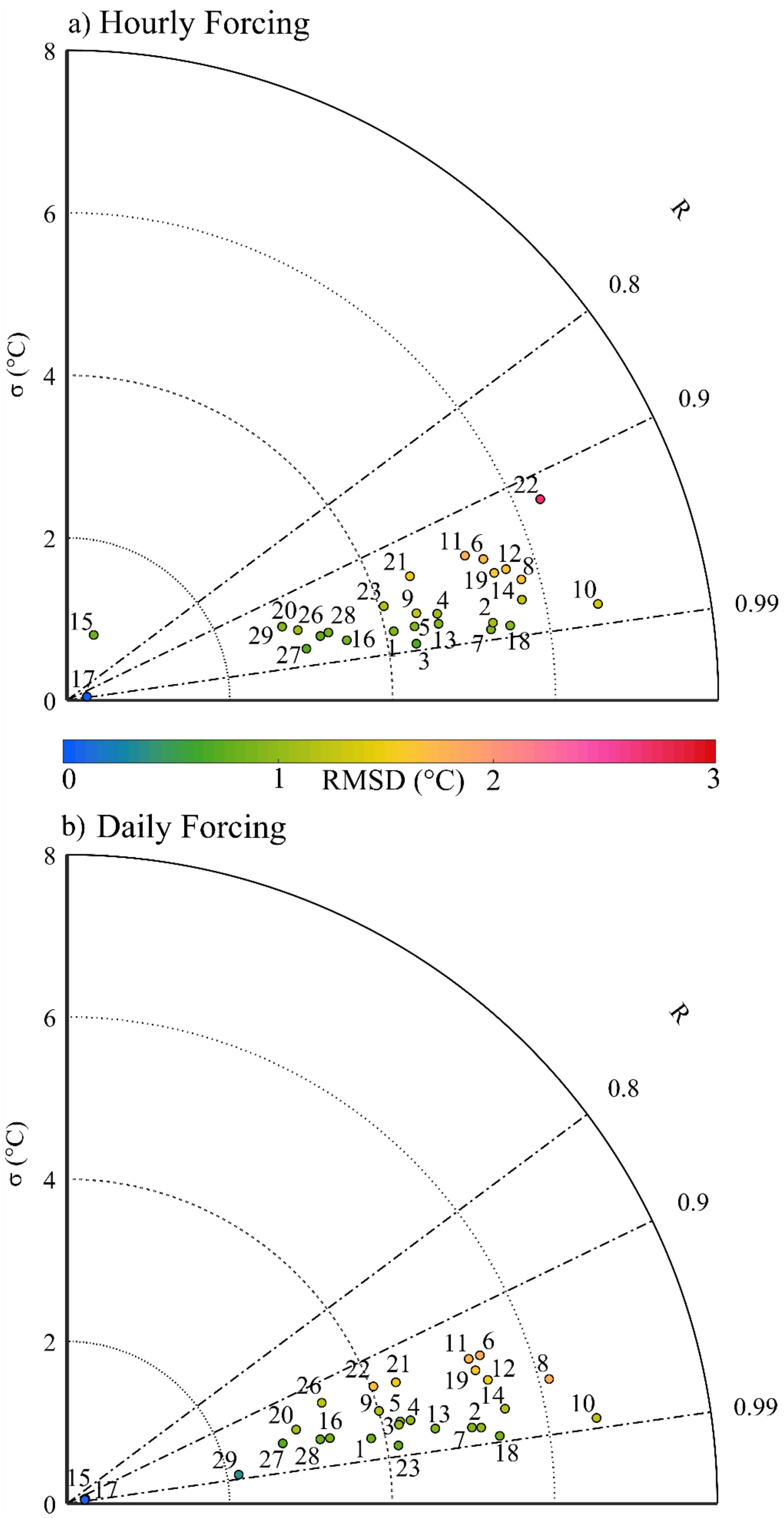
Supplementary Figure 2. Time series (from 1981 to 2099) of projected anomalies of wind speed a) - c), precipitation d) - f) and relative humidity g) – i) for three meteo stations at different elevations. Shaded areas show the full range of annual means relative to a 1981-2010 base period for all models under scenarios RCP8.5 (orange; 17 models), RCP4.5 (green; 7 models) and RCP2.6 (blue; 7 models) with ensemble mean linear trends given for each graph.



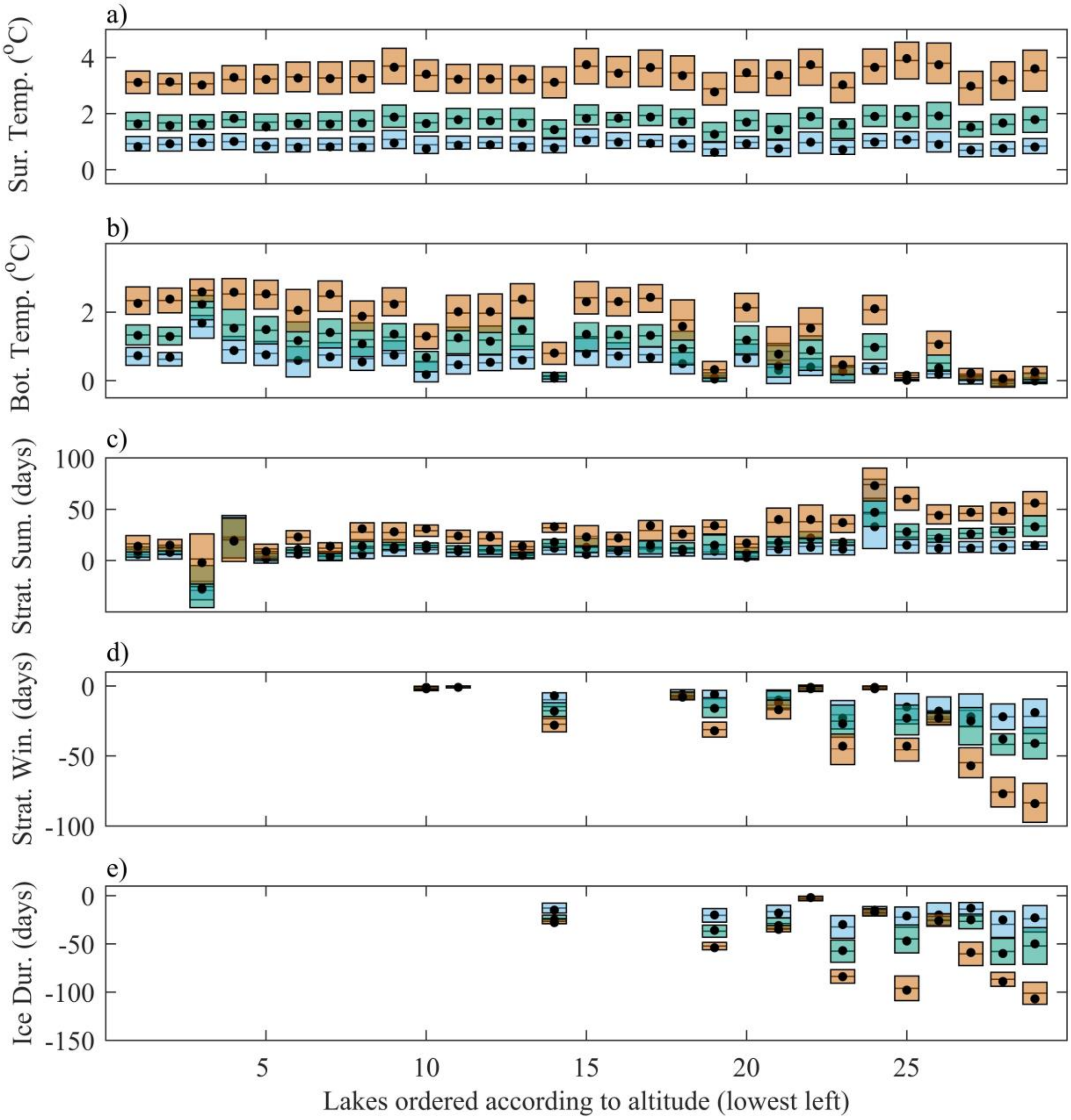
Supplementary Figure 3. Annual mean surface (a, b) and bottom (d, e) water temperature for 29 lakes under climate scenarios RCP2.6 (7 RCMs) and RCP8.5 (17 RCMs) colour coded according to altitude. Range (horizontal bars) and median (squares and circles) values for modelled trends from 1981 to 2099 for surface (c) and bottom (f) temperatures.



Supplementary Figure 4. Modelled (blue) and observed (orange) cloud fraction during the calibration period (lake dependent, see Supplementary Table 2) listed according to meteorological stations used for downward longwave radiation calculations.



Supplementary Figure 5. Modified Taylor diagram for the best fit calibration of the Simstrat lake model obtained with a) hourly and b) daily resolved forcing from weather station measurements. The radial distance from the origin specifies the standard deviation σ of modelled lake temperature. The azimuth position gives the Pearson product-moment correlation coefficient (R) between modelled and measured temperature. *In-situ* measurements with the 3rd radial axis usually displayed on the horizontal axis are omitted for clarity since they would be located at a different point for each lake. Centered root-mean-square differences (RMSD) are instead color-coded. The numbering represents a sequential listing of lakes according to altitude as given in Table 1.



Supplementary Figure 6. Simulated climate model median (black point, displayed in Figure 3 and 4), mean (horizontal box line) and standard deviation (box vertical extent) of change in a) lake surface temperature (at 1 m depth), b) bottom temperature (1 m above lake bottom), c) duration of summer stratification, d) duration of winter stratification and e) duration of ice cover from the reference period (1982-2010) to the late 21st century (1971-2099) for scenario RCP8.5 (orange), RCP4.5 (green) and RCP2.6 (blue). Lakes are ordered by altitude, from the lowest at 193 m. a.s.l. (# 1) to the highest at 1797 m a.s.l. (# 29). For lake details see Table 1.