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Emergence of lake conditions that exceed natural temperature variability

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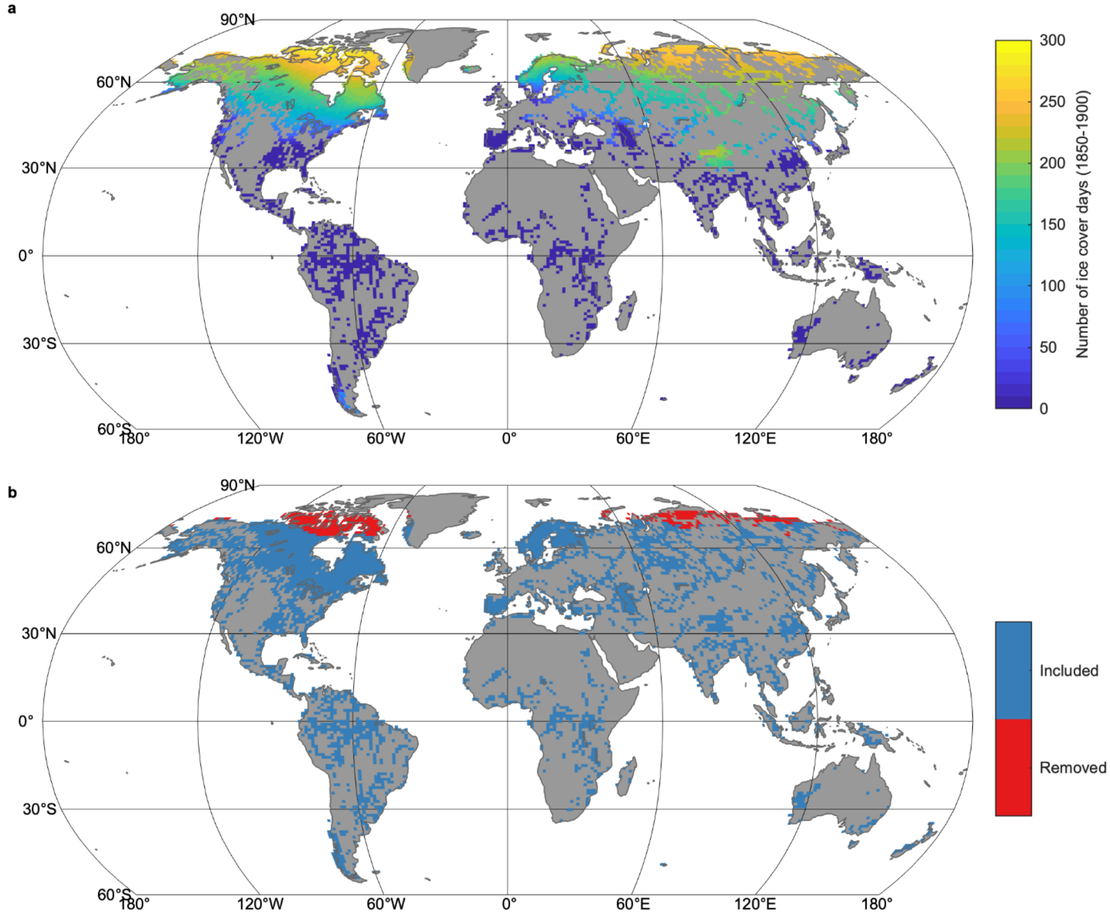
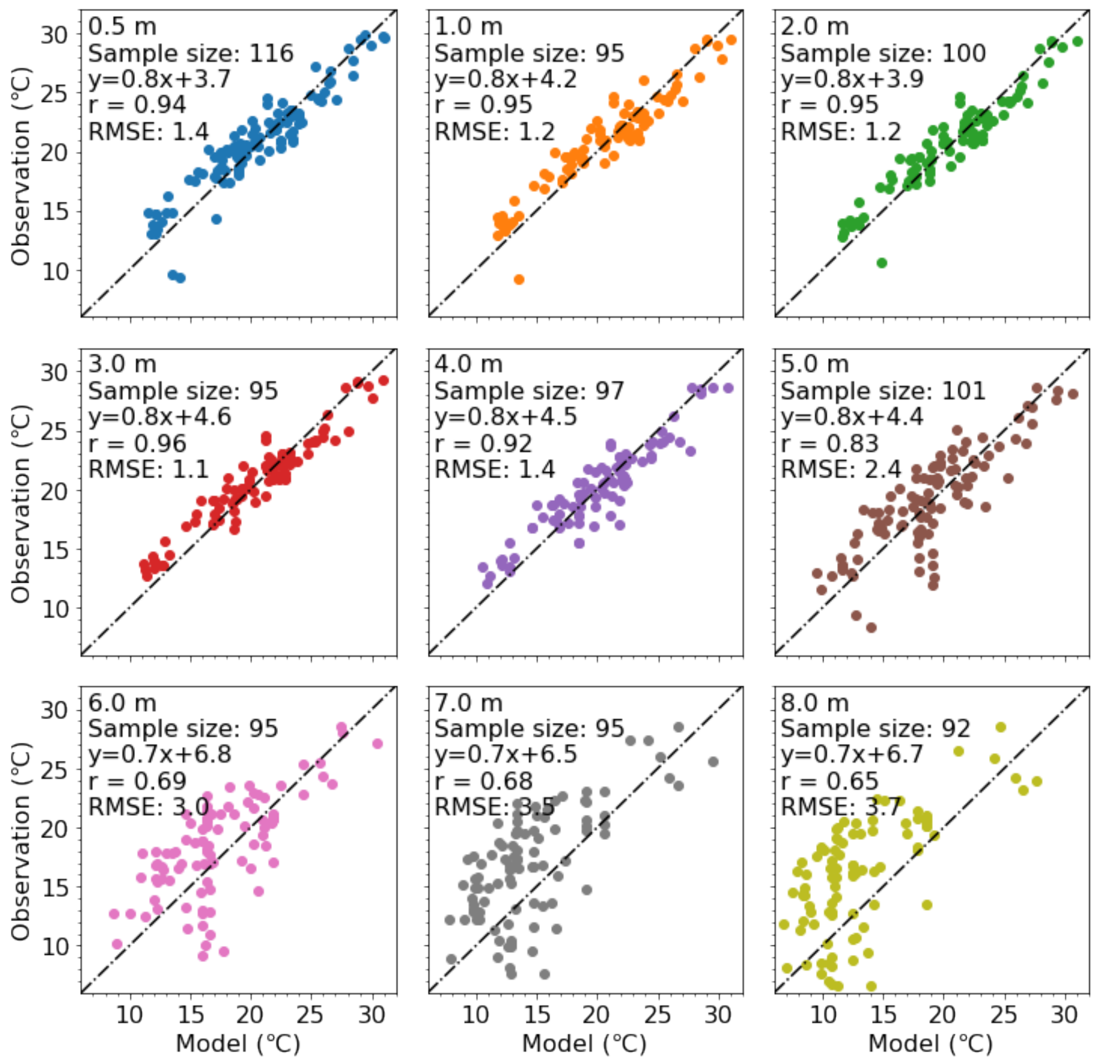
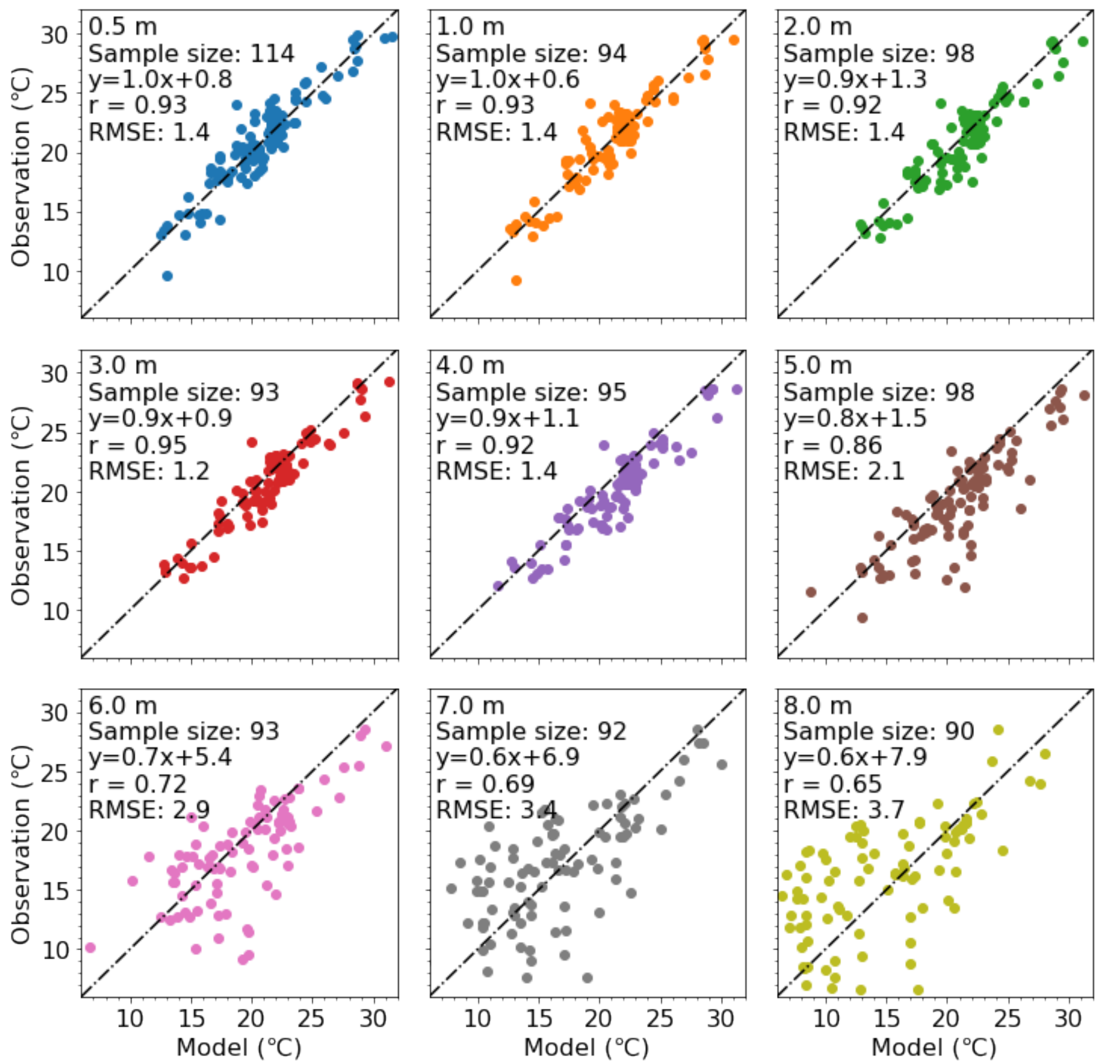
Supplementary Information



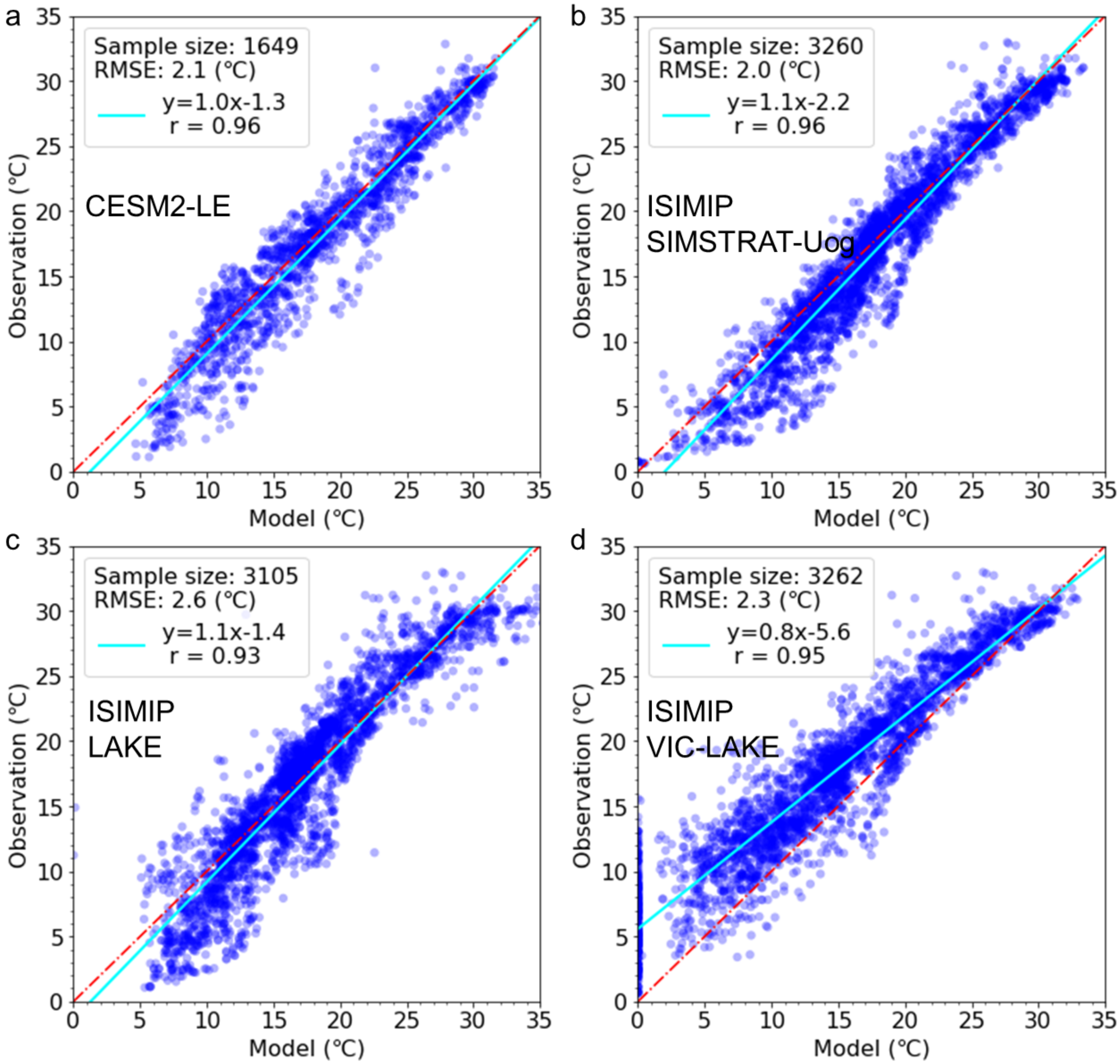
Supplementary Figure 1 | Criteria for selecting the studied lakes from CESM2-LE. In this study we excluded all modelled grids where the simulated lakes experienced at least 8 months of annual ice cover during the historical (1850-1900) period. Here, we show **(a)** the number of annual ice cover days for each lake during the 1850-1900 base-period, and **(b)** a binary map identifying the lakes included in the study, notably those with less than 8 months of annual ice cover. The number of ice cover days in each year was calculated from the average of the model ensembles.



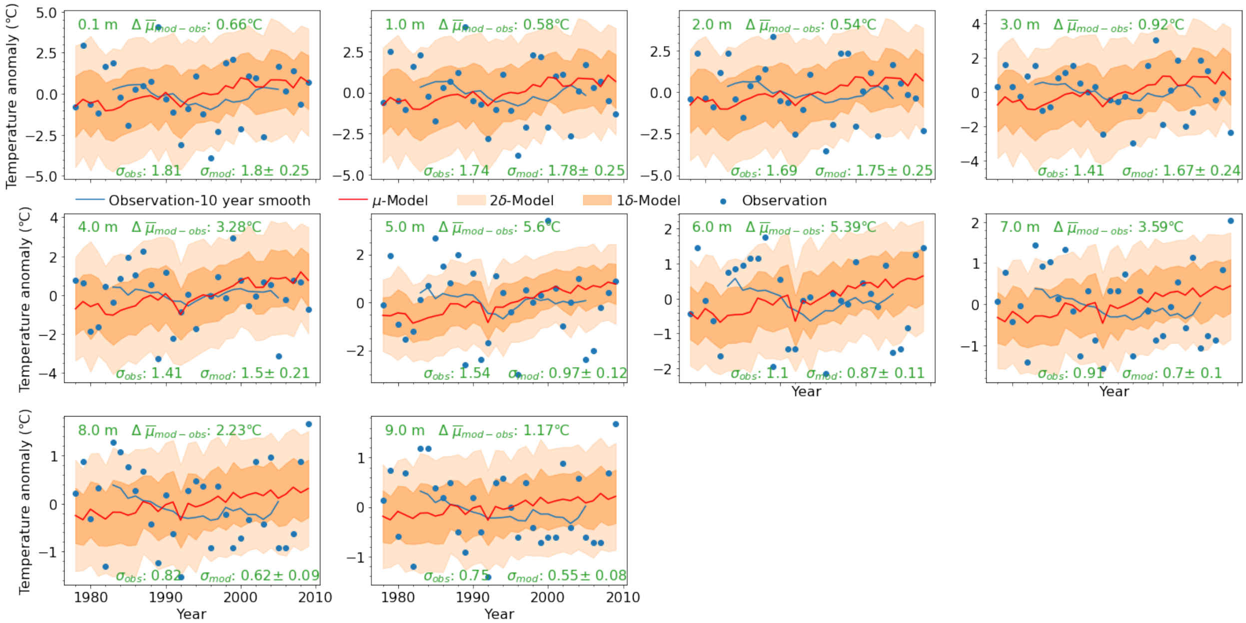
Supplementary Figure 2 | Validation of depth-resolved lake water temperature simulations. Shown are the relationships between simulated and observed climatological mean water temperatures during the warm-season in lakes with available data. Please refer to Supplementary Table 1 for more information about the lakes. Each lake has observations spanning at least 10 years. For each lake, we validate the model only against the observed data for matching years. Note that all the observations taken at a depth <0.5 m were assigned to 0.5 m. Observations taken from a depth range of 0.5 m to 1.5 m were assigned to 1 m in the model comparison, and a similar treatment was applied to the other depths shown.



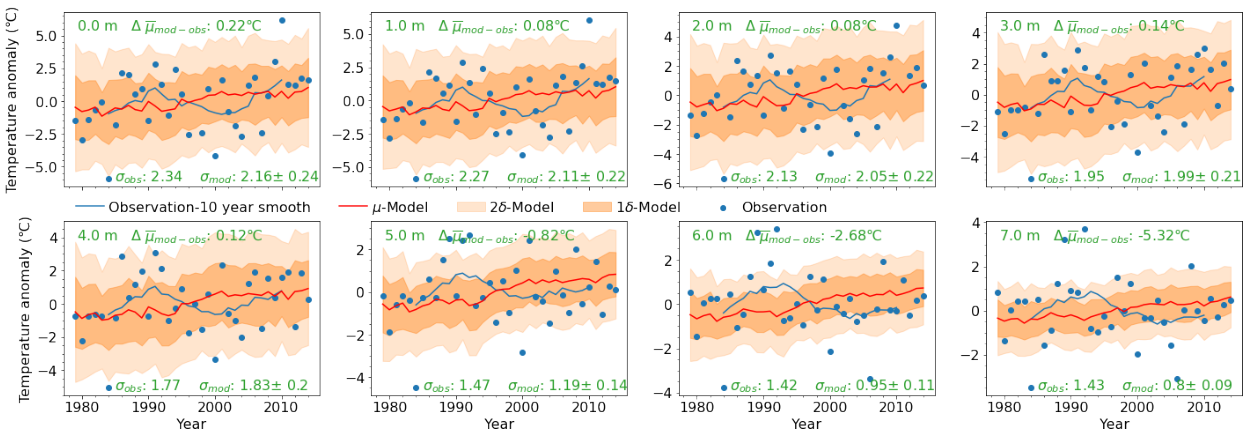
Supplementary Figure 3 | Validation of depth-resolved lake water temperature simulations from SimStrat-UoG. Similar to Supplementary Figure 2 but comparing observed temperatures with model simulations from the Simstrat-UoG model (see Methods).



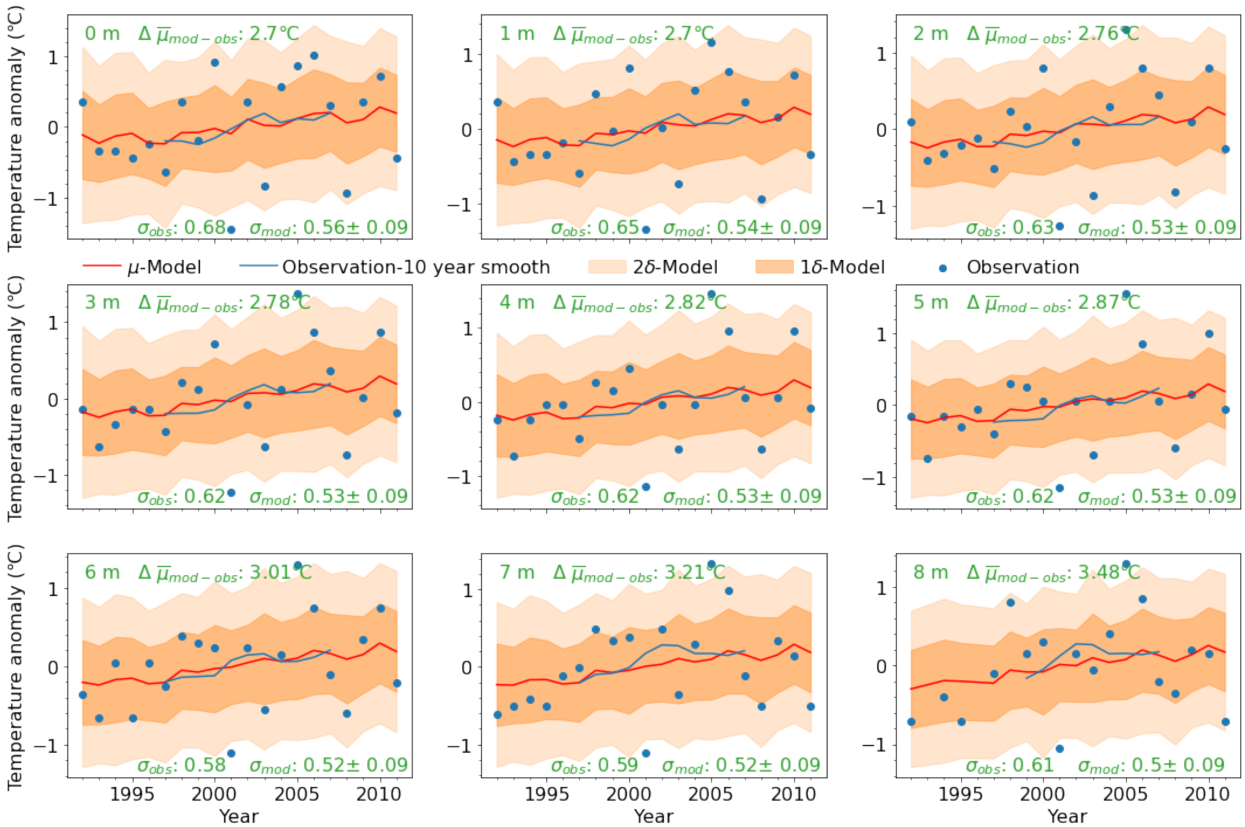
Supplementary Figure 4 | Validation of simulated surface water temperatures against satellite observations. Shown in panel **a** is a comparison of satellite-derived warm-season lake surface water temperatures and those simulated by CESM2-LE. The simulated temperatures shown are based on the mean of the 100-member ensemble. Monthly satellite-derived water temperatures were extracted from the ARC-Lake v3.0 data product. Panels **b-d** show similar comparisons to panel **a** but for three lake model simulations available from ISIMIP2b at a 0.5° by 0.5° longitude-latitude resolution (compared to 1° for CESM2-LE): (**b**) SimStrat-UoG, (**c**) LAKE, and (**d**) VIC-LAKE. In each panel we show the sample size, the calculated Root Mean Square Error (RMSE), and the linear fit between the simulations and observations.



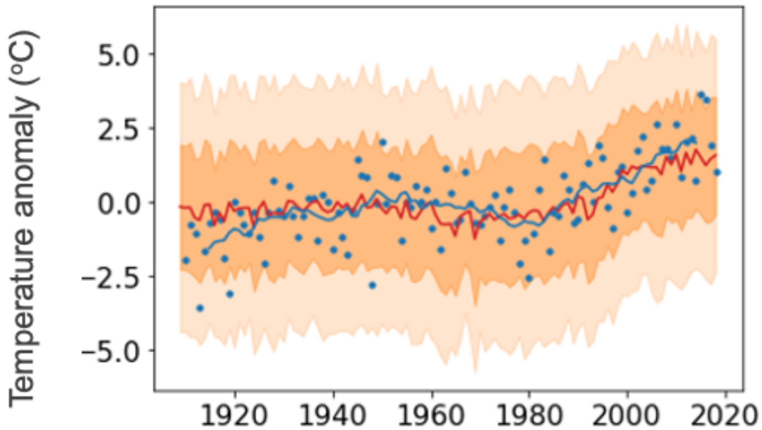
Supplementary Figure 5 | Simulated and observed temperatures from Lake Dickie (Canada). Shown is a comparison of the simulated and observed warm-season water temperature anomalies for Lake Dickie (45.2 °N, -79.1 °E). The blue line with circles demonstrates the in-situ observations. The red line demonstrates the simulated ensemble mean, and the dark and light orange shadings demonstrate one and two standard deviations of all ensemble members around the mean, respectively. The temperature anomaly is calculated against the climatological mean. The depth of water temperature shown in each panel are given on the top left. $\Delta\overline{\mu}$ denotes the difference of climatological mean between the simulations and observations. δ_{obs} and δ_{mod} denotes the standard deviation of the observations and simulations, respectively.



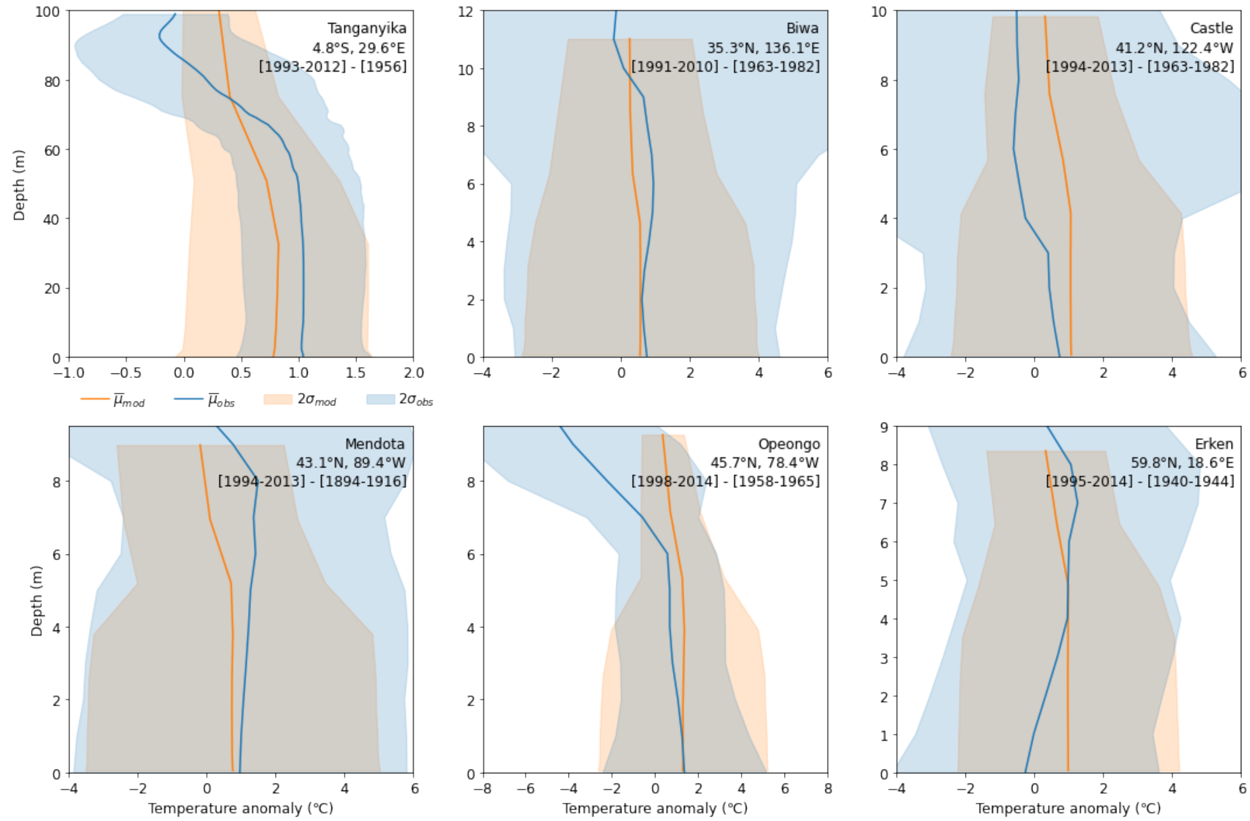
Supplementary Figure 6 | Simulated and observed depth-resolved temperatures from Müggelsee (Germany). Shown is a comparison of the simulated and observed warm-season water temperature anomalies for Müggelsee (52.4 °N, 13.7 °E). The blue line with circles demonstrates the in-situ observations. The red line demonstrates the simulated ensemble mean, and the dark and light orange shadings demonstrate one and two standard deviations of all ensemble members around the mean. The data treatment and legends are the same as Supplementary Figure 5.



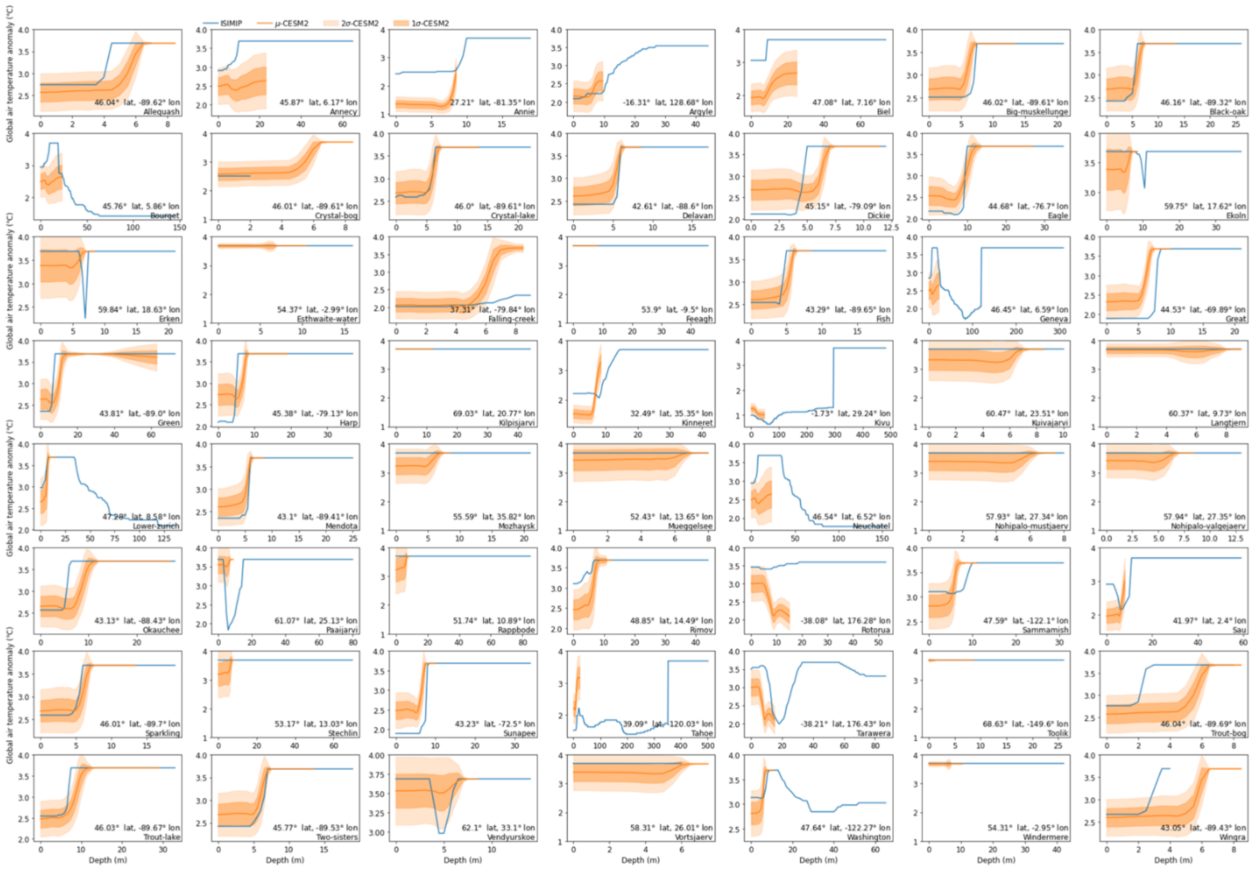
Supplementary Figure 7 | Simulated and observed depth-resolved temperatures from Lake Nkuruba (Uganda). Shown is a comparison of the simulated and observed warm-season water temperature anomalies in Lake Nkuruba (0.52 °N, 30.3 °E). The blue line with circles demonstrates the in-situ observations. The red line demonstrates the simulated ensemble mean, and the dark and light orange shadings demonstrate one and two standard deviations of all ensemble members around the mean. The data treatment and legends are the same as Supplementary Figure 6.



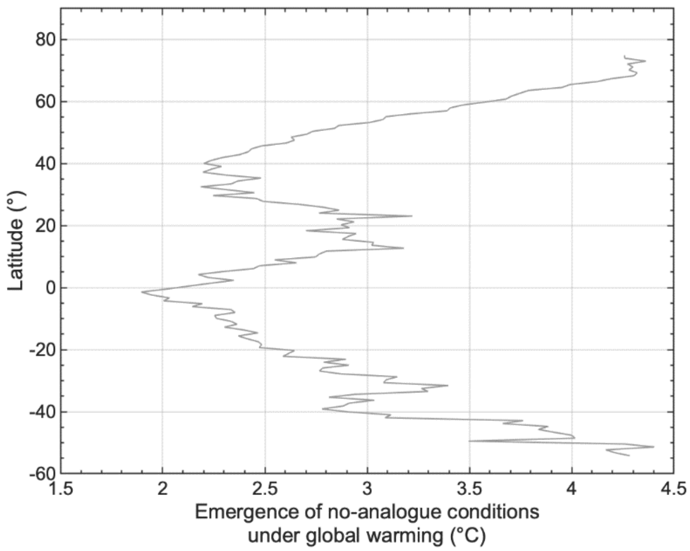
Supplementary Figure 8 | Simulated and observed temperatures from Wörthersee (Austria). Shown is a comparison of the simulated and observed water temperature anomalies for Wörthersee (46.6 °N, 14.2 °E). The blue line with circles demonstrates the in-situ observations. The red line demonstrates the simulated ensemble mean, and the dark and light orange shadings demonstrate one and two standard deviations of all ensemble members around the mean, respectively. The temperature anomaly is calculated against the climatological mean.



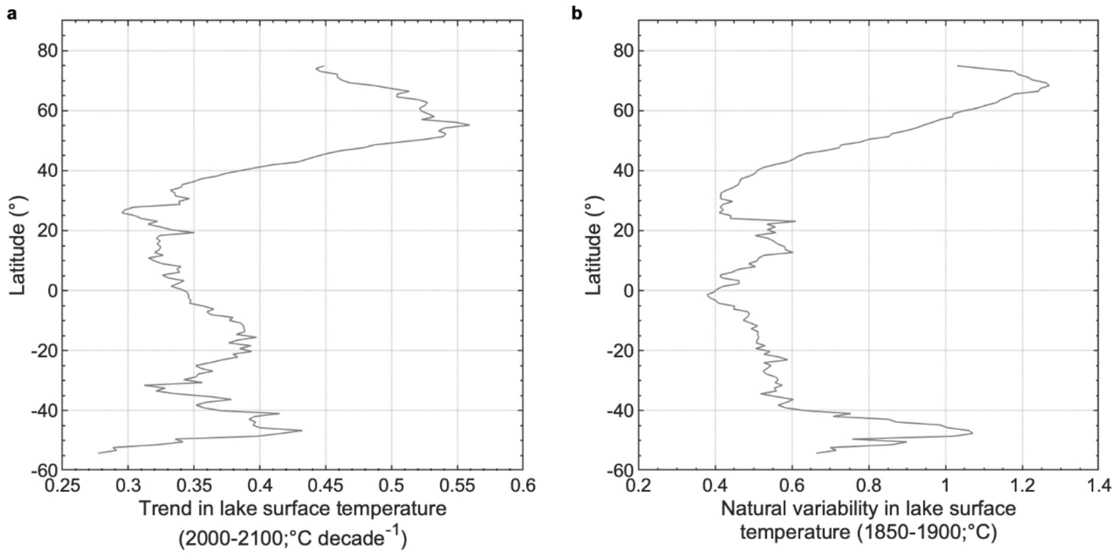
Supplementary Figure 9 | Simulated and observed depth-resolved water temperatures. Shown is a comparison of the simulated and observed water temperature anomalies (from bottom to top) in six lakes situated across climatic gradients. Temperature anomalies are shown for the most recent 20 years and are calculated relative to the periods illustrated in the legends. Note observational records have hiatus and thus some years are missing. Solid lines represent the mean of the most recent 20 years, and the shaded regions represent 2 times the standard deviation, shown for both the model and observations.



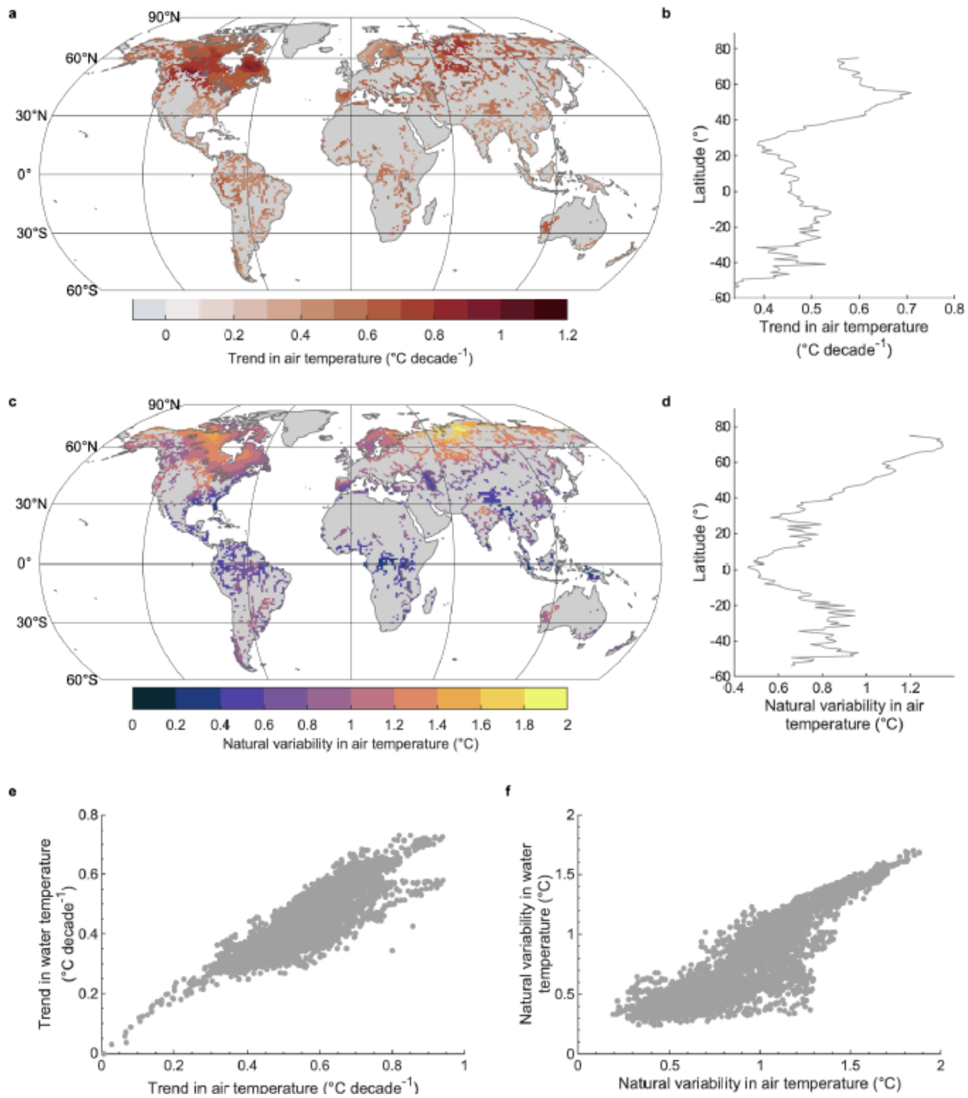
Supplementary Figure 10 | Vertical profile of emergence of no-analogue conditions in 56 lakes projected by the ISIMIP and CESM2-LE. The Y-axis represents the magnitude of projected global warming corresponding to the year of no-analogue conditions emerging. The orange solid line demonstrates the mean of ensemble members in CESM2-LE, and the dark and light orange shadings demonstrate one and two standard deviations of all ensemble members around the mean. The highest magnitude of global warming in ISIMIP is 3.7 °C. Any calculations that no-analogue conditions will not emerge under the warming magnitude of 3.7 °C are assigned with the value of 3.7 °C.



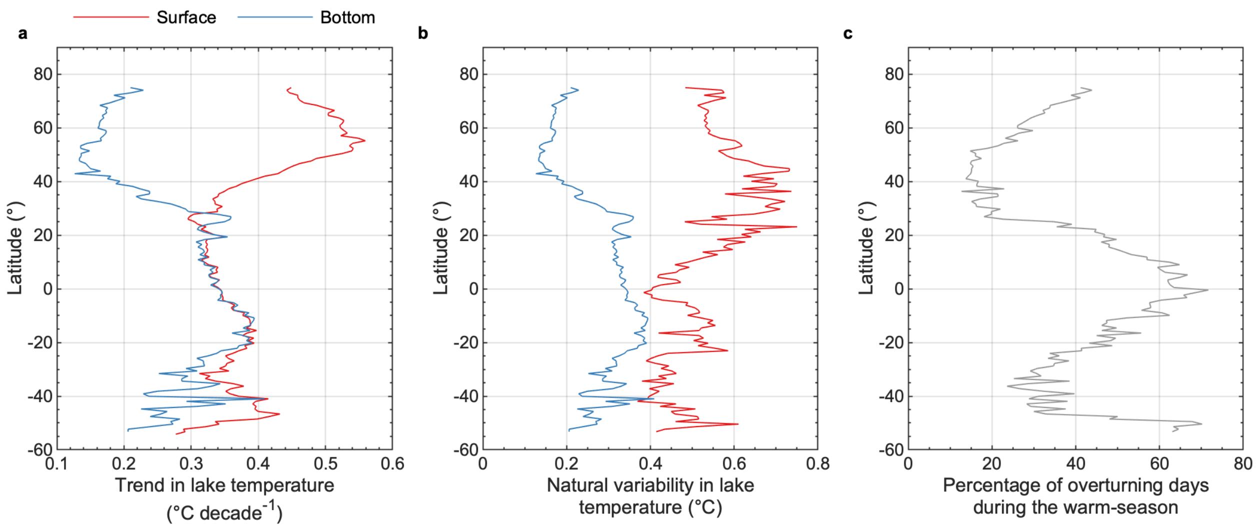
Supplementary Figure 11 | Latitudinal distribution in the emergence of no-analogue conditions at the lake surface. Shown is the projected emergence of no-analogue conditions at the lake surface under global warming, averaged across latitudes. The values shown illustrate the global warming levels projected to result in no-analogue conditions across the studies lakes.



Supplementary Figure 12 | Latitudinal distribution in the trend and natural variability of surface water temperature. Shown are **(a)** the projected rate of change (2000-2100), and **(b)** the natural variability (1850-1900) in surface water temperature, averaged across latitudes. The trend in surface water temperature is calculated from the average of the 100-member ensemble, using a linear regression model.



Supplementary Figure 13 | Across-lake differences in the trend and natural variability in air temperature. Shown are **(a-b)** the rate of change (2000-2100) and **(c-d)** the natural variability (1850-1900) in air temperature across the studied lake locations (i.e., selecting only the grids where lakes were present), and **(b, d)** averaged across latitudes. The trend in air temperature is calculated from the average of the 100-member ensemble, using a linear regression model. Also shown are the relationships between the **(e)** trend and **(f)** natural variability in air temperature and those projected for lake surface water temperature.



Supplementary Figure 14 | Latitudinal distribution in the trend and natural variability of surface and bottom water temperature. Shown are the latitudinal distributions in **(a)** the projected trends (2000-2100) and **(b)** the natural variability (1850-1900) in surface (red) and bottom (blue) water temperature in lakes. Also shown is **(c)** the latitudinal variation in the percentage of overturning days during the warm-season (1850-1900). The trend and natural variability in lake surface and bottom water temperature are similar when the percentage of overturning days is high.

Supplementary Table 1 | Overview of lakes with observational data investigated in this study. Shown are the names of each lake, their latitude, longitude, elevation (m), surface area (km^2), maximum depth (m), and mean depth (m). Latitude and longitude are shown here to two decimal places.

Lake ID	Lake Name	Latitude	Longitude	Elevation (m)	Surface Area (km^2)	Max Depth (m)	Mean Depth (m)
1	Acton	39.56	-84.47	286	2.5	8	4
2	Aleknagik	59.34	-158.78	10	83	110	43
3	Allequash	46.04	-89.62	494	1.68	8	2.9
4	Allgjuttern	57.90	18.46	126.3	0.19	40.7	11.4
6	Annie	27.21	-81.35	33.7	0.37	20.7	8.26
8	Baikal	51.88	105.08	456.4	32500	1750	720
9	Bassenthwaite Lake	54.39	-3.13	69	5.3	19	5.3
10	Batorino	54.85	26.97	163	6.3	5.5	3
11	Beverley	59.67	-158.78	30	90	188	55
12	Big Muskellunge	46.02	-89.61	500	3.96	21.3	7.5
14	Biwa	35.31	136.12	84.37	670.25	103.58	41.2
15	Blelham Tarn	54.24	-2.59	47	0.1	14.5	6.8
16	Blue Chalk	45.20	-78.94	343.5	0.5235	23	8.5
18	Brunner	-42.62	171.45	186	41	109	55.00
19	Brunnsjön	57.48	13.62	94.4	0.11	10.6	5.3
20	Bubble Pond	44.34	-68.24	101	0.13	11.9	6.4
21	Burley-Griffin	-35.30	149.07	556	6.64	17	5
22	Byglandsfjorden	58.78	7.82	203	33	167	
23	Castle	41.23	-122.38	1646	0.2	35	11.4
24	Champlain: Mallet's Bay	44.58	73.28	29.1	54.1	32	13.35
25	Chignik	56.26	-158.83	5	22	64	26
27	Clearwater	46.37	-81.05	267	0.76	21.5	8.4
28	Constance	47.62	9.38	395	473	251	101
30	Crosson	45.08	-79.04	332	0.5674	25	9.2
32	Crystal Lake	46.00	-89.61	502	0.37	20.4	10.4
33	Derwent Water	54.58	-3.14	75	5.4	22	5.5
34	Dickie	45.15	-79.09	354.5	0.936	12	5
35	Douglas	45.57	-84.67	217	13.74	24.38	4.96

36	Eagle	44.36	-68.25	84	1.77	33.6	13.4
38	Erken	59.84	18.63	11.1	24.2	20.65	9
39	Esthwaite Water	54.37	-2.99	65	1	15.5	6.9
40	Eucha	36.38	-94.93	237	11.38	28.3	
41	Fiolen	57.06	16.57	226	1.64	10.5	3.8
42	Fish	43.29	-89.65		0.87	18.9	6.6
43	Flathead	47.90	-114.10	882	495.9	105	39
44	Fräcksjön	58.15	13.85	58	0.28	14.5	6
45	Garda	45.70	10.72	65	368	350	133
47	Giles	41.38	-75.09	428	0.48	24	10.1
49	Grasmere	54.27	-3.01	62	0.6	21.5	7.7
50	Harp	45.38	-79.14	327	0.7138	37.5	13.32
53	Heney	45.13	-79.10	345.5	0.2137	5.8	3.3
56	Hornindalsvatnet	61.95	6.39	53	51	514	
58	IISD Experimental Lake 224	49.69	-93.72		0.26	27.4	11.6
59	IISD Experimental Lake 239	49.66	-93.72	393	0.56	30.4	10.5
60	IISD Experimental Lake 240	49.65	-93.73		0.44	13.1	6.1
61	IISD Experimental Lake 373	49.74	-93.80		0.27	20.8	11
62	IISD Experimental Lake 442	49.78	-93.82		0.16	17.8	9
63	Inarijärvi	69.08	27.92	118.7	1081.92	92	14.3
64	Iseo	45.72	10.07	186	62	251	123
65	Jordan Pond	44.33	-68.26	84	0.76	45.7	25.6
66	Kallavesi	62.76	27.78	81.8	480.31	75	9.6
67	Katepwa	50.69	-103.96	478.2	22.6	22	14.3
68	Kinneret	32.83	35.59	-210	166.7	46.1	25.6
69	Kivu	-2.28	28.98	1463	2370	240	485
70	Konnevesi	62.63	26.60	95.4	190.28	57.1	10.6
71	Konnevesi	62.63	26.60	95.4	190.28	57.1	10.6
72	Kulik	59.80	-158.89	43	45	160	77
73	Kurilskoye Lake	51.42	157.08	104	77.05	316	195
76	Lillinonah	41.48	-73.35	59	6.26	33	13
77	Little Togiak	59.58	-159.16	23	6	77	30
78	Lower Lake Zurich	47.30	8.60	406	67	136	49
79	Lugano.North	46.01	9.02	271	27.5	288	171
80	Lugano.South	45.96	8.89	271	20.3	95	55
82	Maggiore	45.94	8.63	193.88	212.5	370	176.5
83	Mascardi	-41.33	-71.51	807	39.2	218	111
84	Mendota	43.10	-89.41		39.38	25.3	12.8
85	Mjøsa	60.69	11.06	123	362	453	

86	Mohonk	41.77	-74.16	379	0.07	18.5	6
87	Mondsee	47.82	13.37	481	13.8	68	36
88	Monona	43.06	-89.36		13.24	22.5	8.2
90	Müggelsee	52.44	13.66	34	7.43	7.7	4.9
91	Myastro	54.87	26.88	162	13.1	11.3	5.4
92	Naroch	54.89	26.72	161	79.6	24.8	8.9
93	Näsijärvi	61.83	23.82	95.4	256.48	65.6	13.6
94	Nerka	59.57	-159.01	21	201	164	39
96	Nkuruba	0.52	30.30	1518	0.03	38	16
97	North Pine	-27.26	152.94	32	20.75		10.1
98	Okareka	-38.17	176.37	355	3.4	34	20
99	Okaro	-38.30	176.40	419.7	0.3	18	6
100	Okataina	-38.13	176.41	302	10.73	78.5	26.2
101	Okeechobee	26.97	-80.83	4.6	1780	5.5	2.7
102	Opeongo	45.71	-78.37	404	58.08	49.4	14.6
103	Övre Skärjön	59.78	17.83	218.7	1.73	32	5.7
104	Øyeren	59.85	11.18	101	85	76	
105	Päijänne	61.61	25.48	78.3	1082.01	94	14.2
106	Päijänne	61.61	25.48	78.3	1082.01	94	14.2
107	Pesiöjärvi	64.95	28.65	213.9	12.73	15.8	3.9
108	Piburgersee	47.20	10.89	913	0.13	24.6	14
109	Pielinen	63.27	29.61	93.7	895.47	61	10.1
111	Plastic	45.18	-78.82	253.9	0.3214	16.3	7.9
112	Plusssee	54.15	14.38	24	0.14	29	9.4
113	Pyhäjärvi	61.00	22.29	44.9	155.33	26	5.5
114	Pyhäselkä	62.53	29.75	75.9	361.1	67	8.76
115	Red Chalk Main	45.19	-78.95	343	0.4408	38	16.7
116	Remmarsjön	63.81	20.54	234.1	1.36	14.4	5.2
117	Rerewhakaaitu	-38.29	176.50	438	5.17	15.8	5.3
118	Rotehogstjärnen	58.83	13.27	120.5	0.17	9.4	3.4
120	Rotoiti	-38.04	176.44	279	34.3	126	42
121	Rotoma	-38.06	176.59	316	11.6	83	27.7
122	Rotorua	-38.07	176.26	280	80.48	44.8	10.8
123	Sans Chambre	46.72	-81.13	379	0.15	15	5.6
124	Selbusjøen	63.24	10.99	157	58	206	
125	Shira	54.51	90.19	356	35.9	24	11
129	Sparkling Lake	46.01	-89.70	495	0.64	20	10.9
130	Spavinaw	36.39	-95.05	201	6.39	14	
131	St Skärsjön	56.66	14.75	60	0.31	11.5	3.8

132	Stensjön	61.58	18.93	268	0.57	8.5	4.2
133	Stora Envättern	59.07	19.89	62	0.37	11.2	5
134	Strynevatnet	61.93	7.04	29	23	230	
135	Sunapee	43.39	-72.06	333	16.6	33.7	10
136	Tanganyika	-4.85	29.59	773	32600	1471	580
137	Tarawera	-38.20	176.45	298	41	87	56.37
138	Taupo	-38.81	175.91	356	616	160	91.55
139	Texoma	33.83	-96.57	188	356.12	31	11
140	Thunderbird	35.22	-97.22	317	21.76	17.7	4.7
141	Tikitapu	-38.12	176.33	418	1.44	27.5	18
142	Toolik	68.38	-149.38	719	1.5	25	1.7
143	Traunsee	47.85	13.80	422	24.4	191	89.7
145	Trout Lake	46.03	-89.67	492	16.08	35.7	14.6
146	Vänern	58.90	13.40	44	5648	72	27
148	Wallenpaupack	41.41	-75.24	361	23.07	15.8	8.99
149	Washington	47.63	-122.27	4.9	87.6	65.2	32.9
150	Whitepine	47.28	-80.83	393	0.67	22	5.6
151	Windermere North Basin	54.24	-2.58	39	8.1	64	25.1
152	Wingra	43.05	-89.43		1.4	6.7	2.7
153	Vulture Lake	64.76	-110.53	416	1.8	42	