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Supplement of

Timing of spring events changes under modelled future climate scenarios in a mesotrophic lake

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S1. Model performance time series

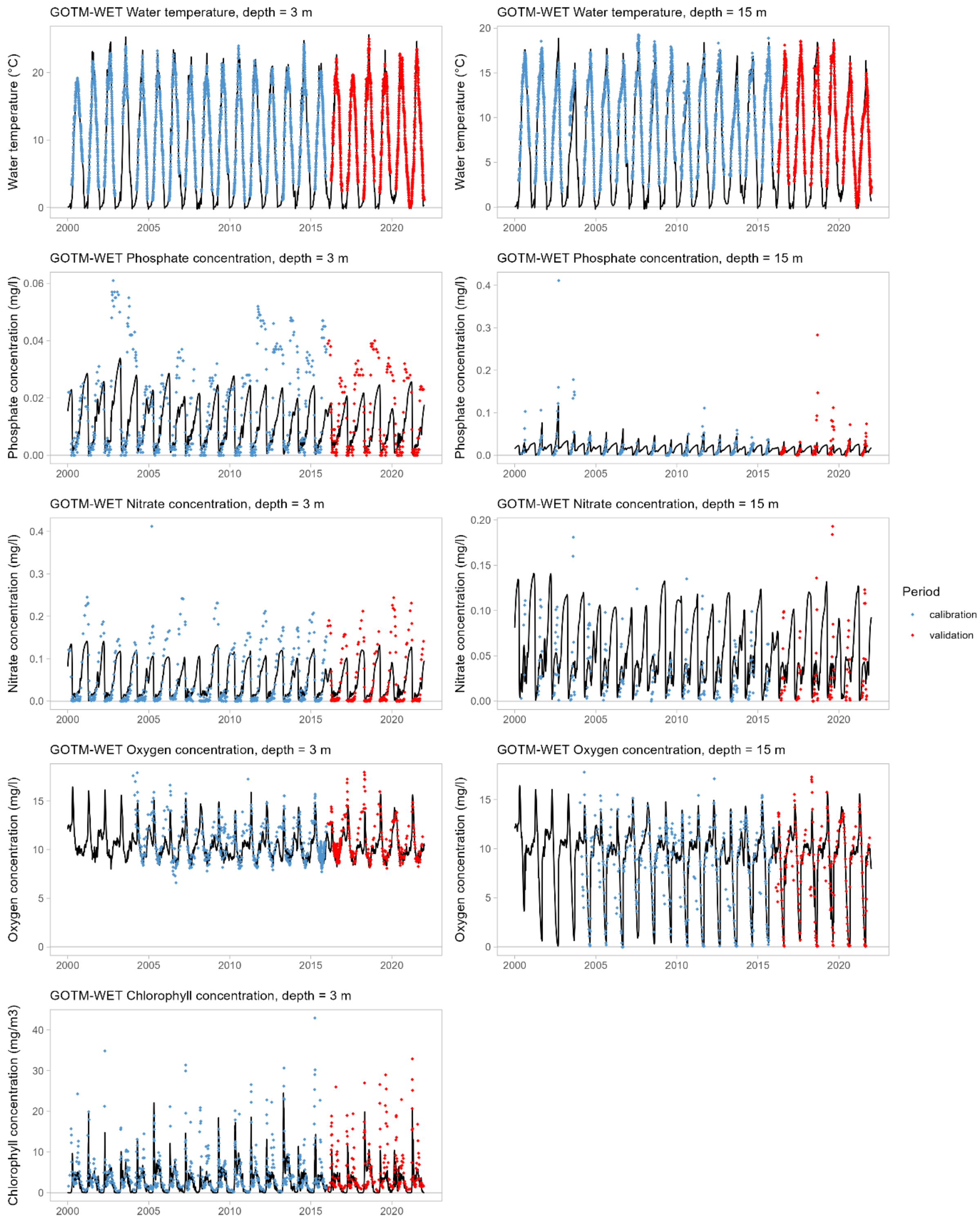


Figure S1. Time series of modelled (black line) and observed (blue dots for calibration, red dots for validation period) GOTM-WET variables.

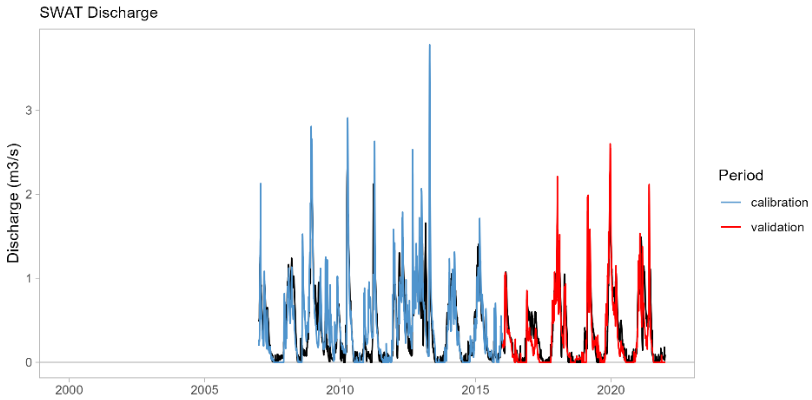


Figure S2. Time series of modelled (black line) and observed (blue line for calibration, red line for validation period) discharge.

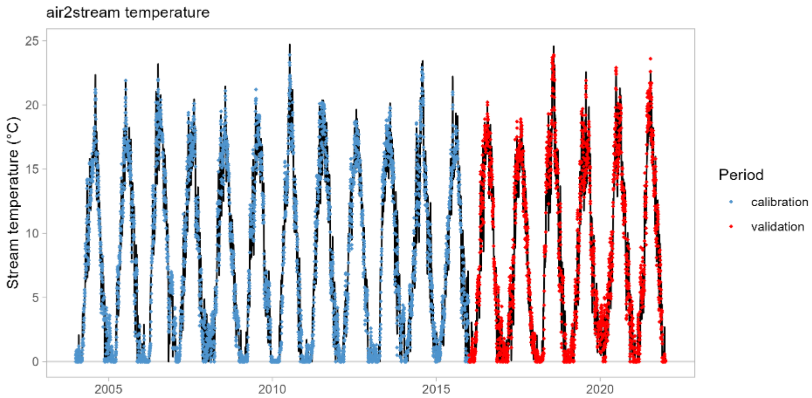


Figure S3. Time series of modelled (black line) and observed (blue dots for calibration, red dots for validation period) stream temperature.

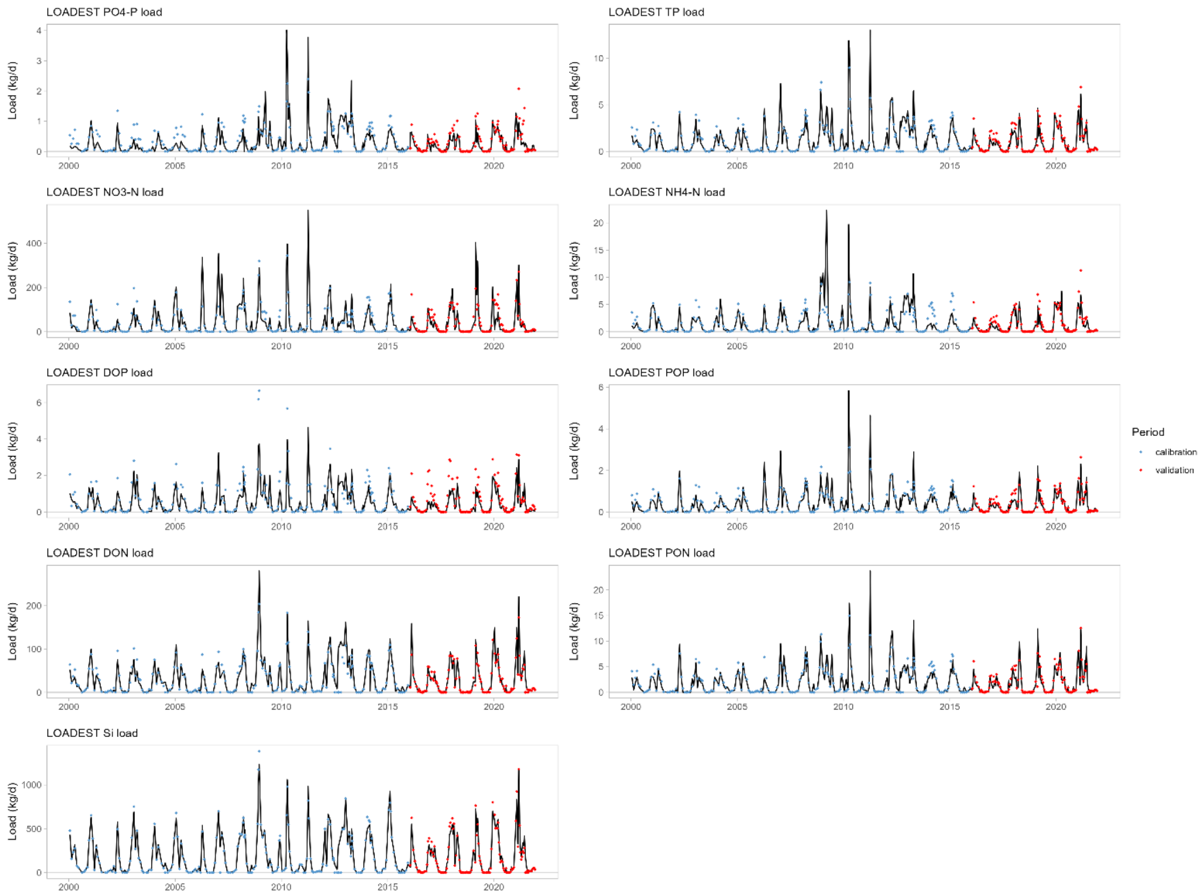


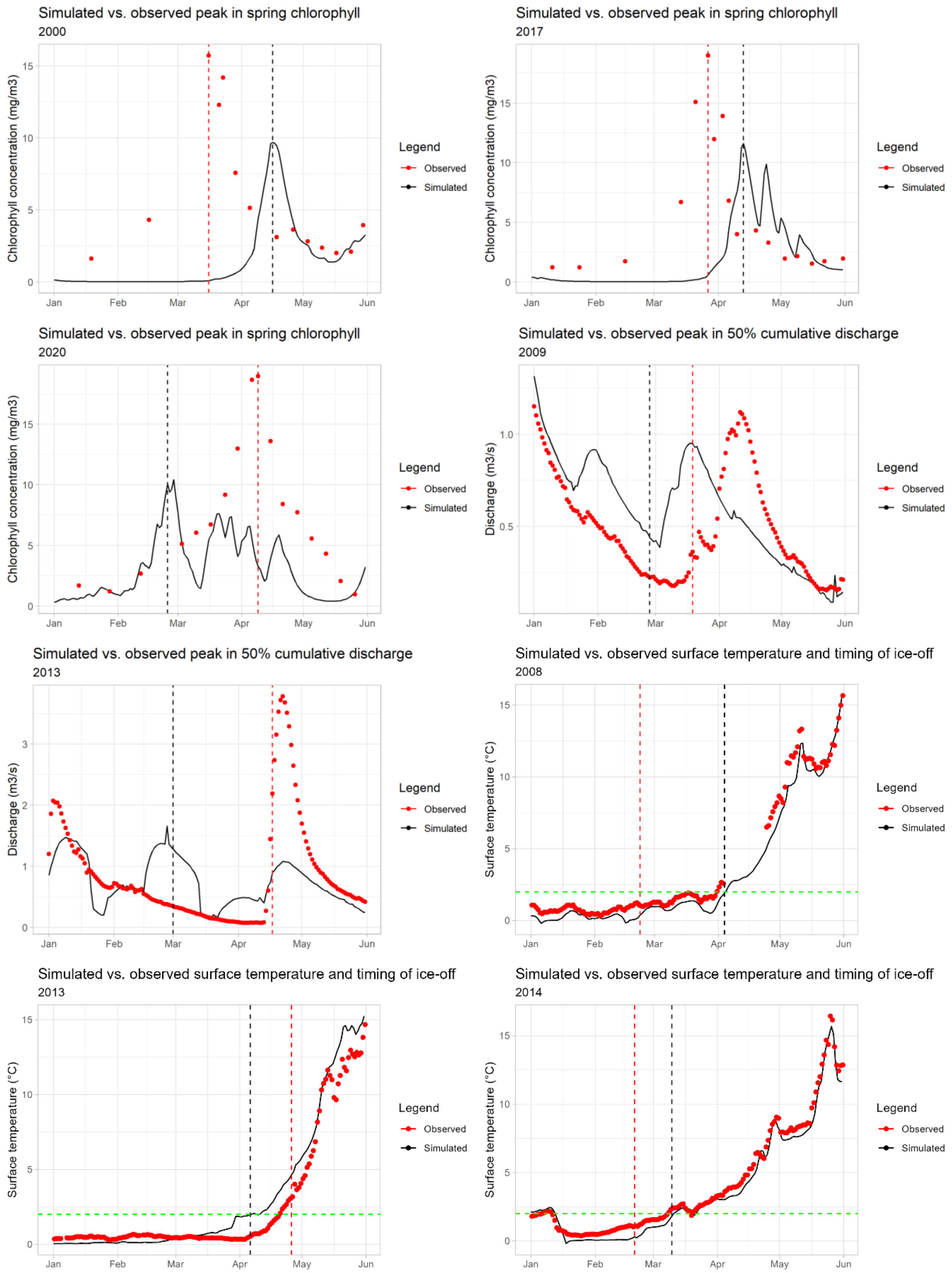
Figure S4. Time series of modelled (black line) and observed (blue dots for calibration, red dots for validation period) nutrient loads. Nutrient concentrations were simulated with LOADEST statistical models and both the observed and simulated concentrations were fitted to simulated discharges.

S2. CSPS model validation

Table S1. Validation following the CSPS-framework (Conceptual-State-Process-System validation, Hipsey et al., 2020). The validation levels assessed in this table are 1b (derived metrics describing model state), 1c (metrics describing multi-scale variability in model state), 2 (process validation), and 3 (system validation), and the properties assessed were chosen based on data availability. This validation is an addition to the largely level 1a validation (direct comparison between simulations and observations) that was conducted by Jiménez-Navarro et al. (2023) and the comparison of spring event timing (level 1b) in the main text. The performance is assessed as bad, moderate, or good, and is a subjective assessment of the simulation of both year-to-year variation (represented by R^2, NRMSE, and visual inspection) and the quantiles and medians (assessed by boxplots). In cases where R^2 and NRMSE could not be determined, the performance was solely based on visual inspection. NRMSE stands for Normalised Root Mean Square Error, and was normalised by the observation mean. A script for the generation of these statistics and plots is provided by Mesman et al. (2024).

Property	Description	Validation level	R^2	NRMSE	Comment	Performance
Ice	Duration of ice cover	1b	0.58	0.29	Dynamic over time is reproduced well, with exception of a single year (2008)	Good
Stratification	Duration of stratification	1b	0.57	0.12	A good dynamic over time, apart from the year 2000	Good
Stratification	Schmidt stability	1b	0.86	0.27	-	Good
Oxygen	Oxycline depth	1b	0.30	0.10	Interannual variation only weakly represented, but right order of magnitude.	Moderate
Oxygen	Cumulative distribution plot, oxygen at 15 m depth	1c	NA	NA	Simulated and observed distribution functions are similar	Good
Oxygen	Depletion rate in summer	2	0.06	0.20	Essentially no year-to-year variation (0.12-0.2 g/m3/d) is captured, though the order of magnitude is the same.	Bad/Moderate
Oxygen	Hypoxic factor (4 mg/l)	3	0.64	0.34	Rather good agreement, but some variation is unexplained.	Moderate
Light	Secchi depth	1b	0.39	0.34	Simulations overestimate Secchi depth by about 1 – 1.5 m.	Bad/Moderate
Nutrients	TN:TP ratio	1b	0.07	0.55	Model consistently underestimates the N:P ratio, and simulates little of the year-to-year variation. Seasonal pattern of an increase in N:P in summer is reproduced.	Bad
Phytoplankton	Phytoplankton species distribution between spring and summer	3	NA	NA	Simulations overestimate contribution of diatoms and downplays other groups, but otherwise the spring/summer difference is accurate.	Moderate

S3. Investigation of events with an error larger than 14 days



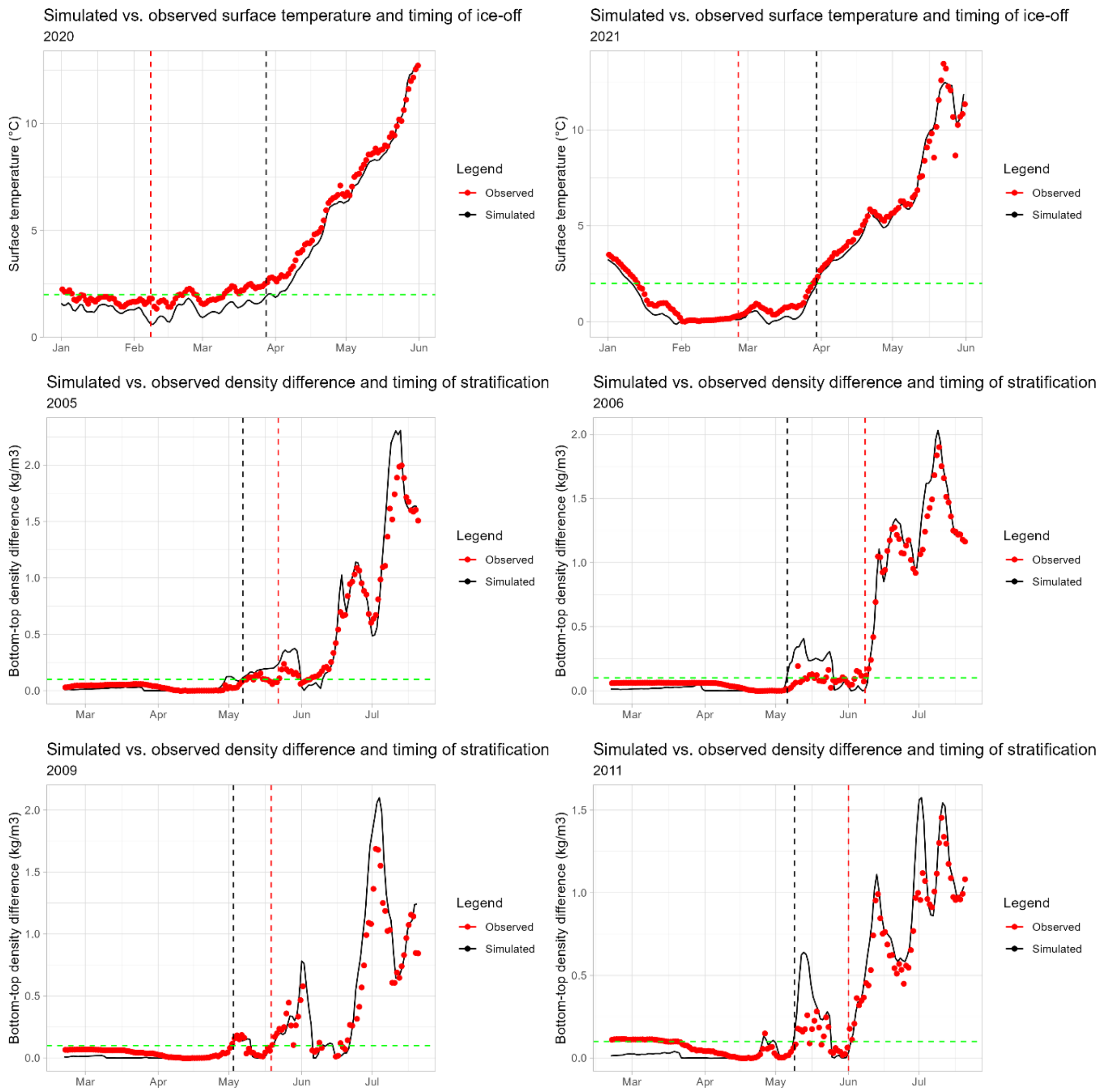


Figure S5. Plots of simulated (black line) and observed (red dots) values related to the peak in chlorophyll, date of ice-off, date of 50% cumulative spring discharge, and onset of stratification, where error values exceeded 14 days. Vertical dashed lines indicated the timing calculated for the simulations (black) and observations (red). A horizontal green line is plotted to denote the threshold values for simulated timing of ice-off (2 °C) and density-difference for onset of stratification (0.1 kg/m^3).

Table S2. Reason for bad fit for each of the events plotted in Figure S5. "Model failure" indicates that the model did not capture the dynamics of the lake. "Method failure" indicated that the method to identify the peak was the main cause of the discrepancy between model and observations, rather than the inability of the model to capture in-lake dynamics. [a]Years with lowest recorded ice duration in study period.

Year	**Event**	**Reason for bad fit**
2000	Chlorophyll peak	Model failure. Perhaps related to a short spin-up period
2017	Chlorophyll peak	Model failure
2020	Chlorophyll peak	Either model failure or a gap in observations missed the real first spring peak. Observations before and after the simulated peak are in line with the simulation, but there is an observation gap of 20 days, in which the model simulated a peak in chlorophyll, which cannot be confirmed by measurements.
2009	Discharge peak	Model failure
2013	Discharge peak	Model failure
2008	Ice-off	Method failure[a]
2013	Ice-off	Model failure and method failure
2014	Ice-off	Method failure[a]
2020	Ice-off	Method failure[a]
2021	Ice-off	Method failure[a]
2005	Stratification onset	Method failure. A temporary stratification event lasted slightly longer than 7 days in the simulation and slightly shorter in the observations, causing a mismatch. The start of the permanent stratification period was simulated well.
2006	Stratification onset	Same as above
2009	Stratification onset	Same as above
2011	Stratification onset	Same as above

S4. Future projections - Time periods 1985-2014, 2040-2069, and 2070-2099

Table S3. Average values for time periods 1985-2014, 2040-2069, and 2070-2099 under the SSP 2-45 and 5-85 scenarios.

			SSP 2-45		SSP 5-85	
Variable	**Unit**	**1985-2014**	**2040-2069**	**2070-2099**	**2040-2069**	**2070-2099**
Chlorophyll peak date	DOY	108.31	87.46	89.66	86.01	77.64
Peak spring chlorophyll concentration	mg/m^3	14.53	11.71	11.22	11.81	10.84
50% spring discharge date	DOY	78.37	60.43	59.13	57.52	55.31
Cumulative spring discharge	m^3	$8.92 \cdot 10^6$	$1.10 \cdot 10^7$	$1.16 \cdot 10^7$	$1.20 \cdot 10^7$	$1.29 \cdot 10^7$
Ice-off date	DOY	101.93	90.50	83.83	80.96	68.15
Ice-on date	DOY	3.79	28.01	35.03	34.21	45.24
Number of days with ice	days	72.02	31.31	24.16	21.06	7.04
Average ice thickness	m	0.155	0.061	0.048	0.039	0.014
Stratification onset	DOY	140.71	132.26	130.78	128.61	125.65
End of stratification	DOY	261.49	267.89	267.81	271.13	273.29
Number of stratified days	days	122.11	136.56	138.56	143.41	149.11
Average Schmidt stability during stratification	J/m^2	177.71	221.87	232.13	236.61	266.61
Average mixed layer depth during stratification	m	6.53	6.35	6.32	6.00	6.01

S5. Mann-Kendall test results for the relative comparisons

Table S4. Results of Mann-Kendall trend tests for relative trends of the timing of spring events during the future climate scenarios.

Variable	**Relative to**	**SSP**	**p-value**	**Sen's slope (days/decade)**	**Intercept (days)**
50% spring discharge	Chlorophyll peak	2-45	0.994	0	-27.40
Ice-off	Chlorophyll peak	2-45	0.555	0.3	-4.58
50% spring discharge	Ice-off	2-45	0.766	-0.12	-24.90
Chlorophyll peak	Stratification onset	2-45	0.001	-1.23	-31.26
50% spring discharge	Stratification onset	2-45	$4.8 \cdot 10^{-4}$	-1.07	-62.99
Ice-off	Stratification onset	2-45	$5.6 \cdot 10^{-6}$	-0.94	-34.57
50% spring discharge	Chlorophyll peak	5-85	$3.7 \cdot 10^{-4}$	1.12	-33.51
Ice-off	Chlorophyll peak	5-85	0.388	-0.21	-5.18
50% spring discharge	Ice-off	5-85	$3.6 \cdot 10^{-4}$	1.44	-31.35
Chlorophyll peak	Stratification onset	5-85	$2.0 \cdot 10^{-10}$	-1.87	-31.36
50% spring discharge	Stratification onset	5-85	0.103	-0.58	-66.66
Ice-off	Stratification onset	5-85	$3.4 \cdot 10^{-15}$	-2.00	-33.20

S6. Surface water temperature, nitrate, and phosphate concentrations, underwater shortwave radiation during the spring chlorophyll peak

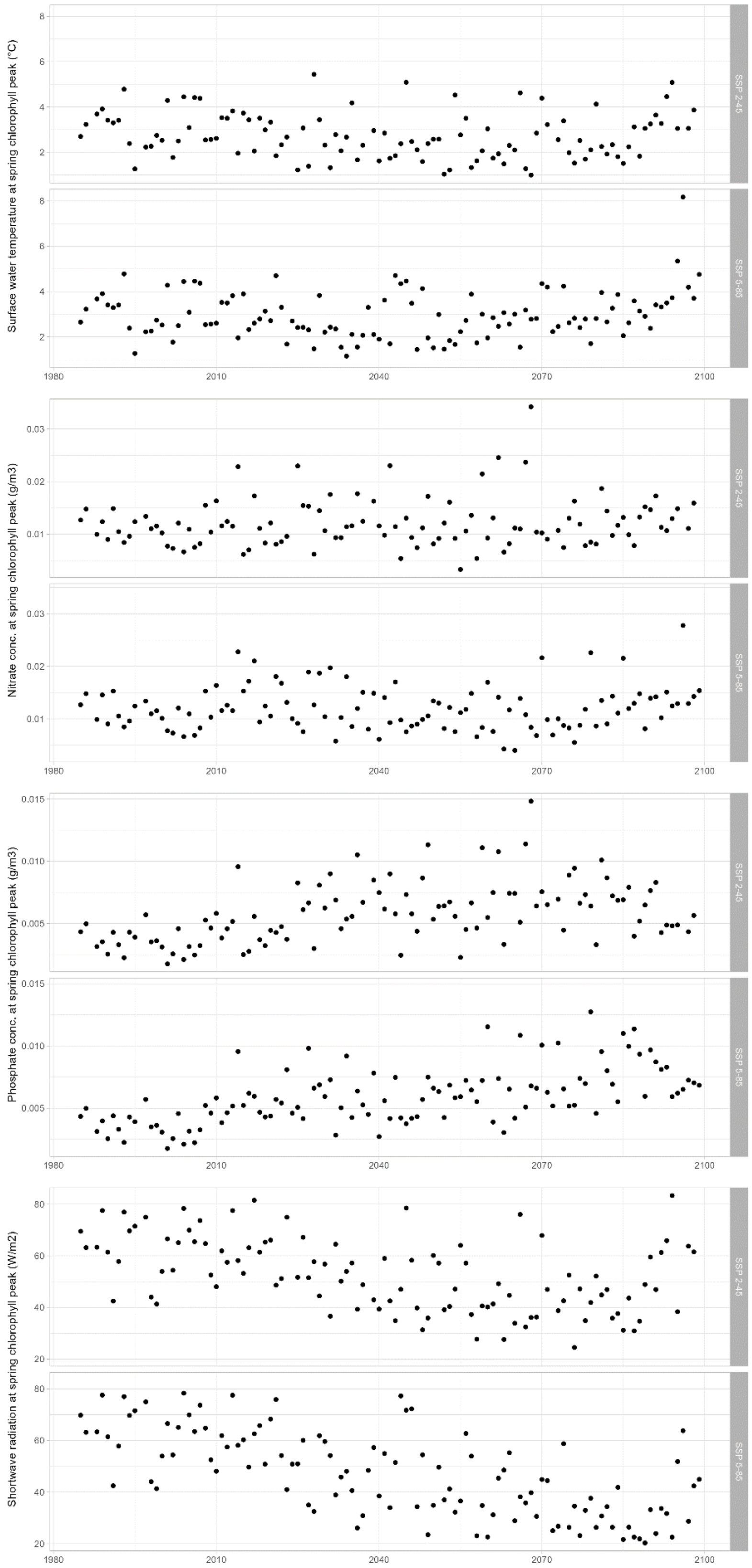


Figure S6. Surface water temperature, nitrate concentration, phosphate concentration, and underwater shortwave radiation (top to bottom) at 0.5 m depth during the spring chlorophyll peak, averaged over all GCMs, for both SSP 2-45 and SSP 5-85.

S7. Zooplankton dynamics

The zooplankton simulations could not be compared to detailed field data and the concentrations simulated by the model are unlikely to be in line with observations, as also predators of zooplankton (e.g. fish) were absent in the simulations. Although zooplankton grazing on phytoplankton is indeed likely to occur throughout the year, especially the summer zooplankton concentrations would be strongly suppressed by fish predation in Lake Erken. These results are shown primarily as supporting information for how they may have influenced the simulated phytoplankton dynamics.

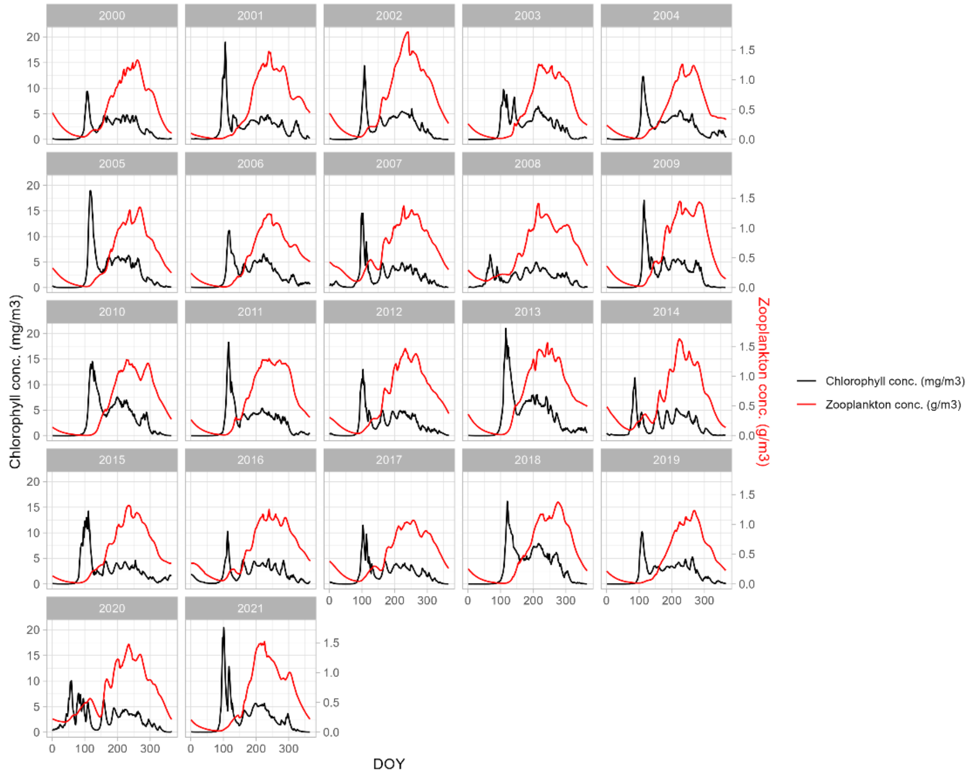


Figure S7. Chlorophyll (black line, left y-axis) and zooplankton concentration (red line, right y-axis) per day-of-the-year (DOY), for every year in the calibration run. Simulated concentrations at 0.5 m depth are shown.

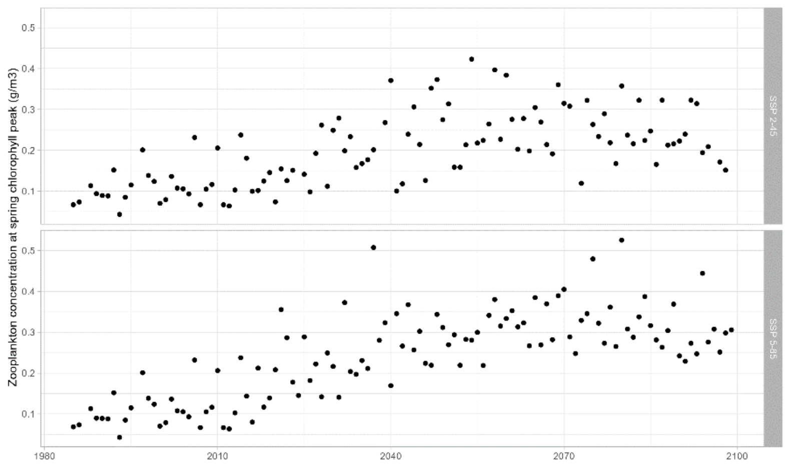


Figure S8. Zooplankton concentration at 0.5 m depth during the spring chlorophyll peak, averaged over all GCMs, for both SSP 2-45 and SSP 5-85 (top and bottom panel, respectively).