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Multi-fidelity model assessment of climate change impacts on river water temperatures and thermal extremes and potential effects on cold-water fish in Switzerland

Love Råman Vinnå et al.

Correspondence to: Jannis Epting (jannis.epting@unibas.ch)

S1: Description of water temperature models

S1.1 air2stream

The river temperature model air2stream can be used with five different degrees of complexity, which differ in their level of parameterization (Piccolroaz et al., 2016; Toffolon & Piccolroaz, 2015), where some parameters are neglected (Eq. S1 to S5). In air2stream, water temperature (T_w) [°C] is calculated from air temperature (T_a) [°C] and from discharge (Q) in either a 3-, 4-, 7-, or 8-parameter configuration.

8-parameter version

$$\frac{\Delta T_w}{\Delta t} = \frac{1}{\delta}\left\{a_1 + a_2 T_a(t) - a_3 T_w(t) + \theta\left[a_5 + a_6 \cos\left(2\pi\left(\frac{t}{t_y} - a_7\right)\right) - a_8 T_w(t)\right]\right\} \tag{S1}$$

where, T_w is water temperature, T_a air temperature, t represents the day of the year, t_y is the duration of one year, a_1 is a fitting parameter with units °C/day and a_2-a_8 are dimensionless fitting parameters, δ represents the dimensionless depth and is defined as $\delta = \theta^{a_4}$, while θ represents the dimensionless flow defined as $\theta = Q(t)/\bar{Q}$, with $Q(t)$ being flow and $\bar{Q}$ the mean flow.

7-parameter version:

$$\frac{\Delta T_w}{\Delta t} = a_1 + a_2 T_a(t) - a_3 T_w(t) + \theta\left[a_5 + a_6 \cos\left(2\pi\left(\frac{t}{t_y} - a_7\right)\right) - a_8 T_w(t)\right] \tag{S2}$$

Here, δ is set equal to 1 and the influence of river depth on water temperature is not explicitly considered anymore.

5-parameter version:

$$\frac{\Delta T_w}{\Delta t} = a_1 + a_2 T_a(t) - a_3 T_w(t) + a_6 \cos\left(2\pi\left(\frac{t}{t_y} - a_7\right)\right) \tag{S3}$$

With both δ and θ set to 1, no depth or discharge input is required and the effect of both depth and discharge on water temperature is approximated by the fitting constant a_1.

The 3- and 4-parameter versions are recommended for cases where both discharge and the thermal effect of tributaries at a given observation point along a stream are considered small.

4-parameter version:

$$\frac{\Delta T_w}{\Delta t} = \frac{1}{\delta}\{a_1 + a_2 T_a(t) - a_3 T_w(t)\} \tag{S4}$$

In this version, θ is set to 0 and it is assumed that the mean temperature of tributaries is approximately equal to the temperature of the river itself, i.e., the longitudinal (spatial) gradient of temperature is small. Moreover, seasonal effects are neglected.

3-parameter version:

$$\frac{\Delta T_w}{\Delta t} = a_1 + a_2 T_a(t) - a_3 T_w(t) \tag{S5}$$

In this simplest version of air2stream, θ is set to 0 and δ to 1, such that no discharge input is required and flow, depth, seasonality, and temperature gradients are approximated via fitting the constant a_1.

S1.2 air2water

With the air2water model, surface water temperature (T_w) [°C] is calculated towards a reference temperature (T_r) [°C], with air temperature (T_a) [°C] as the only input. T_r links surface temperature to bottom temperature. The lake model can be used in three versions (Piccolroaz, 2016; Toffolon et al., 2014; Piccolroaz et al., 2013), with 8, 6, or 4 parameters (Eq. S6 to S8).

8-parameter version

$$\frac{\Delta T_w}{\Delta t} = \frac{1}{\delta}\left\{a_1 + a_2 T_a - a_3 T_w + a_5 \cos\left[2\pi\left(\frac{t}{t_y} - a_6\right)\right]\right\} \tag{S6}$$

In the 8-parameter version all dimensionless fitting parameters a_1-a_8 are active together with δ known as the volume ratio or normalized depth defined as:

$$\delta = exp\left(-\frac{T_w - T_r}{a_4}\right) \qquad \text{for} \quad (T_w \geq T_r)$$

$$\delta = exp\left(-\frac{T_r - T_w}{a_7}\right) + exp\left(-\frac{T_w}{a_8}\right) \qquad \text{for} \quad (T_w < T_r)$$

δ is theoretically defined in the range between 0 and 1, with the value 1 corresponding to the maximum volume of the surface layer, decreasing values account for increasingly strong stratification, which reduce the water volume affected by the surface heat budget (Toffolon et al., 2014). $T_w < T_r$ represent a inversely stratified lake in winter with colder water (< 4 °C) on-top of warmer, while $T_w > T_r$ represent a stratified lake in summer with warmer water (> 4 °C) on top of colder water (Piccolroaz et al., 2013). Ice is not included in the model.

6-parameter version;

$$\frac{\Delta T_w}{\Delta t} = \frac{1}{\delta}\left\{a_1 + a_2 T_a - a_3 T_w + a_5 \cos\left[2\pi\left(\frac{t}{t_y} - a_6\right)\right]\right\} \tag{S7}$$

$$\delta = exp\left(-\frac{T_w - T_r}{a_4}\right) \qquad \text{for} \quad (T_w \geq T_r)$$

$$\delta = 1 \qquad \text{for} \quad (T_w < T_r)$$

In the 6-parameter version, δ is set to 1 for $T_w < T_r$ i.e., the lake does not become inversely stratified.

4-parameter version

$$\frac{\Delta T_w}{\Delta t} = \frac{1}{\delta}\{a_1 + a_2 T_a - a_3 T_w\} \tag{S8}$$

$$\delta = exp\left(-\frac{T_w - T_r}{a_4}\right) \qquad \text{for} \quad (T_w \geq T_r)$$

$$\delta = 1 \qquad \text{for} \quad (T_w < T_r)$$

Here, a_5 is set to 0 and, as in the 6-parameter version, δ is set 1 for $T_w < T_r$. By setting a_5 to 0, the 4-parameter version lacks the imposed sinusoidal forcing. Additionally, the physical meaning of parameters differs here from the 8-parameter version, as the terms including T_a and T_w now indirectly consider the periodicity of external meteorological forcing's. This version is preferable when the annual cycles of T_a or T_w are approximately sinusoidal (Piccolroaz, 2016).

S2: Supporting Figures and Tables

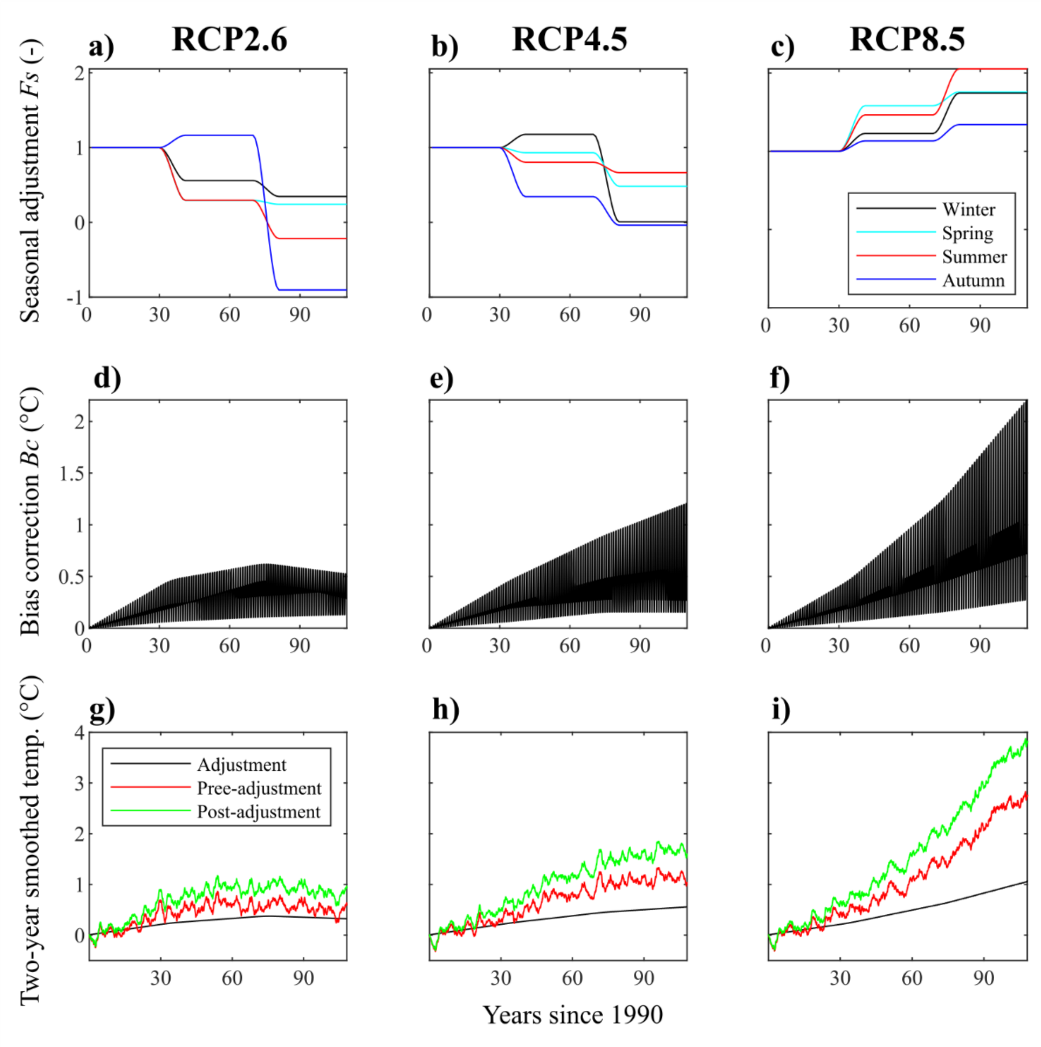

Figure S1. Trend bias correction example for station 2612 belonging to the Swiss Plateau regime simulated with air2stream. (a-c): seasonal adjustment factors for winter (December to February), spring (March-May), summer (June-August), autumn (September-November). (d-f) seasonal and thermal regime dependent bias correction *Bc*. (g-i) *Bc* added to the projections of river temperature.

Table S1. Temperature model calibration setup and cluster results. ALP: Alpine regime; DLA: Downstream lake regime; SPJ: Swiss Plateau regime; HYP: Influenced by hydropeaking; 3/5*: discharge data not available therefore only air2stream tested with 3 and 5 parameters.

ID	**Tested model/s**	**Thermal regime**			**Thermal clusters**
		Derived here	Michel et al., 2020	Piccolroaz et al., 2016	**DTWARP_PER_33**
2009	air2stream	Regulated	HYP	Regulated	Cluster 7.3
2016	air2stream & air2water	Downstream Lake	DLA	Outlet	Cluster 2.4
2018	air2stream & air2water	Downstream Lake	DLA		Cluster 2.4
2019	air2stream3/5*	Regulated	HYP	Regulated	Cluster 8.1
2029	air2stream & air2water	Downstream Lake	DLA	Outlet	Cluster 2.4
2030	air2stream & air2water	Downstream Lake	DLA	Outlet	Cluster 3.2
2033	air2stream	Alpine			Cluster 8.4
2034	air2stream	Swiss Plateau	SPJ	Natural low-land	Cluster 3.3
2044	air2stream	Swiss Plateau	SPJ	Natural low-land	Cluster 3.3
2056	air2stream	Regulated	HYP	Regulated	Cluster 8.2
2068	air2stream3/5*	Regulated	HYP		Cluster 6
2070	air2stream	Swiss Plateau	SPJ	Natural low-land	Cluster 6
2084	air2stream	Regulated	HYP		Cluster 7.3
2085	air2stream & air2water	Downstream Lake	DLA	Outlet	Cluster 2.3
2091	air2stream & air2water	Downstream Lake	DLA	Outlet	Cluster 1.3
2104	air2stream & air2water	Downstream Lake	DLA		Cluster 3.2
2106	air2stream	Swiss Plateau	SPJ		Cluster 3.6
2109	air2stream	Alpine	ALP		Cluster 8.2
2112	air2stream	Swiss Plateau		Natural low-land	Cluster 7.2
2113	air2stream3/5* & air2water	Downstream Lake			Cluster 1.3
2126	air2stream	Swiss Plateau		Natural low-land	Cluster 3.5
2130	air2stream3/5* & air2water	Downstream Lake			Cluster 1.3
2135	air2stream & air2water	Downstream Lake	DLA	Outlet	Cluster 3.2
2139	air2stream3/5*	Swiss Plateau			
2143	air2stream & air2water	Downstream Lake	DLA	Outlet	Cluster 2.2
2150	air2stream	Alpine			Cluster 7.2
2152	air2stream & air2water	Downstream Lake	DLA	Outlet	Cluster 2.4
2159	air2stream	Swiss Plateau		Natural low-land	Cluster 4.3
2161	air2stream	Alpine		Snow-fed	Cluster 10
2167	air2stream & air2water	Downstream Lake			Cluster 1.1
2170	air2stream3/5*	Swiss Plateau	ALP		Cluster 6
2174	air2stream3/5* & air2water	Downstream Lake	DLA		Cluster 2.3
2176	air2stream	Swiss Plateau			
2179	air2stream	Swiss Plateau		Natural low-land	Cluster 5.2
2181	air2stream	Swiss Plateau			
2210	air2stream	Swiss Plateau			Cluster 4.3
2232	air2stream	Alpine		Snow-fed	Cluster 8.4
2243	air2stream & air2water	Downstream Lake	DLA		Cluster 1.3
2256	air2stream	Alpine		Snow-fed	Cluster 9
2265	air2stream	Alpine			
2269	air2stream	Alpine	ALP		Cluster 9
2276	air2stream	Alpine		Snow-fed	Cluster 7.3
2282	air2stream3/5*	Swiss Plateau			Cluster 7.2
2288	air2stream & air2water	Downstream Lake			Cluster 2.2
2290	air2stream3/5*	Spring			
2307	air2stream	Swiss Plateau			Cluster 6
2308	air2stream	Swiss Plateau		Natural low-land	Cluster 5.2
2327	air2stream	Alpine		Snow-fed	Cluster 9
2343	air2stream	Swiss Plateau		Natural low-land	Cluster 5.3
2347	air2stream3/5*	Alpine		Natural low-land	Cluster 8.3
2351	air2stream	Alpine			Cluster 8.2
2366	air2stream	Alpine		Snow-fed	Cluster 9
2369	air2stream	Swiss Plateau		Natural low-land	Cluster 5.2
2372	air2stream	Regulated	HYP	Regulated	Cluster 7.3
2374	air2stream	Swiss Plateau		Natural low-land	Cluster 6
2386	air2stream	Swiss Plateau			Cluster 3.1
2392	air2stream3/5* & air2water	Downstream Lake			Cluster 2.2
2410	air2stream3/5*	Swiss Plateau			Cluster 5.4
2414	air2stream	Swiss Plateau		Natural low-land	Cluster 6
2415	air2stream	Swiss Plateau	SPJ	Natural low-land	Cluster 1.3
2432	air2stream	Swiss Plateau			Cluster 3.5
2433	air2stream3/5*	Swiss Plateau			Cluster 6
2434	air2stream	Swiss Plateau			
2457	air2stream3/5* & air2water	Downstream Lake	DLA	Snow-fed	Cluster 4.4
2462	air2stream	Alpine	ALP		Cluster 9
2467	air2stream3/5*	Regulated			Cluster 5.1
2473	air2stream	Regulated	HYP		Cluster 6
2481	air2stream	Regulated	HYP		Cluster 7.3
2485	air2stream3/5*	Swiss Plateau			Cluster 3.4
2493	air2stream	Swiss Plateau			Cluster 5.3
2499	air2stream3/5*	Spring			
2500	air2stream	Swiss Plateau	SPJ		Cluster 4.4
2604	air2stream	Swiss Plateau			Cluster 7.1
2606	air2stream & air2water	Downstream Lake			Cluster 1.3
2608	air2stream3/5*	Swiss Plateau		Natural low-land	Cluster 5.1
2609	air2stream	Swiss Plateau		Natural low-land	Cluster 6
2612	air2stream	Swiss Plateau		Natural low-land	Cluster 7.1
2613	air2stream3/5* & air2water	Downstream Lake			Cluster 1.3
2617	air2stream	Alpine		Snow-fed	Cluster 8.2
2623	air2stream3/5*	Alpine			Cluster 9
2634	air2stream	Swiss Plateau	SPJ		
2635	air2stream3/5*	Swiss Plateau			

Table S2. Best performing model setup using air2stream (TM1) and air2water (TM2) with corresponding calibration parameter and temporal extent of data used.

Stations Air-River	Model	Calibration			Validation		Parameter Values							
		Time	RMSE (°C)	Mean Q (m^3 s^{-1})	Time	RMSE (°C)	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
AIG-2009	TM1	1990-2019	0.52	184.74	1981-1989	0.59	-0.057	0.362	0.183	0.185	12.158	3.850	0.533	1.921
BUS-2016	TM1	1990-2019	0.81	309.96	1985-1989	0.98	0.603	0.180	0.156		3.849	2.325	0.603	0.357
BUS-2018	TM2	1990-2019	0.96		1985-1989	1.18	1.137	0.090	0.169	9.939	0.549	0.626		
MER-2019	TM1	1990-2019	0.85	36.53	1980-1989	0.68	5.044	0.273	1.233					
BER-2029	TM2	1990-2019	0.87		1980-1989	0.93	0.181	0.023	0.032	12.592	0.052	0.614		
INT-2030	TM2	1990-2017	0.95		1980-1989	1.05	0.398	0.022	0.054	5.819	0.156	0.663		
CHU-2033	TM1	2002-2017	0.75	30.91			0.407	0.364	0.496	-0.690	8.233	5.276	0.585	1.406
PAY-2034	TM1	1990-2019	0.78	7.51	1980-1989	0.84	1.736	0.749	0.748		6.549	3.759	0.579	0.719
SHA-2044	TM1	1990-2019	0.80	46.37	1982-1989	0.78	1.848	0.506	0.537		4.394	2.759	0.582	0.519
ALT-2056	TM1	1990-2019	0.58	42.68	1980-1989	0.76	8.725	1.265	2.981	-0.996	9.003	8.097	0.613	1.628
MAG-2068	TM1	1997-2019	1.04	72.29	1980-1982	0.99	0.376	0.046	0.101					
LAG-2070	TM1	1990-2019	0.85	11.74	1980-1989	1.07	3.984	0.563	0.880		5.420	4.985	0.586	0.780
ALT-2084	TM1	1990-2019	0.78	19.19	1980-1989	0.88	1.118	0.609	0.638	-0.805	18.147	4.980	0.599	2.744
BER-2085	TM1	1990-2016	0.84	175.20	1984-1989	1.05	1.488	0.144	0.158		2.848	2.157	0.606	0.322
BAS-2091	TM2	1990-2007	0.84		1980-1989	0.97	0.308	0.034	0.055	12.167	0.131	0.600		
GLA-2104	TM2	1990-2019	1.14		1980-1989	1.17	0.053	0.010	0.013	6.323				
BAS-2106	TM1	1990-2019	0.60	15.47	1980-1989	0.69	0.649	0.359	0.375		6.512	1.815	0.574	0.664
INT-2109	TM1	1990-2019	0.60	19.08	1980-1989	0.74	9.036	1.678	3.578	-0.001	29.278	4.740	0.476	5.000
STG-2112	TM1	2006-2019	0.80	3.16			-0.417	0.344	0.316		9.488	4.955	0.581	1.299
BUS-2113	TM2	1990-2019	0.99		1985-1989	1.19	0.468	0.041	0.067	11.136	0.154	0.641		
TAE-2126	TM1	2002-2019	0.61	1.70			4.576	0.486	0.719	-0.045	9.981	5.483	0.596	1.072
RUE-2130	TM2	1983-1985	0.78				0.378	0.030	0.054	10.808	0.160	0.602		
BER-2135	TM2	1990-2019	0.91		1980-1989	1.13	0.489	0.026	0.066	4.473	0.199	0.651		
VAD-2139	TM1	2016-2017	0.70	10.70			8.749	0.296	1.112			2.818	0.586	
KLO-2143	TM2	1990-2017	0.91		1980-1989	1.05	0.185	0.033	0.042	12.721	0.057	0.628		
RAG-2150	TM1	2003-2019	0.75	21.61			2.292	0.592	1.058	-0.813	4.882	5.460	0.580	0.937
LUZ-2152	TM2	1990-2019	0.94		1980-1989	1.22	0.254	0.023	0.040	6.979	0.105	0.632		
BER-2159	TM1	2007-2019	0.71	2.57			4.870	1.025	1.292	0.101	14.207	7.657	0.585	1.518
GRC-2161	TM1	2003-2019	0.27	15.76			0.987	0.164	1.343	-0.054	5.115	1.352	0.356	5.000
LUG-2167	TM2	2003-2017	0.81				0.162	0.028	0.036	9.833	0.091	0.612		
GVE-2170	TM1	1990-2017	0.93	72.30	1980-1989	0.79	15.000	0.833	2.856			3.416	0.568	
GVE-2174	TM2	1990-2017	1.49		1980-1989	1.57	0.680	0.054	0.107	5.359	0.268	0.666		
SMA-2176	TM1	1990-2019	0.93	6.76	1986-1989	1.07	0.219	0.611	0.476		6.710	4.764	0.556	0.779
BER-2179	TM1	2004-2019	0.81	8.16			1.182	0.554	0.618		5.696	4.287	0.585	0.672
GUT-2181	TM1	2014-2019	0.75	35.02	1980-1989	0.95	0.281	0.584	0.515	0.111	5.129	2.628	0.575	0.614
FAH-2210	TM1	2002-2019	0.86	30.66			-0.351	0.268	0.177		10.405	4.313	0.557	1.062
ABO-2232	TM1	2002-2017	0.71	1.21			0.739	0.274	0.376		5.840	4.383	0.576	1.130
REH-2243	TM2	1990-2019	1.06		1980-1989	1.22	0.276	0.029	0.044	9.131	0.126	0.623		
SAM-2256	TM1	2004-2019	0.64	2.82			3.067	1.065	1.959		14.254	9.658	0.571	3.247
SCU-2265	TM1	2016-2019	0.67	19.28			1.396	0.572	0.748		3.617	5.290	0.570	0.981
GRC-2269	TM1	1990-2019	0.64	4.72	1980-1989	1.24	7.568	0.783	3.173	-0.526	15.702	10.000	0.597	3.887
ALT-2276	TM1	2005-2019	0.65	1.80			3.925	0.165	0.751	-2.931				
NAP-2282	TM1	2002-2017	0.82	16.18			2.234	0.205	0.493			1.602	0.576	
SHA-2288	TM2	2009-2017	0.85				0.117	0.028	0.033	14.258	0.031	0.659		
BRL-2290	TM1	2010-2012	0.29	4.17			1.935	0.017	0.265					
CHA-2307	TM1	2005-2019	0.71	4.08			-0.877	0.135	-		15.923	3.325	0.553	1.845
GUT-2308	TM1	2005-2019	0.83	1.36			0.101	0.619	0.639	0.170	3.602	2.236	0.591	0.432
DAV-2327	TM1	2004-2019	0.64	1.72			11.627	1.473	3.376		1.574	13.805	0.586	1.979
WYN-2343	TM1	2002-2019	0.51	1.17			8.665	1.078	2.012	-0.430	10.759	6.667	0.620	1.141
GRO-2347	TM1	2003-2017	0.96	0.45			1.410	0.438	1.175			3.711	0.639	
VIS-2351	TM1	2003-2019	0.67	16.62			-1.184	0.362	0.210		17.902	7.284	0.582	3.072
BEH-2366	TM1	2011-2019	0.83	0.55			0.496	0.053	0.141	0.498				
PAY-2369	TM1	2002-2019	0.75	1.43			0.612	0.611	0.707		4.272	2.629	0.591	0.423
GLA-2372	TM1	1990-2019	0.49	31.97	1980-1989	0.64	10.472	0.843	2.093	-0.562	13.870	7.625	0.608	2.140
EBK-2374	TM1	2007-2019	0.74	3.16			1.268	0.744	0.780	0.193	6.815	3.868	0.592	0.884
TAE-2386	TM1	2007-2019	0.64	3.63			2.318	0.573	0.633		9.231	4.664	0.579	0.921
SHA-2392	TM2	1990-2019	0.90		1982-1989	0.95	0.127	0.027	0.033	12.930	0.042	0.627		
VAD-2410	TM1	1996-2017	0.57	4.82			12.705	0.274	1.661			1.971	0.622	
EBK-2414	TM1	2002-2019	0.66	97.72			1.022	0.485	0.653		7.185	4.049	0.622	0.756
KLO-2415	TM1	1990-2019	0.69	7.84	1980-1989	0.84	4.738	0.578	0.759	0.209	9.446	6.190	0.588	0.804
PUY-2432	TM1	2002-2019	0.64	3.61			0.896	0.426	0.483		5.261	1.902	0.585	0.553
CGI-2433	TM1	2011-2019	1.53	4.94			1.761	0.244	0.489			0.467	0.935	
WYN-2434	TM1	2014-2019	0.65	2.78			1.999	0.768	0.812	0.278	9.241	2.520	0.575	0.954
INT-2457	TM2	1990-2003	1.09		1980-1989	1.21	0.093	0.010	0.018	5.727				
SAM-2462	TM1	1999-2019	0.68	21.11			4.733	0.705	0.968		11.342	11.816	0.574	2.740
BER-2467	TM1	2004-2019	0.80	49.02			0.128	0.032	0.043					
VAD-2473	TM1	1990-2019	0.68	230.82	1980-1989	0.82	1.107	0.257	0.287		5.955	3.865	0.568	0.914
LUZ-2481	TM1	1990-2019	0.44	12.31	1983-1989	0.50	7.429	0.929	2.164	-0.210	15.747	4.281	0.617	2.270
FAH-2485	TM1	2002-2019	1.10	3.06			6.004	0.271	0.735			1.127	0.552	
CGI-2493	TM1	2012-2019	0.61	1.63			1.936	0.454	0.658	-0.354	12.248	3.157	0.633	1.410
ALT-2499	TM1	2009-2019	0.19	1.85			2.903	-	0.457					
BER-2500	TM1	1990-2019	0.61	1.01			4.626	0.664	1.006	0.383	12.431	5.116	0.596	1.241
EIN-2604	TM1	2003-2019	0.89	1.07			0.565	0.546	0.584		5.292	4.072	0.577	0.680
GVE-2606	TM2	2003-2015	1.73				0.237	0.030	0.045	5.480	0.094	0.728		
LUZ-2608	TM1	2004-2019	0.79	0.21			3.595	0.467	0.843			1.738	0.604	
EIN-2609	TM1	2006-2017	1.16	2.28			1.126	0.452	0.426	0.571	6.228	4.985	0.579	0.895
OTL-2612	TM1	2004-2018	1.00	2.90			-1.451	0.342	0.375		3.369	2.738	0.613	0.448
BAS-2613	TM2	1995-2018	0.84				0.297	0.036	0.054	12.982	0.114	0.611		
SMM-2617	TM1	2003-2018	0.77	2.47			3.888	0.424	1.166	-0.551				
ULR-2623	TM1	2003-2019	0.70				14.085	1.089	5.000					
LUZ-2634	TM1	1990-2016	0.75	15.30	1980-1989	0.74	1.187	0.789	0.852	0.141	5.369	3.959	0.590	0.739
EIN-2635	TM1	2003-2019	1.04	0.39			4.209	0.653	1.270			3.516	0.593	

Table S3. Spring (March to May) significant ($p < 0.05$) warming trends (°C decade^{-1}) for river measurements and best performing air2stream and air2water models with 30 years (1990-2019) of available data.

		air2stream			air2water		
Station	**Thermal regime**	**Measurements**	**Model**	**Bias**	**Measurements**	**Model**	**Bias**
2009	Regulated	0.17	0.08	0.09			
2016	Downstream lake				0.20	0.21	-0.01
2018	Downstream lake				0.25	0.16	0.10
2044	Swiss Plateau	0.31	0.21	0.10			
2104	Downstream lake	0.23	0.11	0.12	0.23	0.26	-0.03
2109	Alpine	0.23	0.09	0.14			
2113	Downstream lake				0.23	0.17	0.06
2243	Downstream lake				0.16	0.20	-0.03
2372	Regulated	0.20	0.08	0.13			
2392	Downstream lake	0.18	0.21	-0.04	0.18	0.20	-0.03
2415	Swiss Plateau	0.20	0.17	0.03			
2473	Regulated	0.20	0.12	0.08			
			Mean			Mean	
	All stations	0.22	0.13	0.08	0.21	0.20	0.01
	Downstream lake	0.21	0.16	0.04	0.21	0.20	0.01
	Regulated	0.19	0.09	0.10			
	Swiss Plateau	0.25	0.19	0.07			
	Alpine	0.23	0.09	0.14			

Table S4. Summer (June to August) significant ($p < 0.05$) warming trends (°C decade^{-1}) for river measurements and best performing air2stream and air2water models with 30 years (1990-2019) of available data.

		air2stream			air2water		
Station	**Thermal regime**	**Measurements**	**Model**	**Difference**	**Measurements**	**Model**	**Difference**
2009	Regulated	0.14	0.05	0.09			
2016	Downstream lake	0.47	0.24	0.23	0.47	0.42	0.05
2018	Downstream lake	0.42	0.22	0.20	0.42	0.27	0.15
2019	Regulated	0.65	0.09	0.57			
2029	Downstream lake	0.40	0.31	0.08	0.40	0.29	0.11
2034	Swiss Plateau	0.54	0.49	0.05			
2044	Swiss Plateau	0.59	0.39	0.20			
2056	Regulated	0.30	0.09	0.21			
2070	Swiss Plateau	0.55	0.13	0.42			
2084	Regulated	0.14	0.09	0.05			
2104	Downstream lake	0.56	0.16	0.40	0.56	0.45	0.11
2106	Swiss Plateau	0.29	0.29	0.00			
2109	Alpine	0.66	0.09	0.57			
2113	Downstream lake	0.63	0.22	0.40	0.63	0.30	0.32
2135	Downstream lake	0.44	0.13	0.31	0.44	0.17	0.27
2152	Downstream lake	0.40	0.18	0.22	0.40	0.25	0.15
2176	Swiss Plateau	0.43	0.28	0.15			
2243	Downstream lake	0.47	0.24	0.23	0.47	0.37	0.10
2269	Alpine	0.34	0.03	0.31			
2372	Regulated	0.33	0.11	0.22			
2392	Downstream lake	0.58	0.49	0.09	0.58	0.44	0.14
2415	Swiss Plateau	0.47	0.23	0.24			
2473	Regulated	0.38	0.13	0.25			
2481	Regulated	0.24	0.08	0.16			
2500	Swiss Plateau	0.09	0.15	-0.06			
			Mean			Mean	
	All stations	0.42	0.20	0.22	0.48	0.33	0.16
	Downstream lake	0.48	0.24	0.24	0.48	0.33	0.16
	Regulated	0.31	0.09	0.22			
	Swiss Plateau	0.42	0.28	0.14			
	Alpine	0.50	0.06	0.44			

Table S5. Autumn (September to November) significant ($p < 0.05$) warming trends (°C decade^{-1}) for river measurements and best performing air2stream and air2water models with 30 years (1990-2019) of available data.

		air2stream			**air2water**		
Station	**Thermal regime**	**Measurements**	**Model**	**Difference**	**Measurements**	**Model**	**Difference**
2009	Regulated	0.26	0.16	0.10			
2016	Downstream lake	0.45	0.23	0.23	0.45	0.29	0.16
2018	Downstream lake	0.47	0.19	0.28	0.47	0.19	0.28
2019	Regulated	0.40	0.05	0.35			
2029	Downstream lake	0.42	0.26	0.15	0.42	0.17	0.24
2034	Swiss Plateau	0.34	0.39	-0.05			
2044	Swiss Plateau	0.50	0.28	0.22			
2056	Regulated	0.32	0.11	0.21			
2070	Swiss Plateau	0.34	0.14	0.20			
2104	Downstream lake	0.37	0.13	0.24	0.37	0.23	0.14
2106	Swiss Plateau	0.17	0.30	-0.12			
2109	Alpine	0.44	0.13	0.31			
2113	Downstream lake	0.50	0.16	0.34	0.50	0.22	0.28
2152	Downstream lake				0.45	0.17	0.28
2176	Swiss Plateau	0.31	0.31	0.00			
2243	Downstream lake				0.45	0.28	0.17
2269	Alpine	0.15	0.07	0.08			
2372	Regulated	0.33	0.11	0.22			
2392	Downstream lake	0.54	0.37	0.17	0.54	0.31	0.24
2415	Swiss Plateau	0.31	0.19	0.12			
2473	Regulated	0.31	0.15	0.16			
2481	Regulated	0.25	0.08	0.18			
			Mean			Mean	
	All stations	0.36	0.19	0.17	0.46	0.23	0.22
	Downstream lake	0.46	0.22	0.24	0.46	0.23	0.22
	Regulated	0.31	0.11	0.20			
	Swiss Plateau	0.33	0.27	0.06			
	Alpine	0.29	0.10	0.19			

Table S6. Winter (December to February) significant ($p < 0.05$) warming trends (°C decade^{-1}) for river measurements and best performing air2stream and air2water models with 30 years (1990-2019) of available data.

		air2stream			**air2water**		
Station	**Thermal regime**	**Measurements**	**Model**	**Difference**	**Measurements**	**Model**	**Difference**
2009	Regulated	0.09	0.07	0.01			
2016	Downstream lake	0.27	0.13	0.14	0.27	0.23	0.04
2018	Downstream lake	0.29	0.11	0.19	0.29	0.14	0.15
2019	Regulated	0.08	-0.03	0.12			
2029	Downstream lake	0.18	0.20	-0.03	0.18	0.15	0.03
2034	Swiss Plateau	0.10	0.14	-0.05			
2044	Swiss Plateau	0.33	0.14	0.19			
2084	Regulated	0.18	0.11	0.06			
2104	Downstream lake	0.19	0.11	0.07	0.19	0.24	-0.06
2106	Swiss Plateau	0.09	0.13	-0.05			
2109	Alpine	0.17	0.08	0.09			
2113	Downstream lake	0.17	0.12	0.05	0.17	0.16	0.01
2135	Downstream lake				0.15	0.08	0.07
2152	Downstream lake	0.21	0.10	0.11	0.21	0.16	0.05
2243	Downstream lake	0.15	0.14	0.01	0.15	0.24	-0.09
2372	Regulated	0.19	0.08	0.12			
2392	Downstream lake	0.23	0.29	-0.06	0.23	0.25	-0.02
2415	Swiss Plateau	0.09	0.12	-0.03			
2473	Regulated	0.11	0.14	-0.03			
			Mean			Mean	
	All stations	0.17	0.12	0.05	0.20	0.18	0.02
	Downstream lake	0.21	0.15	0.06	0.20	0.18	0.02
	Regulated	0.13	0.07	0.06			
	Swiss Plateau	0.15	0.13	0.02			
	Alpine	0.17	0.08	0.09			

Table S7. The mean difference between significant ($p < 0.05$) observed water temperature trends versus modeled trends (°C $decade^{-1}$) for air2stream an air2water at 25 stations. Differences have been averaged over available simulation and river stations from 1990 to 2019. Results are ordered according to the use of data from climate models or real measurements as atmospheric forcing for the water temperature models. Note that negative values indicate a larger mean modeled water temperature trend compared to the observed trend.

All rivers							
	RCP8.5		RCP4.5		RCP2.6		Real measurements
	Corrected	No correction	Corrected	No correction	Corrected	No correction	No correction
All Year	-0.004	0.097	0.026	0.113	0.049	0.147	0.123
March to May	-0.030	0.016	0.004	0.054	0.000	0.048	0.058
June to August	0.081	0.254	0.089	0.262	0.059	0.233	0.200
September to November	-0.015	0.139	-0.003	0.109	0.041	0.181	0.173
December to February	-0.092	-0.069	-0.066	-0.016	-0.011	0.026	0.037
Alpine							
	RCP8.5		RCP4.5		RCP2.6		Real measurements
	Corrected	No correction	Corrected	No correction	Corrected	No correction	No correction
All Year	-0.047	0.153	-0.033	0.162	-0.022	0.172	0.172
March to May	-0.058	0.067	-0.031	0.076	-0.016	0.102	0.143
June to August	0.043	0.452	0.045	0.453	0.040	0.451	0.437
September to November	0.032	0.195	0.038	0.153	0.054	0.300	0.195
December to February	-0.215	-0.144	-0.198	-0.113	-0.182	-0.090	0.086
Downstream Lake							
	RCP8.5		RCP4.5		RCP2.6		Real measurements
	Corrected	No correction	Corrected	No correction	Corrected	No correction	No correction
All Year	0.003	0.106	0.056	0.132	0.081	0.164	0.125
March to May	-0.059	-0.049	-0.022	0.008	-0.028	-0.012	0.014
June to August	0.124	0.267	0.131	0.272	0.117	0.272	0.175
September to November	0.000	0.192	0.031	0.177	0.110	0.248	0.232
December to February	-0.100	-0.083	-0.066	-0.032	-0.001	0.022	0.032
Regulated							
	RCP8.5		RCP4.5		RCP2.6		Real measurements
	Corrected	No correction	Corrected	No correction	Corrected	No correction	No correction
All Year	-0.030	0.096	-0.004	0.110	0.003	0.136	0.136
March to May	-0.007	0.065	0.017	0.082	0.027	0.095	0.098
June to August	0.003	0.198	0.030	0.220	-0.001	0.195	0.220
September to November	-0.047	0.150	-0.020	0.114	0.005	0.127	0.201
December to February	-0.054	-0.020	-0.069	0.019	-0.017	0.049	0.056
Swiss Plateau							
	RCP8.5		RCP4.5		RCP2.6		Real measurements
	Corrected	No correction	Corrected	No correction	Corrected	No correction	No correction
All Year	0.026	0.071	0.035	0.077	0.074	0.129	0.093
March to May	0.010	0.046	0.051	0.090	0.021	0.069	0.066
June to August	0.114	0.237	0.107	0.236	0.051	0.158	0.143
September to November	-0.015	0.045	-0.041	0.003	-0.014	0.161	0.060
December to February	-0.078	-0.072	-0.026	0.001	0.031	0.046	0.015

Table S8. Mean temperature change from the reference period (1990 to 2019) to the near (2030 to 2059) and far future (2070 to 2099). Stations 2414 and 2462 are not shown since the flow model M_4 lacked 30 years of continuous data.

	Near (Δ°C)			Far (Δ°C)		
Station	**RCP2.6**	**RCP4.5**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP8.5**
Alpine						
2033	0.89	1.08	1.41	1.12	1.70	3.49
2109	0.95	1.08	1.40	1.30	1.82	3.55
2150	0.97	1.11	1.48	1.17	1.71	3.70
2161	0.70	0.89	1.09	0.91	1.48	2.61
2232	0.98	1.17	1.50	1.21	1.94	3.70
2256	0.77	1.04	1.34	0.89	1.78	3.49
2265	1.22	1.42	1.81	1.45	2.19	4.32
2269	0.77	1.03	1.24	0.97	1.71	2.96
2276	0.90	0.89	1.25	1.20	1.41	3.00
2327	0.79	1.08	1.34	0.96	1.73	3.19
2347	0.92	1.15	1.52	0.97	1.88	3.72
2351	1.02	1.12	1.46	1.43	2.04	4.05
2366	1.19	1.42	1.74	1.44	2.30	4.11
2617	1.09	1.32	1.67	1.26	2.10	3.92
2623	0.82	1.10	1.38	0.95	1.83	3.34
Mean	0.93	1.13	1.44	1.15	1.84	3.54
Downstream Lake						
2016	0.79	1.03	1.32	0.86	1.64	3.37
2018	0.72	0.89	1.20	0.74	1.44	3.00
2029	1.13	1.10	1.48	1.33	1.74	3.76
2030	0.87	0.75	1.03	1.06	1.17	2.58
2085	1.01	0.94	1.26	1.30	1.45	3.26
2091	0.86	0.98	1.33	0.88	1.56	3.38
2104	1.09	1.18	1.61	1.17	1.85	4.08
2113	0.77	0.94	1.30	0.79	1.53	3.25
2130	0.88	0.92	1.28	1.00	1.49	3.18
2135	0.85	0.74	1.04	1.04	1.16	2.62
2143	0.97	1.20	1.57	0.99	1.94	3.95
2152	0.86	0.93	1.31	0.91	1.43	3.32
2167	1.00	1.16	1.51	0.99	1.78	3.75
2174	0.88	0.87	1.21	1.05	1.37	3.00
2243	0.84	1.04	1.36	0.85	1.68	3.43
2288	1.03	1.29	1.68	1.02	2.07	4.28
2392	0.97	1.19	1.61	0.96	1.91	4.03
2457	0.77	0.87	1.21	0.78	1.39	3.03
2606	1.09	1.11	1.48	1.29	1.72	3.78
2613	0.84	1.00	1.39	0.85	1.62	3.48
Mean	0.91	1.01	1.36	0.99	1.60	3.43
Regulated						
2009	0.93	0.90	1.15	1.30	1.52	3.21
2019	0.69	0.70	1.00	0.88	1.09	2.43
2056	0.77	0.77	1.07	0.97	1.23	2.71
2068	0.84	1.01	1.33	0.89	1.59	3.20
2084	0.86	0.95	1.23	1.06	1.43	3.14
2372	0.71	0.71	0.99	0.93	1.08	2.45
2467	1.00	1.27	1.70	1.09	2.06	4.24
2473	0.80	0.90	1.15	0.92	1.31	2.92
2481	0.65	0.78	1.08	0.78	1.23	2.68
Mean	0.80	0.89	1.19	0.98	1.39	3.00
Swiss Plateau						
2034	0.90	1.11	1.39	1.02	1.73	3.61
2044	0.75	1.06	1.29	0.83	1.64	3.35
2070	0.60	0.78	0.99	0.72	1.24	2.57
2106	0.66	0.88	1.09	0.72	1.37	2.84
2112	0.59	0.81	1.04	0.63	1.27	2.72
2126	0.52	0.71	0.89	0.62	1.11	2.27
2139	0.46	0.58	0.77	0.51	0.93	1.92
2159	0.62	0.86	1.08	0.70	1.35	2.82
2170	0.47	0.58	0.76	0.57	0.96	1.88
2176	0.77	1.07	1.33	0.85	1.70	3.47
2179	0.69	0.92	1.16	0.77	1.47	3.05
2181	0.78	1.09	1.39	0.84	1.68	3.61
2210	0.66	0.92	1.13	0.70	1.45	2.97
2282	0.56	0.75	0.98	0.61	1.24	2.47
2307	0.42	0.64	0.72	0.47	0.99	1.97
2308	0.72	1.00	1.30	0.79	1.59	3.38
2343	0.46	0.63	0.79	0.52	1.05	2.01
2369	0.75	0.95	1.20	0.86	1.54	3.12
2374	0.73	0.98	1.22	0.83	1.53	3.19
2386	0.64	0.87	1.08	0.72	1.35	2.78
2410	0.36	0.44	0.60	0.43	0.71	1.48
2415	0.57	0.73	0.94	0.64	1.20	2.37
2432	0.72	0.96	1.21	0.77	1.51	3.11
2433	0.61	0.81	1.05	0.70	1.32	2.64
2434	0.68	0.98	1.22	0.74	1.54	3.11
2485	0.50	0.68	0.87	0.56	1.14	2.18
2493	0.54	0.74	0.94	0.59	1.17	2.38
2500	0.52	0.66	0.83	0.64	1.05	2.15
2604	0.71	0.90	1.15	0.81	1.44	3.06
2608	0.64	0.83	1.11	0.71	1.36	2.80
2609	0.71	0.94	1.19	0.84	1.48	3.13
2612	0.69	0.90	1.15	0.67	1.45	2.99
2634	0.76	1.03	1.31	0.88	1.59	3.44
2635	0.63	0.76	1.01	0.72	1.25	2.57
Mean	0.63	0.84	1.06	0.71	1.33	2.75
Spring						
2290	0.06	0.08	0.09	0.06	0.12	0.24
2499	-0.01	-0.01	-0.02	-0.01	-0.02	-0.05
Mean	0.02	0.03	0.04	0.03	0.05	0.10

Table S9. Modelled hysteresis classes during the reference (1990 to 2019), the near (2030 to 2059) and the far future (2070 to 2099) periods for climate scenario RCP4.5. Flow data from models M_1, M_2 and M_3. Stations with no flow measurements for calibration, missing flow model output as forcing or where the use of the air2water model did not require flow as input have been excluded. A change in class from the reference period to the near or far future period is highlighted in *italic*.

RCP4.5									
Station	**Reference**			**Near**			**Far**		
	M_1	**M_2**	**M_3**	**M_1**	**M_2**	**M_3**	**M_1**	**M_2**	**M_3**
Downstream Lake									
2016	4			4			4		
2085	4			4			4		
Regulated									
2009	3			3			*4*		
2056	3	3		3	3		3	3	
2084		4			4			4	
2372	4	4		4	4		4	4	
2473	3			3			*4*		
2481		4	4		4	4		4	4
Swiss Plateau									
2034	-1	-1		*-2*	*-2*		*-2*	*-2*	
2044	4	4	4	*-2*	*-2*	*-2*	*-2*	*-2*	*-2*
2070	4	4		4	4		4	4	
2106	-1	-2		*-2*	-2		*-2*	-2	
2112		4			4			4	
2126		-1			-1			*-2*	
2159		3			*-2*			*-2*	
2176	4	4		*3*	4		4	4	
2179	4	4		4	4		4	4	
2181	4	4		*-1*	4		*-1*	4	
2210		-2			-2			-2	
2307	-1	-1		-1	*-2*		-1	*-2*	
2308		4			*-2*			*-2*	
2343		-1			-1			-1	
2369		-1			*-2*			*-2*	
2374		4			*-2*			*-2*	
2386		-2			-2			-2	
2415	-2	-2		-2	-2		-2	-2	
2432	-1	-1		*-2*	-1		-1	*-2*	
2434		-1			-1			-1	
2493		-1			-1			-1	
2500		-1			-1			-1	
2604		4			4			4	
2609		4			4			4	
2612		3			3			3	
2634		4	4		4	4		4	4
Alpine									
2033	3	3		3	3		3	3	
2109	3		3	3		3	3		3
2150	4			4			4		
2161	1		1	1		1	*2*		*2*
2232		4			4			4	
2256		3			3			3	
2265	3			3			3		
2269			4			4			4
2276		4	4		4	4		4	*3*
2327			3			3			3
2351	3			3			3		
2366		3	3		3	3		3	3
2617		3	3		3	3		3	3

Table S10. Modelled hysteresis classes during the reference (1990 to 2019), the near (2030 to 2059) and the far future (2070 to 2099) periods for climate scenario RCP2.6. Flow data from models M_1, M_2 and M_3. Stations with no flow measurements for calibration, missing flow model output as forcing or where the use of the air2water model didn't require flow as input have been excluded. A change in class from the reference period to the near or far future period is highlighted in *italic*.

RCP2.6									
Station	**Reference**			**Near**			**Far**		
	M_1	**M_2**	**M_3**	**M_1**	**M_2**	**M_3**	**M_1**	**M_2**	**M_3**
Downstream Lake									
2016	3			*4*			*4*		
2085	4			4			4		
Regulated									
2009	3			3			*4*		
2056	3	3		*4*	*4*		*4*	*4*	
2084		4			4			4	
2372	4	4		4	4		4	4	
2473	3			*4*			*4*		
2481		4	4		4	4		4	4
Swiss Plateau									
2034	-1	-1		*-2*	*-2*		*-2*	*-2*	
2044	4	4	4	*-2*	*-2*	*-2*	4	4	4
2070	4	4		4	4		4	4	
2106	-2	-2		-2	-2		-2	-2	
2112		4			4			4	
2126		-1			*-2*			*-2*	
2159		4			4			4	
2176	4	3		4	*4*		4	3	
2179	4	4		4	4		4	4	
2181	4	4		4	4		4	4	
2210		-2			-2			-2	
2307	-1	-1		-1	*-2*		-1	-1	
2308		-2			*3*			-2	
2343		-1			-1			-1	
2369		-1			-1			-1	
2374		4			*-2*			*-2*	
2386		-2			-2			-2	
2415	-2	-2		-2	-2		-2	-2	
2432	-1	-1		-1	-1		-1	-1	
2434		-1			-1			-1	
2493		-1			-1			-1	
2500		-1			-1			-1	
2604		4			4			4	
2609		4			4			4	
2612		3			3			3	
2634		4	4		4	4		4	4
Alpine									
2033	3	3		*4*	*4*		*4*	*4*	
2109	3		3	*4*		3	*4*		3
2150	4			4			4		
2161	1		1	1		*2*	1		1
2232		4			4			4	
2256		3			3			3	
2265	3			3			3		
2269			4			4			4
2276		4	4		4	4		4	4
2327			3			3			3
2351	3			3			*4*		
2366		3	3		3	3		3	3
2617		3	3		3	3		3	3