sustainability

Supplementary Materials

The tables and figures below support statements in the main text and are intended for publication as supplementary material. Supplementary tables are numbered S1–S17 and supplementary figures S1–S3, both in the order in which the main text refers to them.

Table S1. Ice-model parameter uncertainty propagated into the projections, 2071–2100. Fifty coefficient vectors were drawn from the block bootstrap of Table 4 and the projection re-run for each against all five GCMs. Ranges are not comparable between the two sources, because fifty draws sample the tails better than five models can; the standard deviations are, and their ratio is given in the last column.

River and variable	Scenario	Mean days	Parameter 10th–90th	Parameter SD	GCM 10th–90th	GCM SD	Parameter SD / GCM SD
Pilica — ice phenomena	SSP1-2.6	10.63	8.48–13.59	1.97	7.18–14.10	3.43	0.57
Pilica — ice cover	SSP1-2.6	0.34	0.11–0.69	0.24	0.11–0.67	0.30	0.81
Pilica — ice phenomena	SSP3-7.0	6.03	4.69–7.65	1.24	3.54–8.28	2.38	0.52
Pilica — ice cover	SSP3-7.0	0.16	0.04–0.31	0.11	0.05–0.29	0.12	0.89
Pilica — ice phenomena	SSP5-8.5	4.37	3.36–5.47	0.88	1.66–6.71	2.52	0.35
Pilica — ice cover	SSP5-8.5	0.07	0.02–0.13	0.07	0.03–0.10	0.04	1.98
Węgorapa — ice phenomena	SSP1-2.6	28.06	24.18–32.14	3.53	18.89–37.45	9.19	0.38
Węgorapa — ice cover	SSP1-2.6	8.96	7.10–10.97	1.55	4.81–13.62	4.37	0.35
Węgorapa — ice phenomena	SSP3-7.0	14.30	11.90–16.50	2.11	8.53–20.25	5.90	0.36
Węgorapa — ice cover	SSP3-7.0	4.02	2.61–5.37	0.94	2.12–5.94	1.94	0.49
Węgorapa — ice phenomena	SSP5-8.5	10.27	8.26–12.54	1.97	3.54–16.06	6.31	0.31
Węgorapa — ice cover	SSP5-8.5	2.69	1.84–3.63	0.72	0.85–4.20	1.72	0.42

Table S2. Stability of the stochastic ensemble and composition of the projection intervals, 2071–2100 (days per winter). (a) Ensemble statistics from the 20 realisations per GCM and scenario used in the paper (seed 7) and from an independent ensemble of 200 realisations (seed 2026); the 10th and 90th percentiles are taken across the GCM × realisation members, each averaged over 2071–2100. MCSE, Monte Carlo standard error of the mean of a 20-realisation ensemble, from 1000 draws of 20 of the 200 realisations per GCM. (b) Composition of the intervals in Table 6. SD between GCMs, standard deviation of the five GCM means; SD within GCMs, root-mean-square of the standard deviation across the 20 realisations within each GCM; GCM share, between-GCM variance as a percentage of total member variance; widening, percentage increase of the member standard deviation when the parameter standard deviation of Table S1 is added in quadrature.

(a)

River, variable	Scenario	Mean (N = 20)	Mean (N = 200)	MCSE of mean (N = 20)	10th pct (N = 20)	10th pct (N = 200)	90th pct (N = 20)	90th pct (N = 200)
Pilica, ice phenomena	SSP1-2.6	10.90	11.24	0.136	5.99	6.57	15.44	16.27
Pilica, ice phenomena	SSP3-7.0	5.84	6.05	0.099	2.60	2.80	9.18	9.07
Pilica, ice phenomena	SSP5-8.5	4.26	4.44	0.084	1.30	1.30	6.91	7.43
Pilica, ice cover	SSP1-2.6	0.27	0.29	0.024	0.0	0.0	0.80	0.80
Pilica, ice cover	SSP3-7.0	0.16	0.15	0.018	0.0	0.0	0.47	0.47
Pilica, ice cover	SSP5-8.5	0.06	0.08	0.010	0.0	0.0	0.20	0.23
Węgorapa, ice phenomena	SSP1-2.6	28.37	28.39	0.256	15.89	16.46	39.80	40.00
Węgorapa, ice phenomena	SSP3-7.0	14.89	14.96	0.193	7.19	7.63	23.51	23.14
Węgorapa, ice phenomena	SSP5-8.5	10.23	10.32	0.154	2.53	2.90	17.55	17.84
Węgorapa, ice cover	SSP1-2.6	8.69	9.03	0.189	3.36	4.00	15.08	15.37
Węgorapa, ice cover	SSP3-7.0	3.91	4.12	0.130	1.16	1.53	6.92	7.13
Węgorapa, ice cover	SSP5-8.5	2.55	2.75	0.103	0.50	0.50	4.94	5.47

(b)

River, variable	Scenario	SD between GCMs	SD within GCMs	GCM share of variance (%)	Range of GCM means	Parameter SD (Table S12)	Widening (%)
Pilica, ice phenomena	SSP1-2.6	3.79	1.38	88	6.38–14.76	1.97	11
Pilica, ice phenomena	SSP3-7.0	2.46	1.08	84	2.63–8.90	1.24	10
Pilica, ice phenomena	SSP5-8.5	2.37	0.85	89	1.36–7.00	0.88	6

Pilica, ice cover	SSP1-2.6	0.24	0.24	51	0.05–0.60	0.24	22
Pilica, ice cover	SSP3-7.0	0.14	0.21	31	0.04–0.34	0.11	9
Pilica, ice cover	SSP5-8.5	0.04	0.10	13	0.02–0.11	0.07	19
Węgorapa, ice phenomena	SSP1-2.6	9.49	2.73	92	15.82–40.24	3.53	6
Węgorapa, ice phenomena	SSP3-7.0	6.25	2.08	90	7.34–23.45	2.11	5
Węgorapa, ice phenomena	SSP5-8.5	6.20	1.75	93	2.96–16.75	1.97	5
Węgorapa, ice cover	SSP1-2.6	4.52	2.14	82	4.07–15.28	1.55	5
Węgorapa, ice cover	SSP3-7.0	2.00	1.61	61	1.55–6.74	0.94	6
Węgorapa, ice cover	SSP5-8.5	1.57	1.10	67	0.64–4.03	0.72	7

Table S3. Sensitivity of the projections to the treatment of the decadal term. Mean ice days per winter over 2071–2100, averaged across the five GCMs, with the decadal term frozen at its 2022 value as in the main results and with it allowed to continue its fitted decline.

River	Variable	Scenario	Decadal term frozen at 2022 (days)	Decadal term continued (days)	Difference (%)
Pilica	Ice phenomena	SSP1-2.6	10.9	2.5	−77.1
Pilica	Ice cover	SSP1-2.6	0.3	0.0	−95.0
Pilica	Ice phenomena	SSP3-7.0	5.8	1.4	−75.7
Pilica	Ice cover	SSP3-7.0	0.2	0.0	−94.6
Pilica	Ice phenomena	SSP5-8.5	4.3	1.0	−75.5
Pilica	Ice cover	SSP5-8.5	0.1	0.0	−98.3
Węgorapa	Ice phenomena	SSP1-2.6	28.4	11.8	−58.4
Węgorapa	Ice cover	SSP1-2.6	8.7	2.9	−67.1
Węgorapa	Ice phenomena	SSP3-7.0	14.9	5.8	−61.0
Węgorapa	Ice cover	SSP3-7.0	3.9	1.2	−68.8
Węgorapa	Ice phenomena	SSP5-8.5	10.2	4.0	−60.7
Węgorapa	Ice cover	SSP5-8.5	2.5	0.8	−69.4

Table S4. Continuity of the observed ice season, hydrological years 1965–2022. The longest unbroken spell is the longest run of consecutive flagged days in a winter, counted as zero in winters without ice; the number of separate spells is counted only in winters that carry ice. Slopes are Theil–Sen estimates and p-values Mann–Kendall.

River and variable	Indicator	Mean 1965–1994	Mean 1995–2022	Theil–Sen slope per decade	p
Pilica — ice phenomena	Longest unbroken spell (days)	23.6	14.0	−4.00	0.0002
Pilica — ice phenomena	Number of separate spells	4.3	3.3	−0.43	0.0046
Pilica — ice cover	Longest unbroken spell (days)	5.5	1.6	+0.00	0.0344
Pilica — ice cover	Number of separate spells	1.2	1.0	+0.00	0.9323
Węgorapa — ice phenomena	Longest unbroken spell (days)	55.7	37.9	−7.14	0.0030
Węgorapa — ice phenomena	Number of separate spells	3.0	2.7	+0.00	0.5619
Węgorapa — ice cover	Longest unbroken spell (days)	30.6	17.1	−4.00	0.0024
Węgorapa — ice cover	Number of separate spells	1.6	1.2	+0.00	0.8658

Table S5. Fitted Mohseni air–water temperature parameters and goodness of fit, 1965–2022.

Station	μ (°C)	α (°C)	γ	β (°C)	R^2	RMSE (°C)
Pilica (Przedbórz)	−2.38	23.40	0.156	10.33	0.947	1.50
Węgorapa (Mieduniszki)	−5.30	28.19	0.136	10.95	0.968	1.30

Table S6. Two-directional test of stationarity in the temperature–ice relationship, using the temperature-only model and the free-running simulation. A bias that reverses sign with the direction of extrapolation indicates a shift in the relationship itself.

River and variable	Calibration	Simulated	Bias (d)	MAE (d)	AIC (temp. only / + decadal term)
Pilica — ice phenomena	1965–1999	2000–2022	+13.3	16.1	2049 / 2050
	1994–2022	1965–1993	−15.2	18.9	1304 / 1290
Węgorapa — ice phenomena	1965–1999	2000–2022	+10.2	17.5	1562 / 1562
	1994–2022	1965–1993	−13.8	19.1	1187 / 1186
Pilica — ice cover	1965–1999	2000–2022	+1.3	2.6	240 / 236

	1994–2022	1965–1993	−3.0	5.3	61 / 58
Węgorapa — ice cover	1965–1999	2000–2022	+9.5	13.3	835 / 837
	1994–2022	1965–1993	−14.7	19.6	412 / 413

Table S7. Free-running validation: calibration 1965–1999, simulation 2000–2022 driven by temperature alone.

River and variable	Model	Bias (d)	MAE (d)	r
Pilica — ice phenomena	temperature only	+13.3	16.1	0.49
	+ non-stationarity	+7.9	12.0	0.51
Pilica — ice cover	temperature only	+1.3	2.6	0.79
	+ non-stationarity	−1.6	2.0	0.65
Węgorapa — ice phenomena	temperature only	+10.2	17.5	0.65
	+ non-stationarity	−1.4	12.9	0.71
Węgorapa — ice cover	temperature only	+9.5	13.3	0.53
	+ non-stationarity	+5.2	10.8	0.59

Table S8. Skill of the station-level bias correction, November–April air temperature over 1979–2014, averaged across the five GCMs.

Metric	Pilica raw	Pilica corrected	Węgorapa raw	Węgorapa corrected
Mean bias (°C)	+0.50	+0.02	−0.09	+0.02
Standard-deviation ratio	0.98	1.00	0.98	1.00
1st percentile error (°C)	−0.42	−0.05	+0.30	−0.02
5th percentile error (°C)	+0.48	+0.02	−0.31	−0.15
10th percentile error (°C)	+0.75	+0.02	+0.06	+0.05
Days below 0 °C (error, pp)	−6.12	−0.32	+0.35	+0.33
Quantile–quantile R^2	0.9954	0.9996	0.9980	0.9998
Seasonal-cycle R^2	0.936	0.942	0.935	0.939
Perkins skill score	0.908	0.933	0.937	0.940
Kolmogorov–Smirnov statistic	0.075	0.015	0.026	0.013

Table S9. Station-level bias correction and verification of signal preservation. Warming is November–April, 2071–2100 relative to 1985–2014.

River	Nov–Apr mean: obs / raw / corr.	Scenario	Warming raw	Warming corrected
Pilica	1.85 / 2.35 / 1.87	SSP1-2.6	1.69	1.68
		SSP3-7.0	3.98	4.02
		SSP5-8.5	4.82	4.87
Węgorapa	0.96 / 0.87 / 0.98	SSP1-2.6	1.80	1.80
		SSP3-7.0	4.07	4.09
		SSP5-8.5	5.01	5.03

Means and warming are in °C.

Table S10. Skill of the station-level bias correction for each general circulation model separately, November–April air temperature over 1979–2014. Columns as in Table S8; the five-model means are the values reported there.

River	GCM	Forcing	Mean bias (°C)	SD ratio	Days below 0 °C (pp)	Perkins score	KS statistic
Pilica	gfdl-esm4	raw	+0.4894	0.9845	−5.82	0.9131	0.0697
Pilica	ipsl-cm6a-lr	raw	+0.4932	0.9752	−8.04	0.8861	0.0885
Pilica	mpi-esm1-2-hr	raw	+0.4853	0.9727	−4.56	0.9241	0.0646
Pilica	mri-esm2-0	raw	+0.5139	0.9840	−3.64	0.9392	0.0497
Pilica	ukesm1-0-ll	raw	+0.5295	0.9685	−8.52	0.8802	0.1045
Pilica	gfdl-esm4	corrected	+0.0075	1.0029	−0.18	0.9220	0.0110
Pilica	ipsl-cm6a-lr	corrected	+0.0205	1.0044	−1.50	0.9130	0.0252
Pilica	mpi-esm1-2-hr	corrected	+0.0143	0.9962	+0.17	0.9446	0.0094
Pilica	mri-esm2-0	corrected	+0.0161	0.9968	+0.20	0.9428	0.0097
Pilica	ukesm1-0-ll	corrected	+0.0661	1.0055	−0.32	0.9408	0.0192
Węgorapa	gfdl-esm4	raw	−0.1019	0.9848	−0.57	0.9373	0.0213
Węgorapa	ipsl-cm6a-lr	raw	−0.0882	0.9729	−1.08	0.9148	0.0427
Węgorapa	mpi-esm1-2-hr	raw	−0.1151	0.9704	+1.62	0.9503	0.0194
Węgorapa	mri-esm2-0	raw	−0.0851	0.9838	+2.37	0.9413	0.0237
Węgorapa	ukesm1-0-ll	raw	−0.0627	0.9783	−0.58	0.9433	0.0204
Węgorapa	gfdl-esm4	corrected	+0.0048	0.9965	+0.40	0.9445	0.0109

Węgorapa	ipsl-cm6a-lr	corrected	+0.0305	0.9997	−0.15	0.9150	0.0258
Węgorapa	mpi-esm1-2-hr	corrected	+0.0224	0.9909	+0.48	0.9585	0.0094
Węgorapa	mri-esm2-0	corrected	+0.0184	0.9985	+0.60	0.9488	0.0101
Węgorapa	ukesm1-0-ll	corrected	+0.0175	1.0030	+0.31	0.9346	0.0104

Table S11. Hindcast of ice-season timing, 1979–2014, driven by bias-corrected ISIMIP historical forcing. Onset and breakup are hydrological days counted from 1 November and all three indicators are conditional on the winter carrying ice, so winters without ice are excluded from both sides. Bias is simulated minus observed; the Kolmogorov–Smirnov p-value tests the two distributions, since free-running forcing cannot be matched year by year.

River and variable	Indicator	Mean (obs / sim)	SD (obs / sim)	Bias (days)	KS p
Pilica — ice phenomena	Onset (hyd. day)	45.6 / 40.7	22.2 / 25.2	−5.0	0.408
Pilica — ice phenomena	Breakup (hyd. day)	107.5 / 126.3	22.9 / 48.6	+18.8	0.002
Pilica — ice phenomena	Duration (days)	62.8 / 86.6	29.0 / 54.6	+23.8	0.001
Pilica — ice cover	Onset (hyd. day)	74.9 / 67.7	12.3 / 30.9	−7.2	0.479
Pilica — ice cover	Breakup (hyd. day)	90.8 / 83.0	10.5 / 30.0	−7.8	0.337
Pilica — ice cover	Duration (days)	16.9 / 16.3	8.7 / 18.9	−0.6	0.055
Węgorapa — ice phenomena	Onset (hyd. day)	43.0 / 40.7	19.6 / 23.2	−2.3	0.253
Węgorapa — ice phenomena	Breakup (hyd. day)	125.0 / 136.2	23.8 / 37.9	+11.2	0.273
Węgorapa — ice phenomena	Duration (days)	83.0 / 96.5	30.9 / 44.3	+13.5	0.105
Węgorapa — ice cover	Onset (hyd. day)	64.1 / 64.4	27.8 / 31.9	+0.3	0.923
Węgorapa — ice cover	Breakup (hyd. day)	105.1 / 109.8	31.4 / 37.3	+4.7	0.957
Węgorapa — ice cover	Duration (days)	42.0 / 46.4	29.5 / 39.1	+4.4	0.379

Table S12. Projected mean days per winter by period, five-model ensemble mean. The 2071–2100 row of each block repeats Table 6 and is retained so that the trajectory can be read in one place.

River and variable	Period	SSP1-2.6	SSP3-7.0	SSP5-8.5
Pilica — ice phenomena	2023–2040	13.6	12.2	13.2
	2041–2070	11.1	7.9	8.1
	2071–2100	10.9	5.8	4.3
Pilica — ice cover	2023–2040	0.5	0.5	0.3
	2041–2070	0.3	0.2	0.1
	2071–2100	0.3	0.2	0.1
Węgorapa — ice phenomena	2023–2040	34.4	30.0	33.8
	2041–2070	28.1	20.2	20.3
	2071–2100	28.4	14.9	10.2
Węgorapa — ice cover	2023–2040	12.3	9.4	11.0
	2041–2070	8.9	5.5	5.9
	2071–2100	8.7	3.9	2.5

Table S13. Projected continuity of the ice season, 2071–2100, against the observed 1995–2022 baseline. Definitions as in Table S4; the number of spells is counted only in winters that still carry ice, so it must be read together with the proportion of winters that carry none.

River and variable	Scenario	Longest spell (days)	Observed 1995–2022 (days)	Change (days)	Spells per winter with ice	Observed spells
Pilica — ice phenomena	SSP1-2.6	6.9	14.0	−7.1	2.56	3.35
Pilica — ice cover	SSP1-2.6	0.3	1.6	−1.3	1.03	1.00
Pilica — ice phenomena	SSP3-7.0	4.1	14.0	−9.9	1.99	3.35
Pilica — ice cover	SSP3-7.0	0.2	1.6	−1.4	1.03	1.00
Pilica — ice phenomena	SSP5-8.5	3.0	14.0	−11.0	1.87	3.35
Pilica — ice cover	SSP5-8.5	0.1	1.6	−1.5	1.01	1.00
Węgorapa — ice phenomena	SSP1-2.6	20.2	37.9	−17.6	2.41	2.67
Węgorapa — ice cover	SSP1-2.6	8.1	17.1	−9.0	1.25	1.21
Węgorapa — ice phenomena	SSP3-7.0	11.0	37.9	−26.8	1.93	2.67
Węgorapa — ice cover	SSP3-7.0	3.6	17.1	−13.5	1.17	1.21
Węgorapa — ice phenomena	SSP5-8.5	7.8	37.9	−30.1	1.80	2.67
Węgorapa — ice cover	SSP5-8.5	2.7	17.1	−14.4	1.16	1.21

Table S14. Projected November–April water temperature, obtained from the same Mohseni curve that drives the ice model, with the number of days below 2 °C as the range in which ice can form at all. The observed row is the station record for 1995–2022.

River	Scenario	Period	Nov–Apr water temperature (°C)	Change (°C)	Days below 2 °C	Change in days
Pilica	Observed	1995–2022	4.24	—	54.2	—
Pilica	SSP1-2.6	2023–2040	4.56	+0.31	49.2	−4.9
Pilica	SSP1-2.6	2041–2070	4.95	+0.71	40.8	−13.4
Pilica	SSP1-2.6	2071–2100	4.99	+0.75	41.4	−12.8
Pilica	SSP3-7.0	2023–2040	4.80	+0.56	42.5	−11.6
Pilica	SSP3-7.0	2041–2070	5.55	+1.31	29.3	−24.9
Pilica	SSP3-7.0	2071–2100	6.80	+2.56	20.7	−33.5
Pilica	SSP5-8.5	2023–2040	4.66	+0.42	46.6	−7.6
Pilica	SSP5-8.5	2041–2070	5.75	+1.51	29.1	−25.0
Pilica	SSP5-8.5	2071–2100	7.48	+3.23	15.2	−39.0
Węgorapa	Observed	1995–2022	3.04	—	88.0	—
Węgorapa	SSP1-2.6	2023–2040	3.55	+0.51	77.3	−10.7
Węgorapa	SSP1-2.6	2041–2070	3.99	+0.95	68.4	−19.6
Węgorapa	SSP1-2.6	2071–2100	4.01	+0.97	67.6	−20.4
Węgorapa	SSP3-7.0	2023–2040	3.81	+0.77	69.8	−18.3
Węgorapa	SSP3-7.0	2041–2070	4.64	+1.60	54.5	−33.5
Węgorapa	SSP3-7.0	2071–2100	5.86	+2.81	39.7	−48.4
Węgorapa	SSP5-8.5	2023–2040	3.67	+0.63	78.3	−9.7
Węgorapa	SSP5-8.5	2041–2070	4.81	+1.76	53.7	−34.4
Węgorapa	SSP5-8.5	2071–2100	6.65	+3.61	29.8	−58.2

Table S15. Spread in projected ice days (2071–2100) attributable to each source.

River and variable	Bias-correction method	GCM	Scenario
Pilica — ice phenomena	1.25	6.58	6.50
Pilica — ice cover	0.04	0.31	0.22
Węgorapa — ice phenomena	0.14	17.20	18.20
Węgorapa — ice cover	0.05	6.70	5.97

Values are the range of mean ice days per winter across the alternatives in each category, in days.

Table S16. Sensitivity of the projections to the bias-correction method: mean ice days per winter over 2071–2100, five-model ensemble mean, with the identical ice model driven by the three forcings described in Section 2.7. The spread across the three columns is what Table S15 reports as the contribution of the correction method.

River	Variable	Scenario	Raw ISIMIP3b	Monthly mean shift	Quantile mapping
Pilica	Ice phenomena	SSP1-2.6	9.04	10.72	10.84
Pilica	Ice phenomena	SSP3-7.0	4.77	5.72	5.85
Pilica	Ice phenomena	SSP5-8.5	3.45	4.28	4.33
Pilica	Ice cover	SSP1-2.6	0.28	0.34	0.29
Pilica	Ice cover	SSP3-7.0	0.16	0.19	0.17
Pilica	Ice cover	SSP5-8.5	0.06	0.08	0.07
Węgorapa	Ice phenomena	SSP1-2.6	28.62	28.42	28.52
Węgorapa	Ice phenomena	SSP3-7.0	14.71	14.56	14.64
Węgorapa	Ice phenomena	SSP5-8.5	10.38	10.31	10.31
Węgorapa	Ice cover	SSP1-2.6	8.96	8.89	8.88
Węgorapa	Ice cover	SSP3-7.0	3.95	3.90	3.92
Węgorapa	Ice cover	SSP5-8.5	2.86	2.82	2.91

Table S17. Sensitivity of the projections to the stationarity of the air–water temperature relationship: mean ice days per winter over 2071–2100, averaged across the five GCMs and 20 realisations. "Stationary" is the Mohseni curve fitted to 1965–2022, as in the main results; "residual drift continued" extends the observed trend in the Mohseni residual (0.083 °C per decade on the Pilica, 0.033 °C per decade on the Węgorapa; Section 3.2) linearly beyond 2022, raising modelled water temperature by 0.65 °C and 0.26 °C by 2100. Random seeds are identical in both runs. Percentage differences are not given for Pilica ice cover, whose values are below 0.4 days; the small positive change there reflects the collinearity of the temperature terms (Section 3.4) and is not interpretable.

River	Variable	Scenario	Stationary air–water relationship	Residual drift continued	Difference (days)	Difference (%)
Pilica	Ice phenomena	SSP1-2.6	10.90	9.88	−1.02	−9.4
		SSP3-7.0	5.84	5.28	−0.55	−9.5
		SSP5-8.5	4.26	3.86	−0.40	−9.4
	Ice cover	SSP1-2.6	0.27	0.31	+0.04	—
		SSP3-7.0	0.16	0.18	+0.02	—
		SSP5-8.5	0.06	0.07	+0.01	—
Węgorapa	Ice phenomena	SSP1-2.6	28.37	27.13	−1.24	−4.4
		SSP3-7.0	14.89	14.18	−0.71	−4.8
		SSP5-8.5	10.22	9.70	−0.52	−5.1
	Ice cover	SSP1-2.6	8.69	8.61	−0.08	−0.9
		SSP3-7.0	3.91	3.86	−0.05	−1.3
		SSP5-8.5	2.55	2.53	−0.02	−0.6

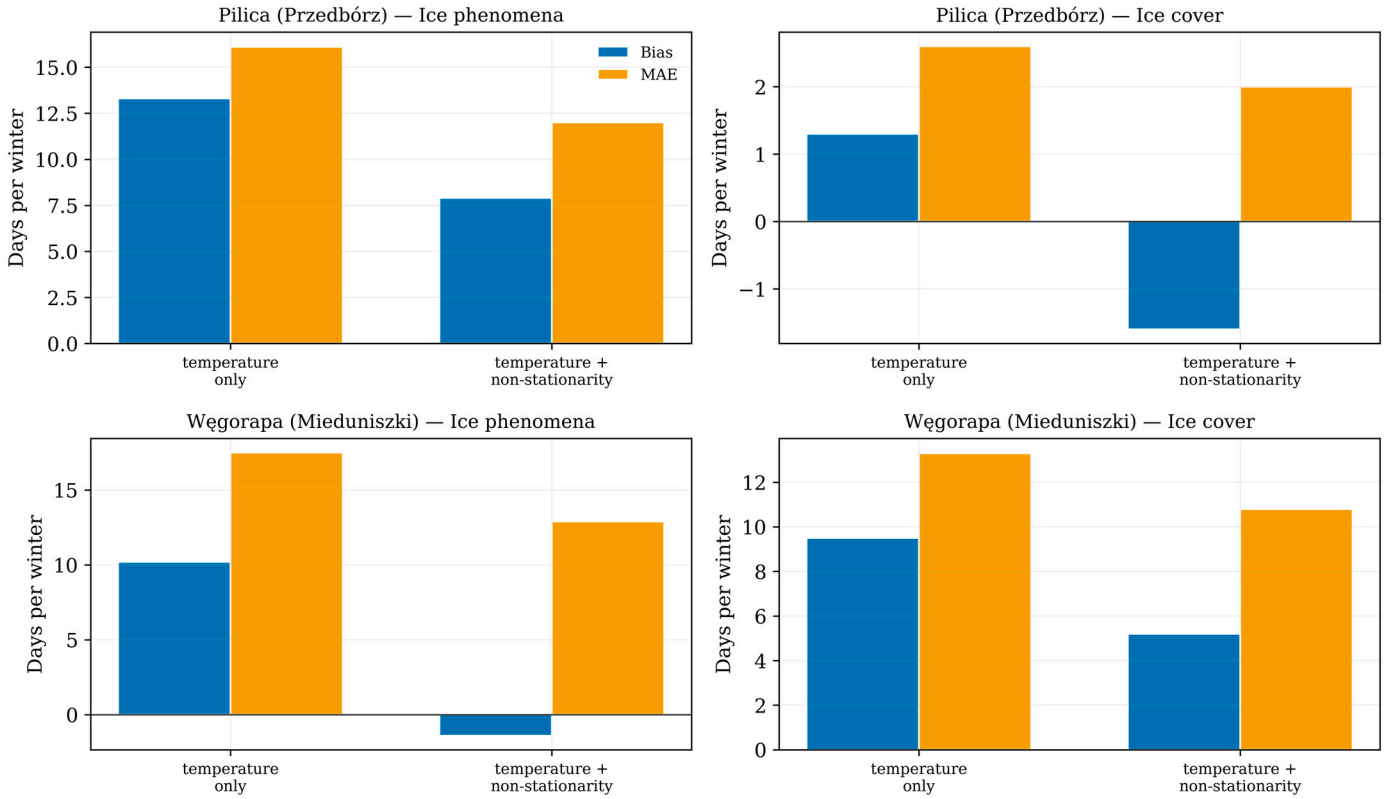


Figure S1. Free-running validation over 2000–2022 for models calibrated on 1965–1999, comparing the temperature-only formulation with the formulation including the decadal term. Bias and mean absolute error are in days per winter.

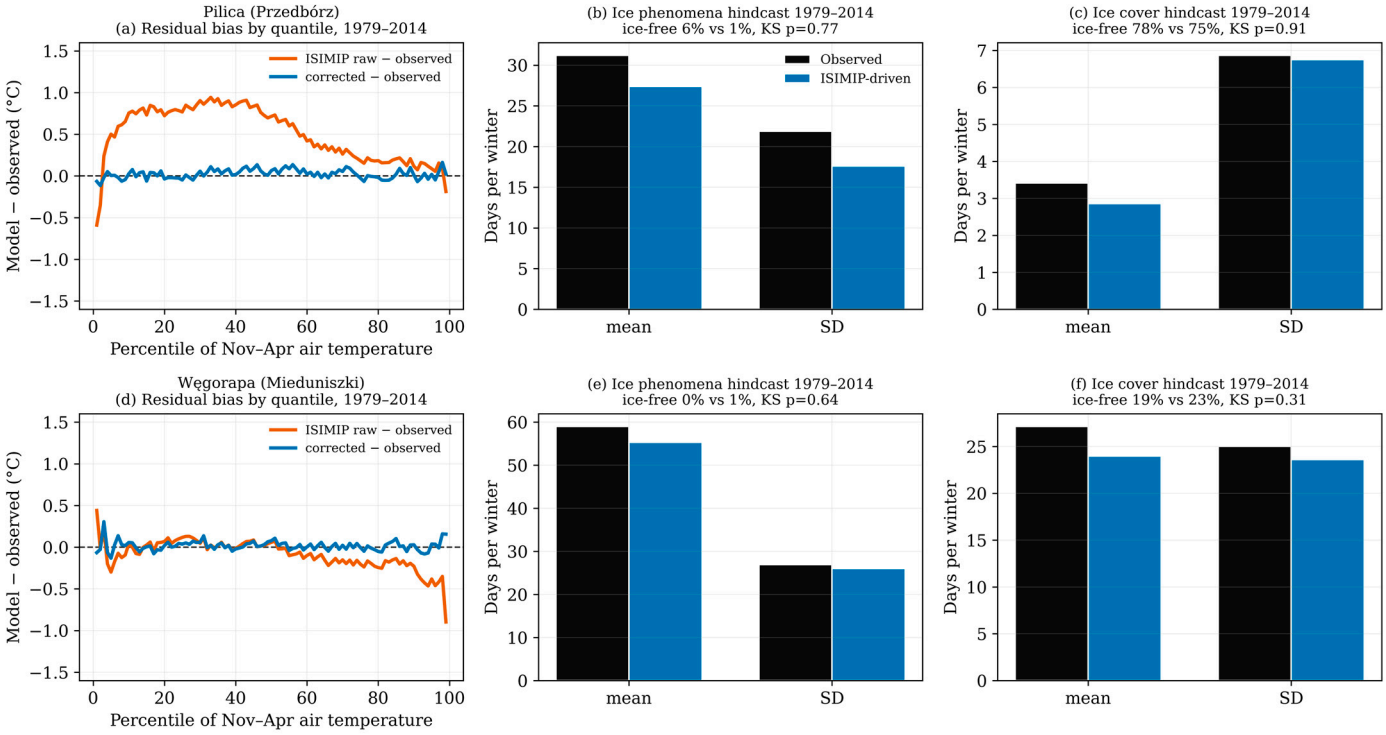


Figure S2. Station-level bias correction of the ISIMIP3b forcing and the resulting ice hindcast. (a, d) Residual bias by quantile of the November–April air temperature distribution, before and after correction, 1979–2014. (b, c, e, f) Observed and ISIMIP-driven mean and standard deviation of seasonal ice days over 1979–2014, with the proportion of winters without ice and the Kolmogorov–Smirnov p-value.

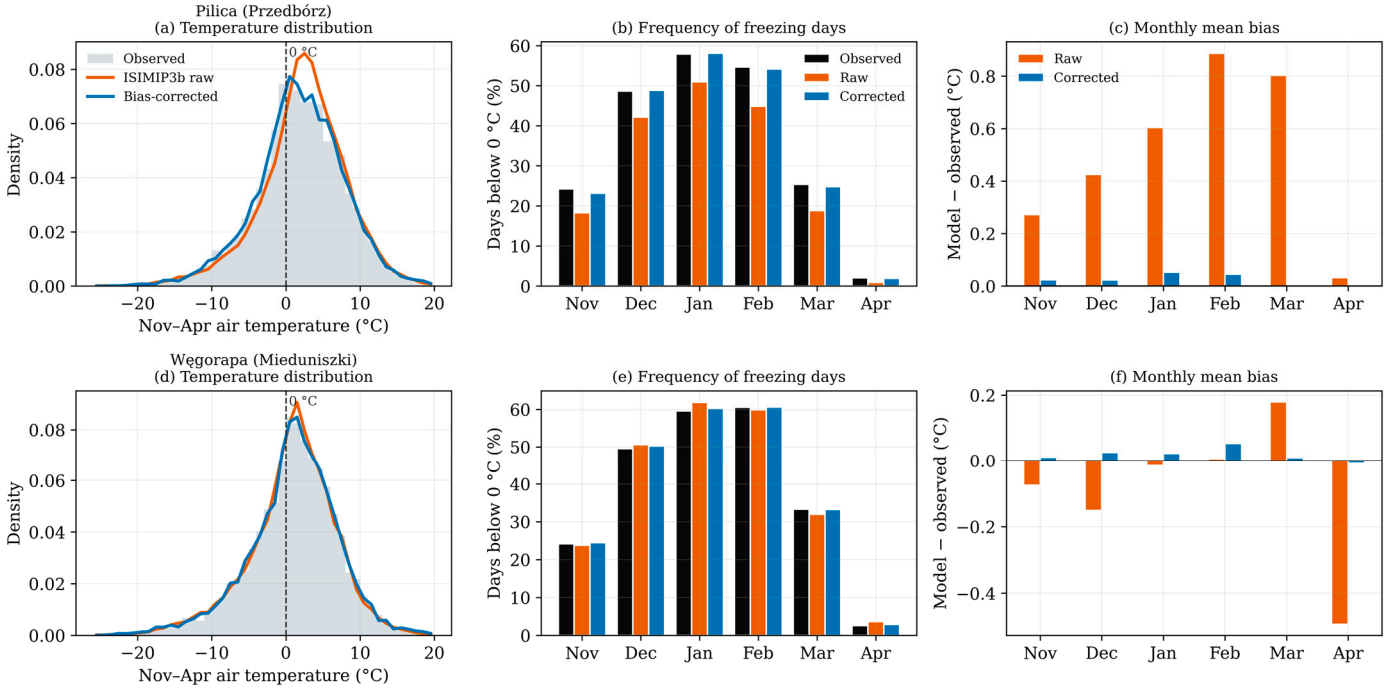


Figure S3. Effect of the station-level bias correction on the ISIMIP3b forcing, 1979–2014. (a, d) Distribution of November–April daily air temperature: observed (shaded), raw ISIMIP3b (orange) and bias-corrected (blue), with the freezing point marked. (b, e) Percentage of days below 0 °C in each month. (c, f) Monthly mean bias, model minus observed. Note the differing vertical scales in (c) and (f): the residual bias on the Pilica is an order of magnitude larger than on the Węgorapa.