



Supplement of

Brief communication: Temperature-driven shrinkage of a disappearing Himalayan glacier

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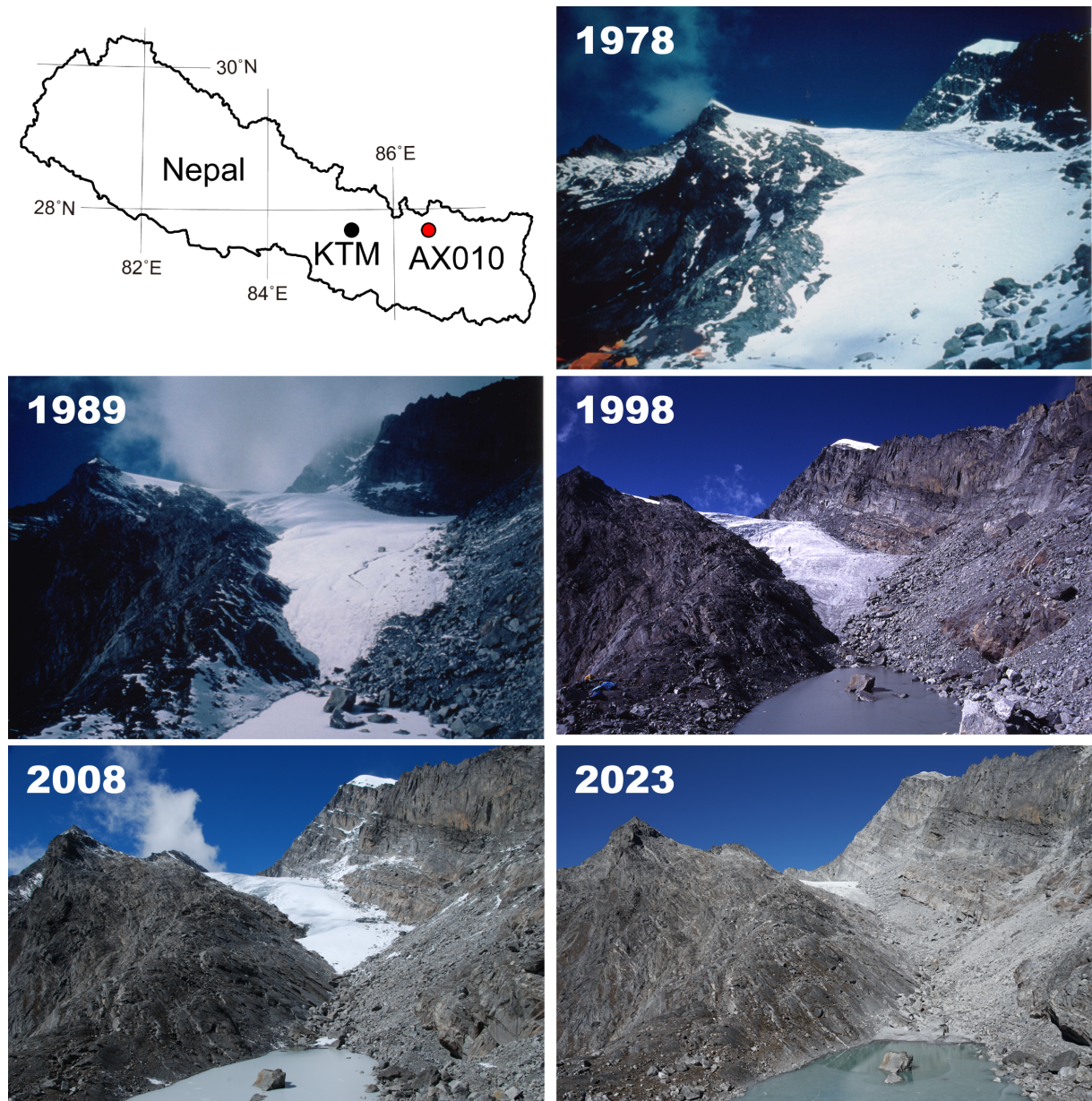


Figure S1: Location and time series photographs of Glacier AX010 in the Shorong region, Nepal Himalaya. KTM denotes Kathmandu, the capital city of Nepal. The 1978 and 1989 photographs were taken by Prof. Yutaka Ageta and Dr. Tsutomu Kadota, respectively. The other photographs were taken by Prof. Koji Fujita, the corresponding author of this study.

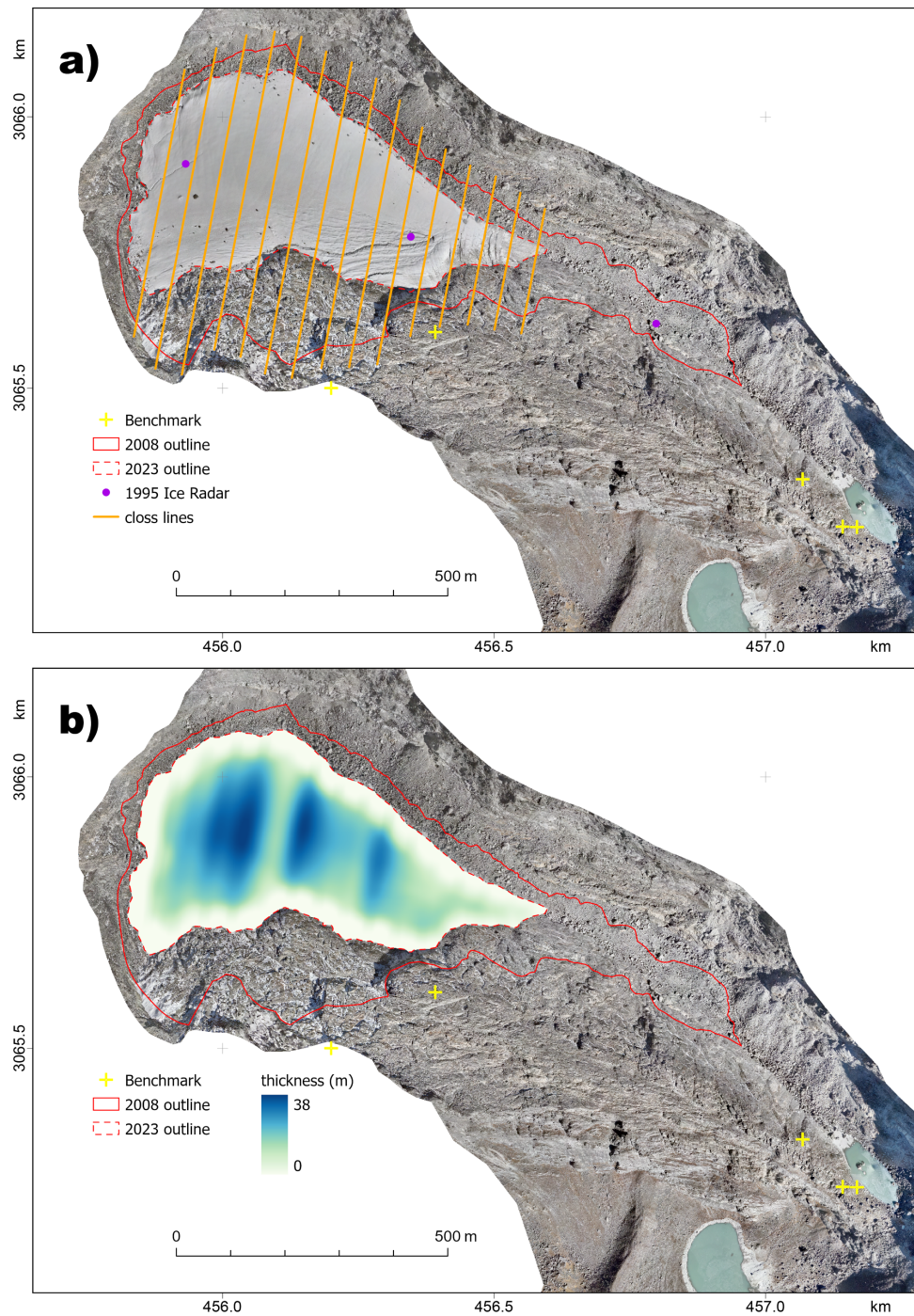


Figure S2: Thickness estimation for Glacier AX010 in the Shorong region, Nepal Himalaya. a) Lines for creating the cross sections (orange lines) are set at a 50-m interval, and b) the thickness distribution. Purple dots denote the location of the ice-radar measurement in 1995 (Kadota et al., 1997).

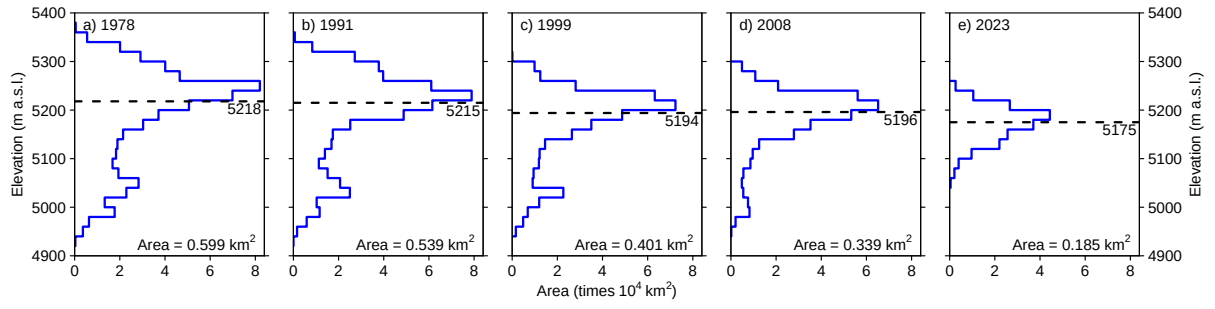


Figure S3: Hypsometry of Glaciers AX010 in the Shorong region, Nepal Himalaya. Dashed line with four digit denotes the median elevation.

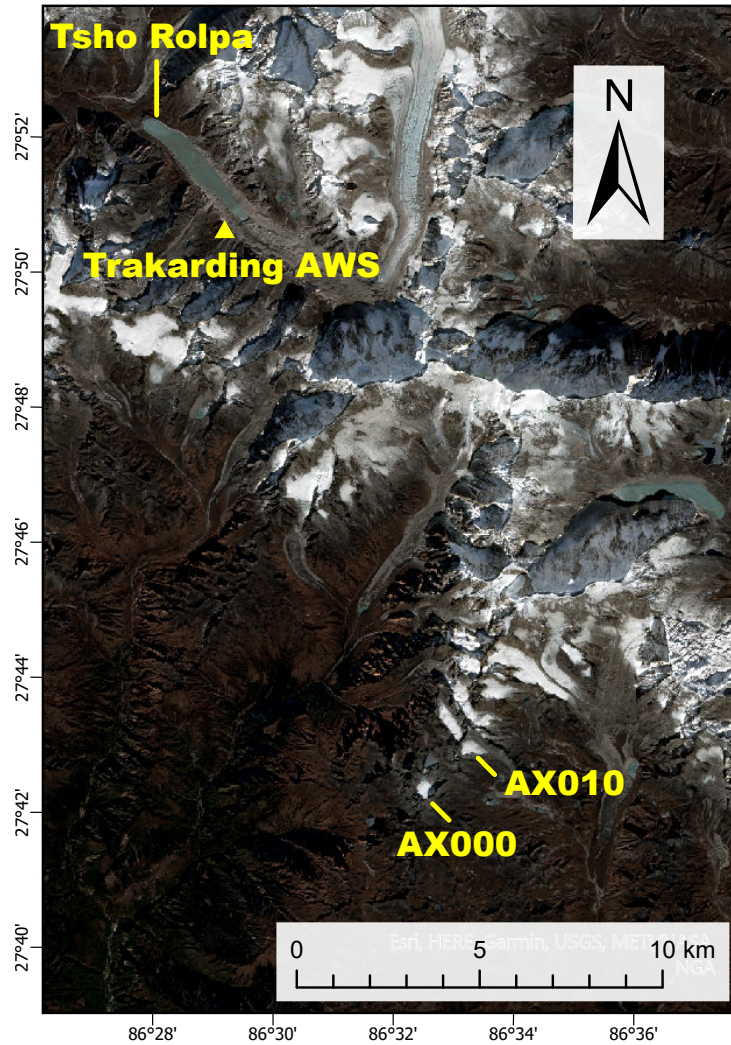


Figure S4: Locations of the automatic weather station (AWS) at Trakarding Glacier in the Rolwaling region and Glaciers AX010 and AX000 in the Shorong region, Nepal Himalaya. Tsho Rolpa is the largest glacial lake in the Nepal Himalaya. The back image is of Sentinel-2 acquired on 23 December 2022.

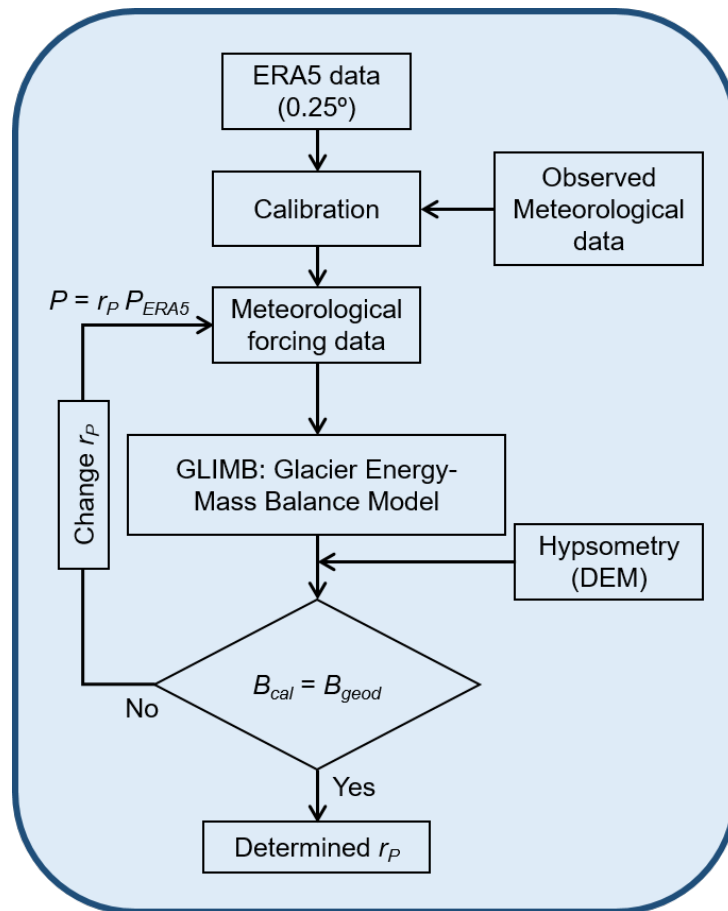


Figure S5: Flowchart for estimating the precipitation parameter (r_P).

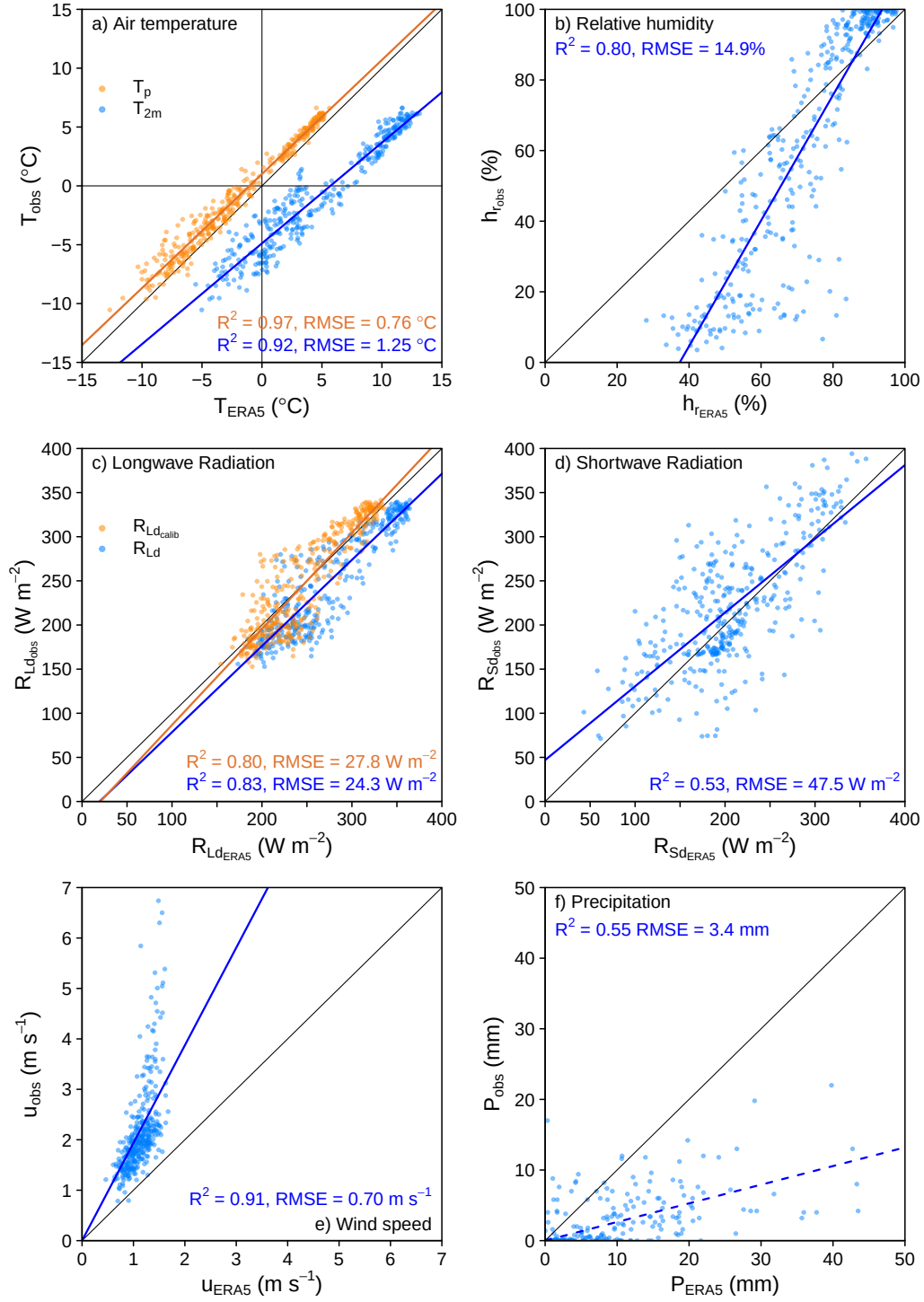


Figure S6: Comparisons of daily meteorological variables in the ERA5 reanalysis (horizontal axes) against the observational data (vertical axes) for the period 2022-2023 at the Trakarding AWS site for a) air temperature, b) relative humidity, c) downward longwave radiation, d) downward shortwave radiation, e) wind speed, and f) precipitation, respectively. Orange dots in panels a) and c) denote air temperature estimated from pressure level data (T_p) and calibrated downward longwave radiation derived from T_p ($R_{Ld,calib}$). Parameters for regressions are summarized in Table S3.

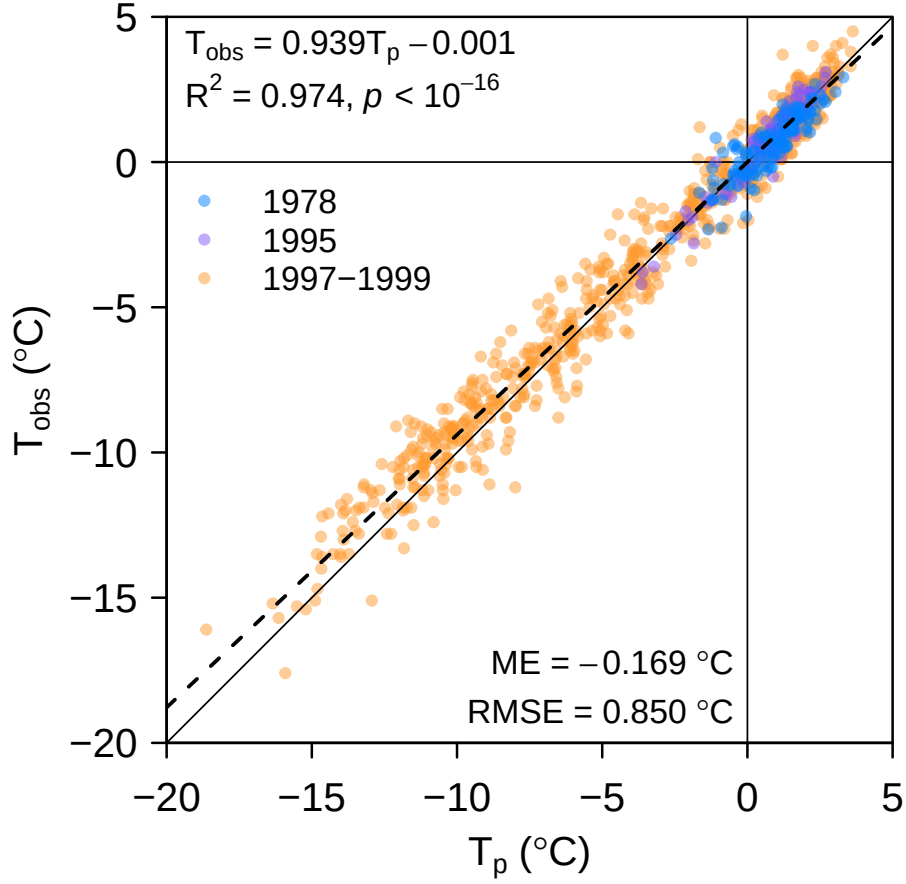


Figure S7: Observed (T_{obs}) and estimated (T_p) daily mean air temperature for Glacier AX010 in 1978 and the 1990s. The dashed line denotes a linear regression for all data. ME and RMSE denote mean error and root mean square error, respectively.

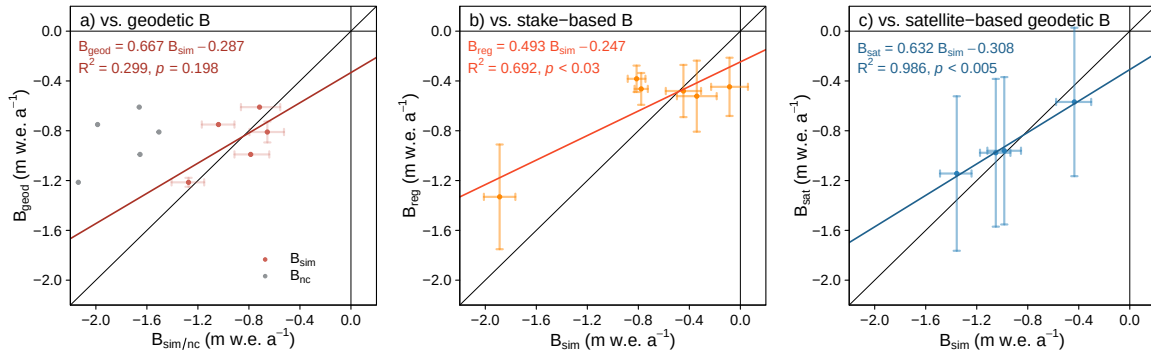


Figure S8: Simulated glacier-wide mass balance (B_{sim}) of Glacier AX010 (horizontal axis) against (a) the ground-based geodetic (B_{geod}), (b) the stake-based glacier-wide mass balance (B_{reg}), and (c) the satellite-based geodetic (B_{sat}) (Hugonnet et al., 2021). Gray dots in panel (a) denote the simulated mass balance with non-calibrated precipitation (B_{nc}). Statistical information is summarized in Tables S4, S5, and S7.

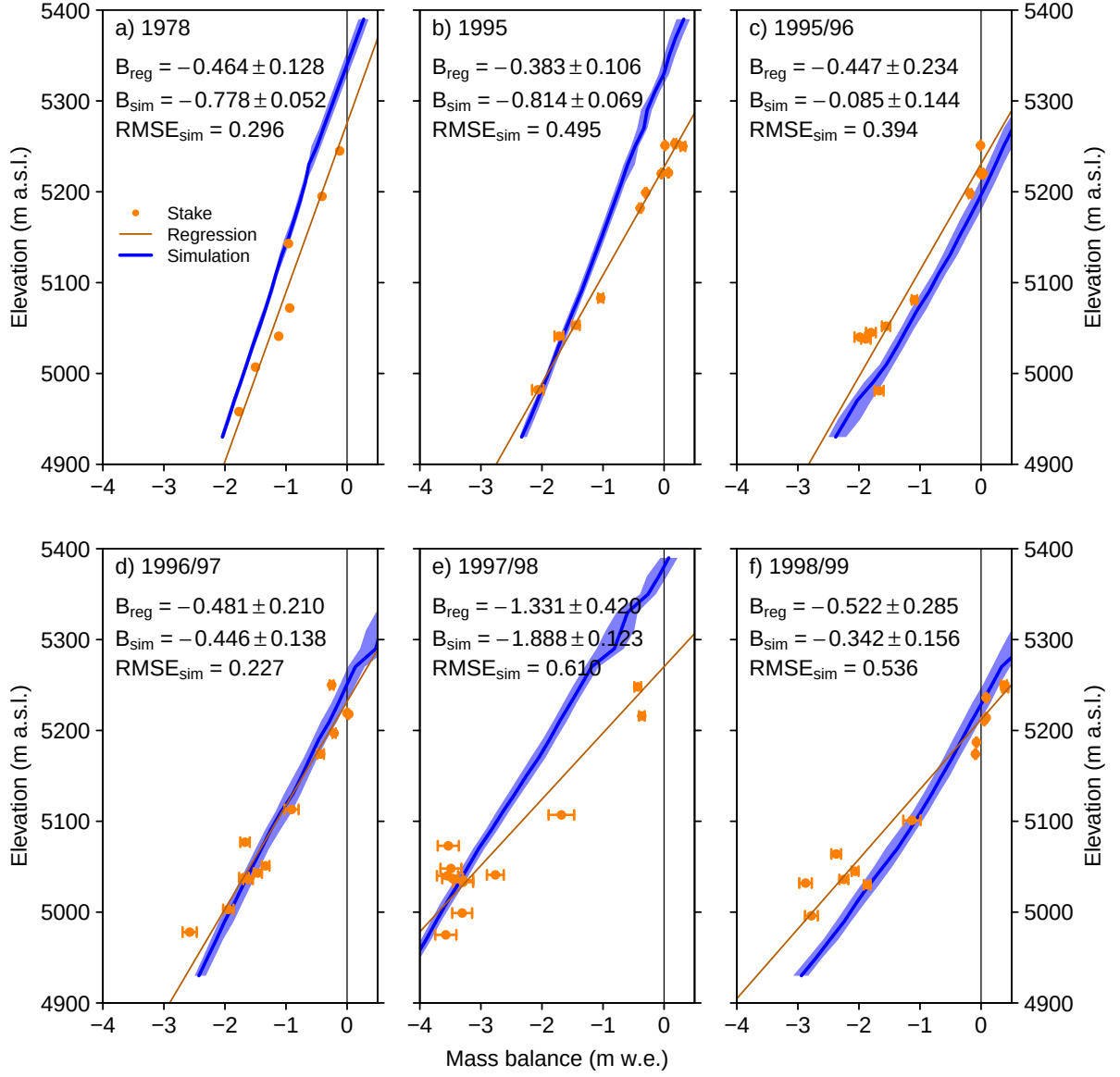


Figure S9: Observed (orange dots) and simulated (blue lines) mass balance of Glacier AX010 in (a) 1978 and (b-f) the 1990s. Blue shading area denotes the uncertainty range due to the precipitation parameter. Brown lines denote linear regressions of the observed mass balance. B_{reg} and B_{sim} denote the glacier-wide mass balance (m w.e.). $RMSE_{sim}$ denotes the root mean square error of the simulated mass balance against observation (m w.e.). Statistical information is summarized in Table S5.

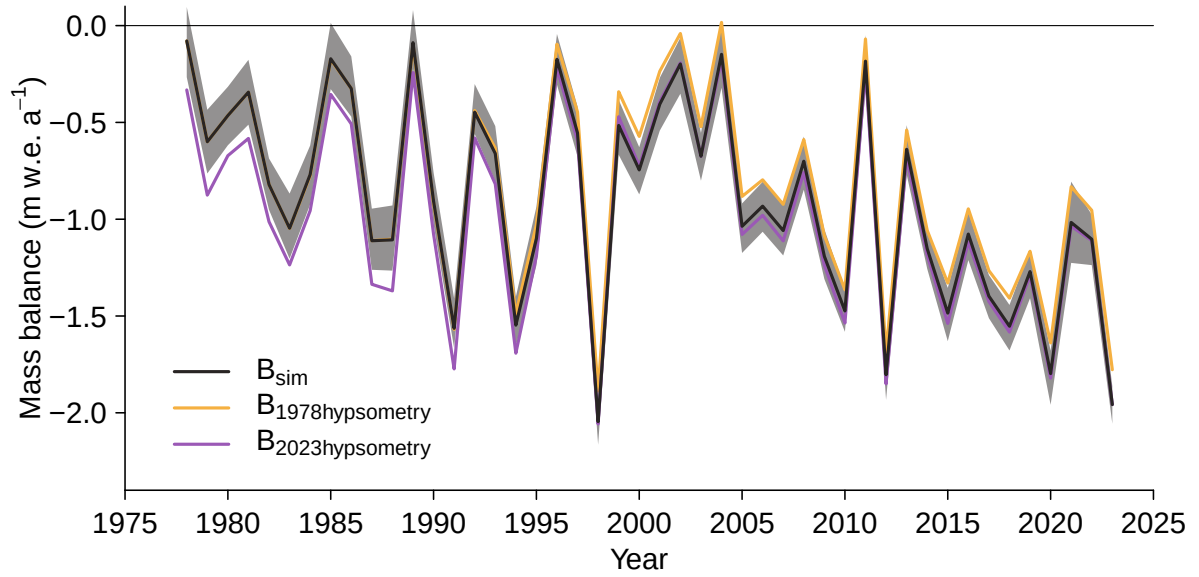


Figure S10: Simulated glacier-wide annual mass balances (B , m w.e.) of Glacier AX010 applied with fixed hypsometry of 1978 (yellow line) and of 2023 (purple line). Black line with gray shading area denote the simulated B with the uncertainty range due to the precipitation parameter.

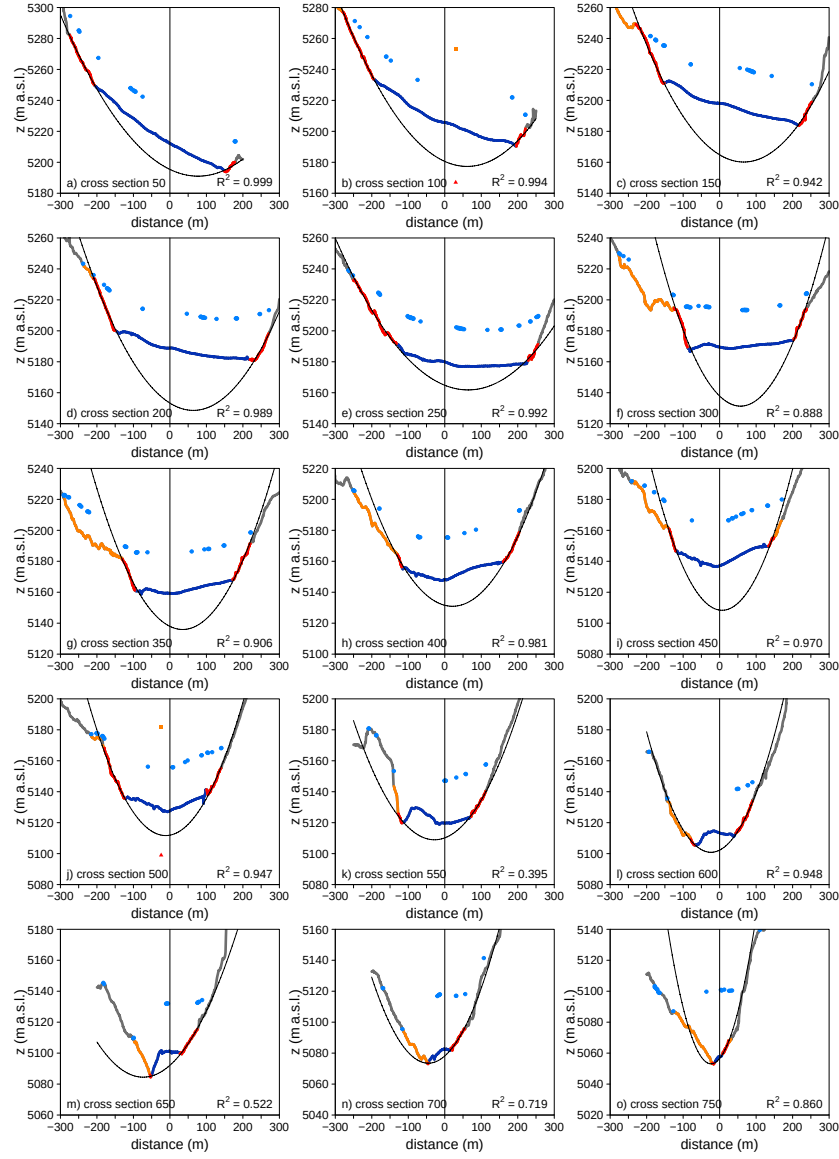


Figure S11: Cross sections from a) upper to o) lower part of Glacier AX010 in the Shorong region, Nepal Himalaya. Blue lines and light blue dots denote the glacier surface in 2023 (drone photogrammetry) and in 2008 (GNSS survey), respectively. Gray lines denote the 2023 off-glacier surface outside the 2008 glacier coverage. Red and orange lines denote the 2023 off-glacier surface under the 2008 glacier coverage used (red) and unused (orange) for the parabolic approximation curve (thin black line). The lines of the cross section are shown in Figure S2a. The number for the cross section denotes the distance in meters from the top boundary. The surface (orange squares) and bottom (red triangles) estimated from the ice radar measurements in 1995 are plotted in the closest cross sections (b) 100 for IR3 and (j) 500 for IR2, respectively.

Table S1: Locations of the benchmarks for surveying Glaciers AX010 and AX000 in the Shorong region, Nepal Himalaya.

BM-M for AX010	86.55764071°E, 27.71403452°N, 5168.110 m a.s.l.
BM-08 for AX000	86.54385780°E, 27.70820903°N, 5053.591 m a.s.l.

Table S2: Location and observed variables of the automatic weather station at Trakarding Glacier in the Rolwaling region, Nepal.

Location	86.485°E, 27.844°N, 4806 m a.s.l.
Instruments & Variables	Vaisala WXT536 (2.07 m): Air temperature, Relative humidity, Wind speed & direction Kipp & Zonen CNR4 (1.47 m): Downward and upward shortwave radiation, Downward and upward longwave radiation Onset RG3-M (tipping bucket on ground): Precipitation Data Logger: Campbell CR1000X
Interval	10 sec sampling & 15 min recording

Table S3: Bias and root mean square difference (RMSD) between ERA5 and observed meteorological variables (v_{ERA5} and v_{obs}), and parameters and statistics for the regressions ($v_{obs} = av_{ERA5} + c$) shown in Figure S6. All regressions have p -values less than 0.001.

Variable	Bias	RMSD	a	c	R^2	RMSE
T_{2m}	5.56 °C	5.75 °C	0.856	-4.887	0.924	1.25 °C
T_p	-1.07 °C	1.32 °C	0.969	1.008	0.971	0.76 °C
R_{Ld}	25.6 W m ⁻²	35.4 W m ⁻²	1.089	-19.059	0.825	24.3 W m ⁻²
$R_{Ld_{calib}}$	0.2 W m ⁻²	26.1 W m ⁻²	1.089	-22.166	0.804	27.8 W m ⁻²
R_{Sd}	-13.0 W m ⁻²	50.2 W m ⁻²	0.836	46.960	0.533	47.5 W m ⁻²
u	-1.03 m s ⁻¹	1.28 m s ⁻¹	1.936	0	0.909	0.70 m s ⁻¹
h_r	10.6%	22.5%	1.778	0.665	0.801	14.9%
P	10.17 mm	13.17 mm	0.264	0	0.549	3.39 mm

T_{2m} and T_p denote air temperature at 2-m height and air temperature from pressure level data. R_{Ld} and $R_{Ld_{calib}}$ denote ERA5 and calibrated downward longwave radiation, R_{Sd} , u , h_r , and P denote downward shortwave radiation, wind speed, relative humidity, and precipitation, respectively.

Table S4: Glacier-wide geodetic mass balance (B_{geod}) of Glacier AX010 in the Shorong region, Nepal Himalaya. B_{geod} before 2008 are from Fujita et al. (2001) and Fujita and Nuimura (2011). Estimated precipitation multiplier (r_P), simulated mass balance with calibrated precipitation (B_{sim}) and with non-calibrated precipitation (B_{nc}) shown in Figure S8a are listed. B_{geod} for Glacier AX000 is also listed.

Period	B_{geod} , m w.e. a ⁻¹	r_P	B_{sim} , m w.e. a ⁻¹	B_{nc} , m w.e. a ⁻¹
1978 – 1991	-0.610	1.54	-0.717 ± 0.154	-1.660
1991 – 1996	-0.990	1.36	-0.786 ± 0.137	-1.654
1996 – 1999	-0.750	1.66	-1.039 ± 0.128	-1.987
1999 – 2008	-0.810 ± 0.084	1.39	-0.656 ± 0.135	-1.506
2008 – 2023	-1.214 ± 0.036	1.49	-1.273 ± 0.128	-2.138
2008–2023 for AX000	-1.060 ± 0.023	NA	NA	NA

Table S5: Statistical information for the observed and simulated mass balance of Glacier AX010 in 1978 and the 1990s. Observation periods are expressed in the YYYYMMDD format. a and c denote the parameters for linear regressions ($b_{reg} = az + c$, z is elevation in m a.s.l.). R^2 denotes the coefficient of determination for the linear regression. All regressions have p -values less than 0.001. B and RMSE with subscripts reg and sim denote glacier-wide mass balance and root mean square error against the observed stake mass balance of linear regression and simulation, respectively (unit: m w.e. a⁻¹). B_{reg} and B_{sim} are depicted in Figure S8b.

Period	From	To	$a(\times 10^{-3})$	c	R^2	B_{reg}	RMSE _{reg}	B_{sim}	RMSE _{sim}
1978	19780630	19780915	5.368	-28.320	0.942	-0.464	0.128	-0.778 ± 0.052	0.296
1995	19950620	19951010	8.404	-43.930	0.982	-0.383	0.106	-0.814 ± 0.069	0.495
1995/96	19951010	19961015	8.536	-44.655	0.920	-0.450	0.234	-0.085 ± 0.144	0.394
1996/97	19961015	19971105	8.756	-45.806	0.933	-0.480	0.210	-0.446 ± 0.138	0.227
1997/98	19971105	19981028	13.705	-72.228	0.868	-1.330	0.420	-1.888 ± 0.123	0.610
1998/99	19981028	19991026	13.025	-67.857	0.946	-0.520	0.285	-0.342 ± 0.156	0.536

Table S6: Effect of precipitation calibration on mass balance, accumulation, and melt of Glacier AX010 in the Shorong region, Nepal Himalaya for the period 1978-2023 (unit: m w.e. a⁻¹). *sim* and *nc* denote calibrated and non-calibrated precipitation, respectively.

	<i>sim</i>	<i>nc</i>	$\Delta(sim - nc)$
Mass balance	-0.919 ± 0.516	-1.809 ± 0.494	0.890 ± 0.113
Accumulation	1.948 ± 0.238	1.315 ± 0.161	0.633 ± 0.077
Melt	2.942 ± 0.322	3.129 ± 0.372	-0.187 ± 0.093

Table S7: Satellite-based (*sat*, Hugonnet et al., 2021) and simulated (*sim*) glacier-wide mass balance (B , m w.e. a⁻¹) of Glaciers AX010 and AX000 in the Shorong region, Nepal Himalaya, for a five-year interval (Figure S8c).

Period	B_{sat} for AX010	B_{sim} for AX010	B_{sat} for AX000
2000 – 2004	-0.569 ± 0.596	-0.434 ± 0.138	-0.413 ± 0.620
2005 – 2009	-0.961 ± 0.592	-0.984 ± 0.132	-0.546 ± 0.617
2010 – 2014	-0.977 ± 0.593	-1.050 ± 0.119	-0.801 ± 0.628
2015 – 2019	-1.143 ± 0.621	-1.357 ± 0.124	-0.998 ± 0.647

Table S8: Trend statistics (trend per decade and p -value by Mann-Kendall trend analysis) for the simulated annual mass balance and meteorological variables for the period 1941-2023. Those for the limited periods identified by the breakpoint analysis (Zeileis et al., 2002) are also shown (only those with p -values < 0.005).

Variable	Trend per decade	p -value
B_{sim}	$-0.153 \text{ m w.e. a}^{-1}$	< 0.001
T_{sum}	$0.089 \text{ }^{\circ}\text{C}$	< 0.001
PDD	$10.81 \text{ }^{\circ}\text{C day}$	< 0.001
T_{equi}	$0.004 \text{ }^{\circ}\text{C}$	0.648
P	$-0.049 \text{ m w.e. a}^{-1}$	< 0.007
P_{snow}	$-0.095 \text{ m w.e. a}^{-1}$	< 0.001
P_{rain}	$0.046 \text{ m w.e. a}^{-1}$	$= 0.001$
M	$0.039 \text{ m w.e. a}^{-1}$	$= 0.012$
d_{melt}	0.413 day	0.299
B_{sim} (1971-2023)	$-0.245 \text{ m w.e. a}^{-1}$	< 0.001
B_{sim} (1999-2023)	$-0.473 \text{ m w.e. a}^{-1}$	< 0.001
T_{sum} (1971-2023)	$0.172 \text{ }^{\circ}\text{C}$	< 0.001
T_{sum} (1999-2023)	$0.351 \text{ }^{\circ}\text{C}$	< 0.001
PDD (2001-2023)	$50.67 \text{ }^{\circ}\text{C day}$	< 0.001
P (1974-2023)	$0.101 \text{ m w.e. a}^{-1}$	< 0.004
P_{snow} (1955-2023)	$-0.069 \text{ m w.e. a}^{-1}$	< 0.001
P_{rain} (2007-2023)	$0.376 \text{ m w.e. a}^{-1}$	< 0.001
M (1971-2023)	$0.126 \text{ m w.e. a}^{-1}$	< 0.001

B_{sim} denotes glacier-wide mass balance. T_{sum} and T_{equi} denote summer mean temperature and equilibrium summer mean temperature yielding a zero mass balance. PDD denotes positive degree day. P , P_{snow} , and P_{rain} denote precipitation, snow, and rain, respectively. M and d_{melt} denote melt amount and number of melt days.

Table S9: Bottom elevations (z_{btm}) estimated by ice-radar measurement (IR) in 1995 (Kadota et al., 1997) and this study (m a.s.l.). h in 1995 denotes ice thickness (m). The IR positions (m in UTM) are shown in Figure S2a.

	UTM east	UTM north	1995 z_{btm} (h)	2023 z_{btm}	$\Delta z_{1995-2023}$
IR 1	456799	3065619	5001 (51)	4976	25
IR 2	456347	3065779	5099 (83)	5112	-13
IR 3	455932	3065913	5167 (86)	5182	-15

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