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Debris cover effects on energy and mass balance of Batura Glacier in the Karakoram over the past 20 years

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Supplementary Tables

Table S1 Technical characteristics of the sensors at Batura Glacier at AWS1 and AWS2.

AWS	Variable	Instrument	Accuracy
AWS1	Air temperature	Campbell CS215	0.9℃(-40~60 ℃)
	Relative humidity	Campbell CS215	4% (0~100%)
	Radiation	Campbell CNR4-L	5% (daily totals)
	Wind speed	Young	±0.3m/s (-50~50 ℃)
	Wind direction	Young	±3° (-50~50 ℃)
	Rain gauge	T-200B	0.1% FS (-40~60 ℃)
AWS2	Air temperature	Zhiyuxiang MULTI-7P	0.3℃(-40~60 ℃)
	Air temperature	Zhiyuxiang MULTI-7P	0.3hpa
	Relative humidity	Zhiyuxiang MULTI-7P	2% (0~100%)
	Radiation	Jinzhou Sunshine TBB-2	5% (daily totals)
	Wind speed	Zhiyuxiang MULTI-7P	0.3m/s (-50~50 ℃)
	Wind direction	Zhiyuxiang MULTI-7P	3° (-50~50 ℃)
	Surface temperature	Campbell TP107	0.3°

Table S2 The primary parameters in the energy balance model.

Parameter	Setting value	Sampled values for calibrated parameters (min, max, step)	Reference
firn albedo	0.53	0.53, 0.62, 0.03	(Mölg et al., 2012)
ice albedo	0.3	0.25, 0.4, 0.05	(Mölg et al., 2012)
surface roughness length for aged snow	6 mm	1.5, 6, 0.5	(Brock et al., 2006; Mölg et al., 2012)
surface roughness length for ice	2.5 mm	0.7, 3.1, 0.6	(Brock et al., 2006; Mölg et al., 2012)
fresh snow albedo	0.88		(Mölg et al., 2012)
surface roughness length for fresh snow	0.24 mm		(Gromke et al., 2011)
albedo timescale	13 days		(Mölg et al., 2012)
albedo depth scale	3 cm		(Mölg et al., 2012)
temperature threshold of rain/snow ratio	[-0.5~4.5℃]		(Huintjes et al., 2015)
ice density	550 kg/m^3		(Mölg et al., 2012)
firn density	875 kg/m^3		(Mölg et al., 2012)
density of freshly fallen snow	250 kg/m^3		(Mölg et al., 2012)
Surface emission coefficient	0.97		(Bintanja and Van, 1995)
melting temperature	273.15 K		(Mölg et al., 2012)
bottom temperature	265.15 K		(Mölg et al., 2012; Huintjes, 2014)
thickness of snow layers	2 cm		(Sauter et al., 2020)
thickness of glacier ice layers	50 cm		(Sauter et al., 2020)

Table S3 The key parameters in the energy balance of debris.

Parameter	Setting value	Sampled values for calibrated parameter (min, max, step)	Reference
debris albedo	0.13	0.1, 0.4, 0.03	(Giese et al., 2020; Reid and Brock, 2010)
Debris thermal conductivity	0.76 W m^{-1} K^{-1}	0.6,1.32, 0.08	(Giese et al., 2020; Reid and Brock, 2010)
debris density	1496 kg m^{-3}		(Reid and Brock, 2010)
debris specific heat capacity	900 J kg^{-1} m^{-3}		(Reid and Brock, 2010)
debris volumetric heat capacity	1418208 J m^{-3} K^{-1}		(Reid and Brock, 2010)
ice emissivity	0.94		(Reid and Brock, 2010)
debris aerodynamic roughness length for debris	0.016 m		(Reid and Brock, 2010)
debris layer thickness*	0.01		(Reid and Brock, 2010)

*When there are fewer than 10 layers, it is adjusted to have 10 layers with a thickness of total thickness divided by 10 for each layer.

Supplementary Figures

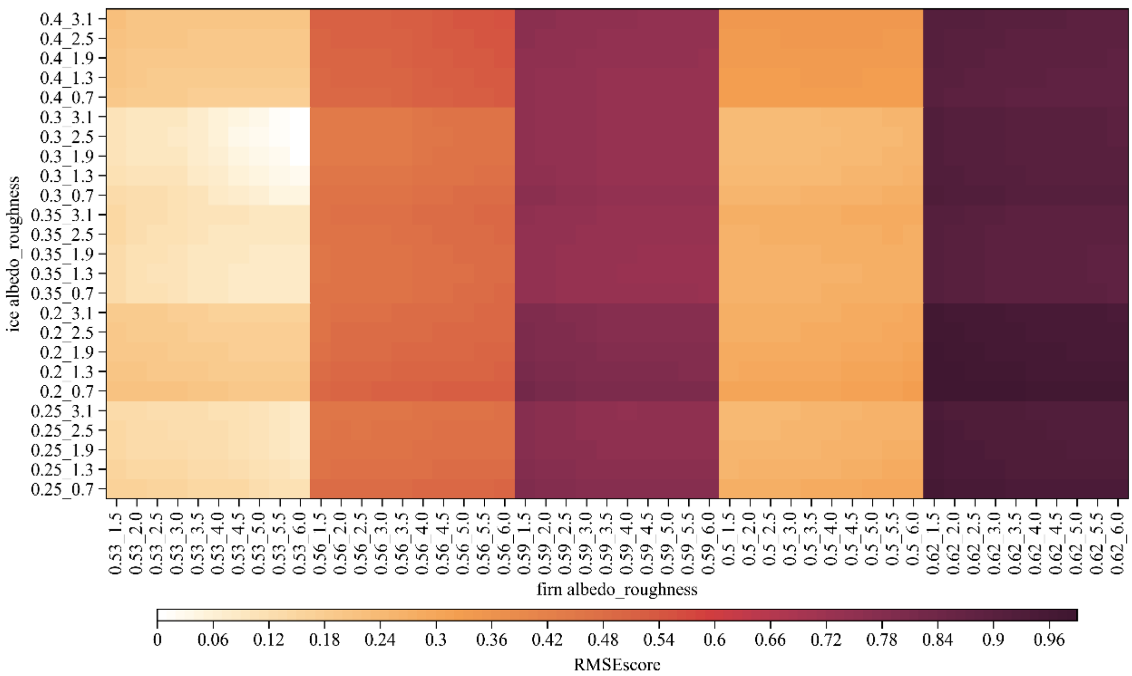

Figure S1 Heat plots of $RMSE_{score}$ for the model-inherent calibration at AWS1.

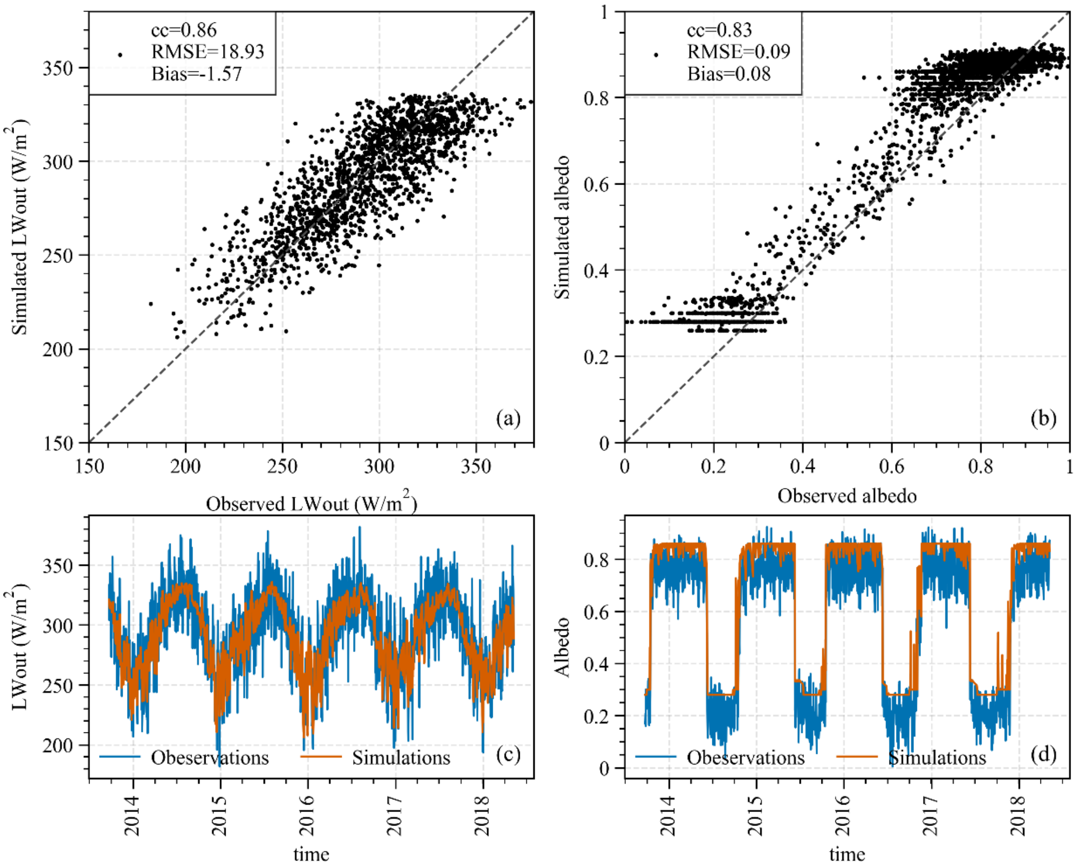

Figure S2 Comparison of observed and simulated (a), (c) outgoing longwave radiation and (b), (d) albedo at AWS1.

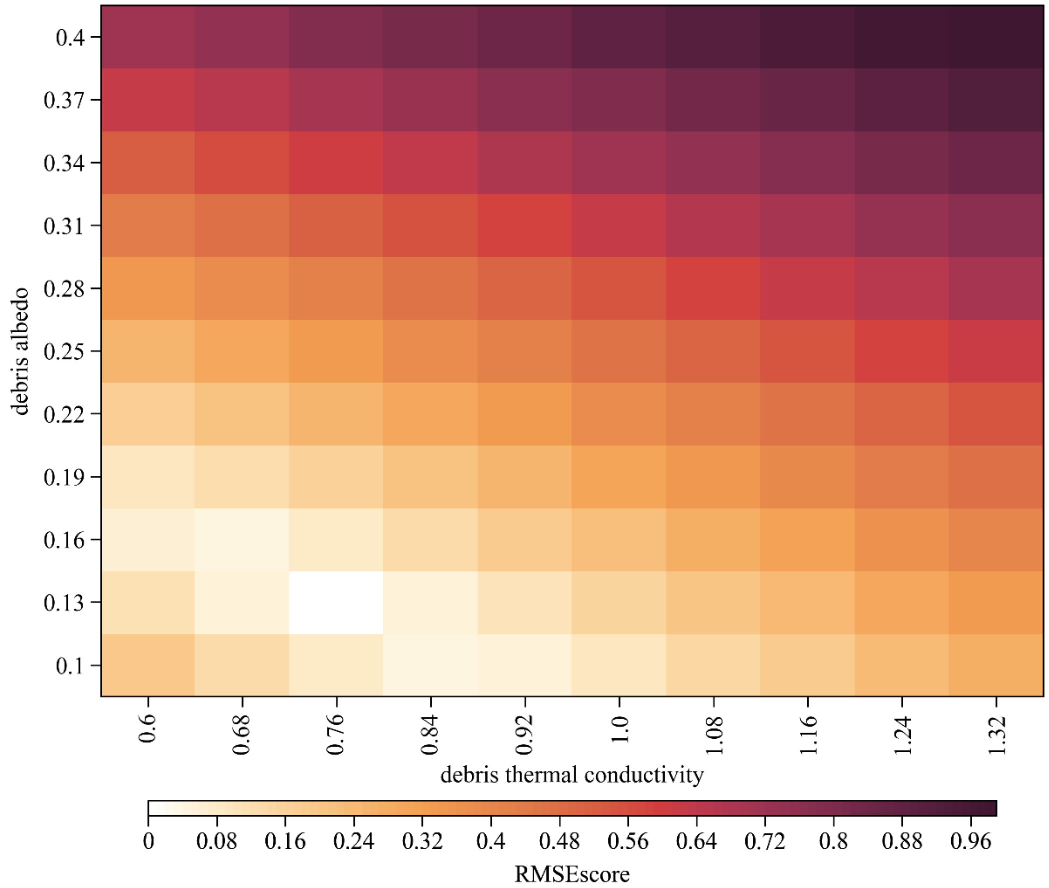

Figure S3 Heat plots of $RMSE_{score}$ for the model-inherent calibration at AWS2.

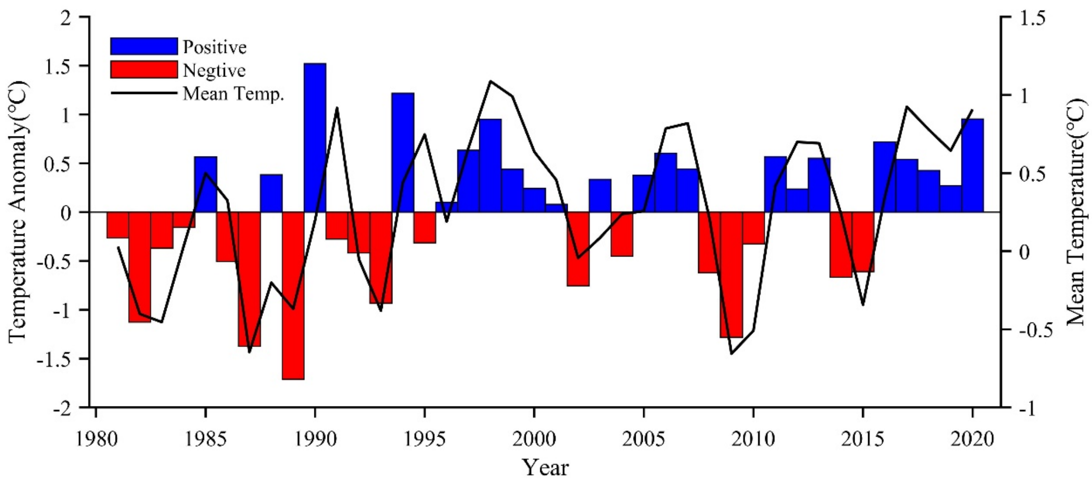

Figure S4 Average air temperature in Hunza basin from 1980 to 2020 derived from ERA5.

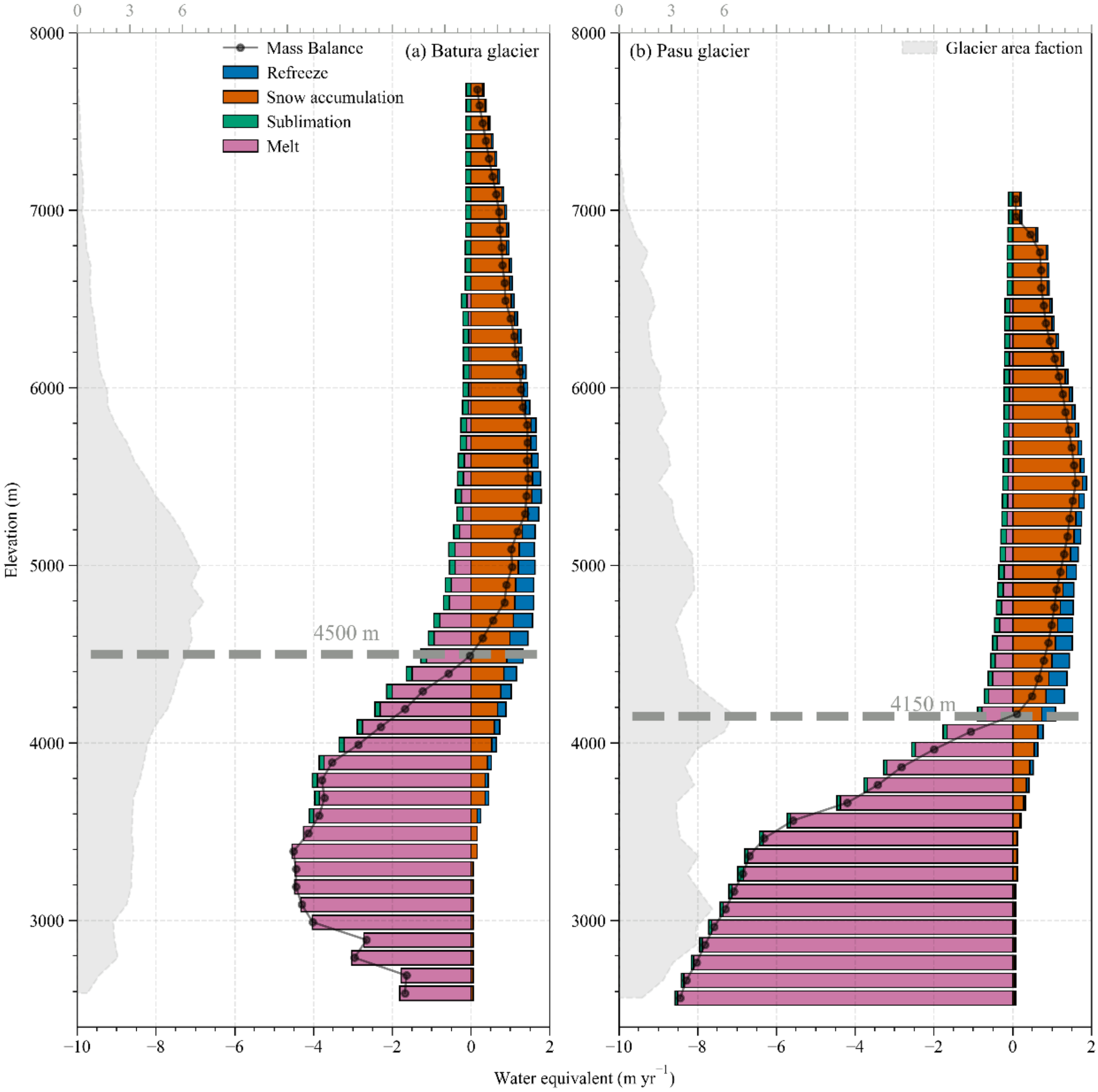

Figure S5 Characteristics of altitude gradient of components in mass balance. (a) Batura Glacier; (b) Pasu Glacier. The glacier ratio fraction (%) represents proportion of the glacier area in each elevation zone to total area of the glacier.

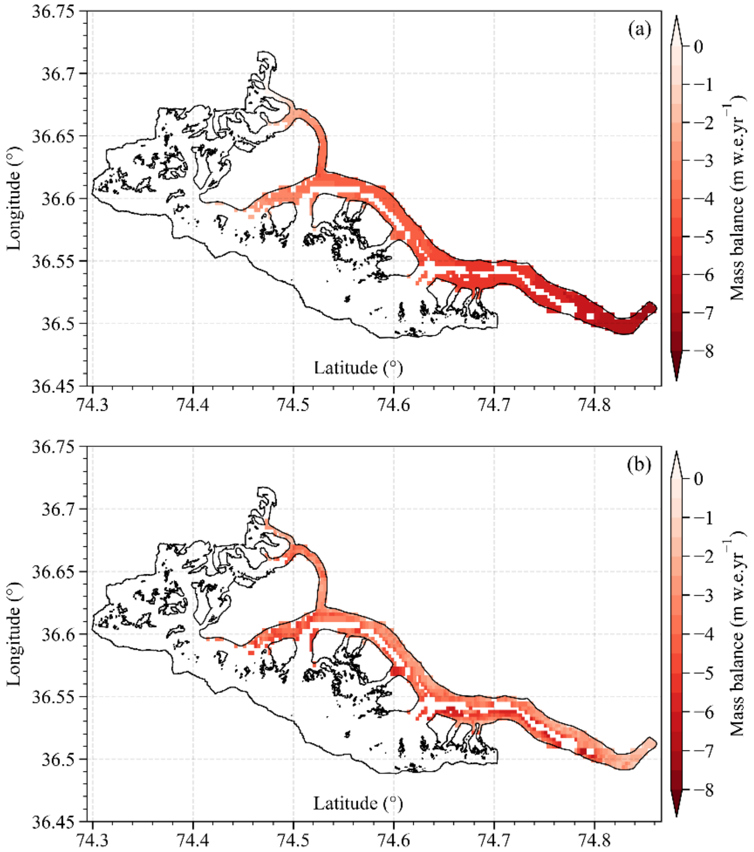

Figure S6 Spatially-distributed annual ablation with no debris cover (a) and with debris cover (b).

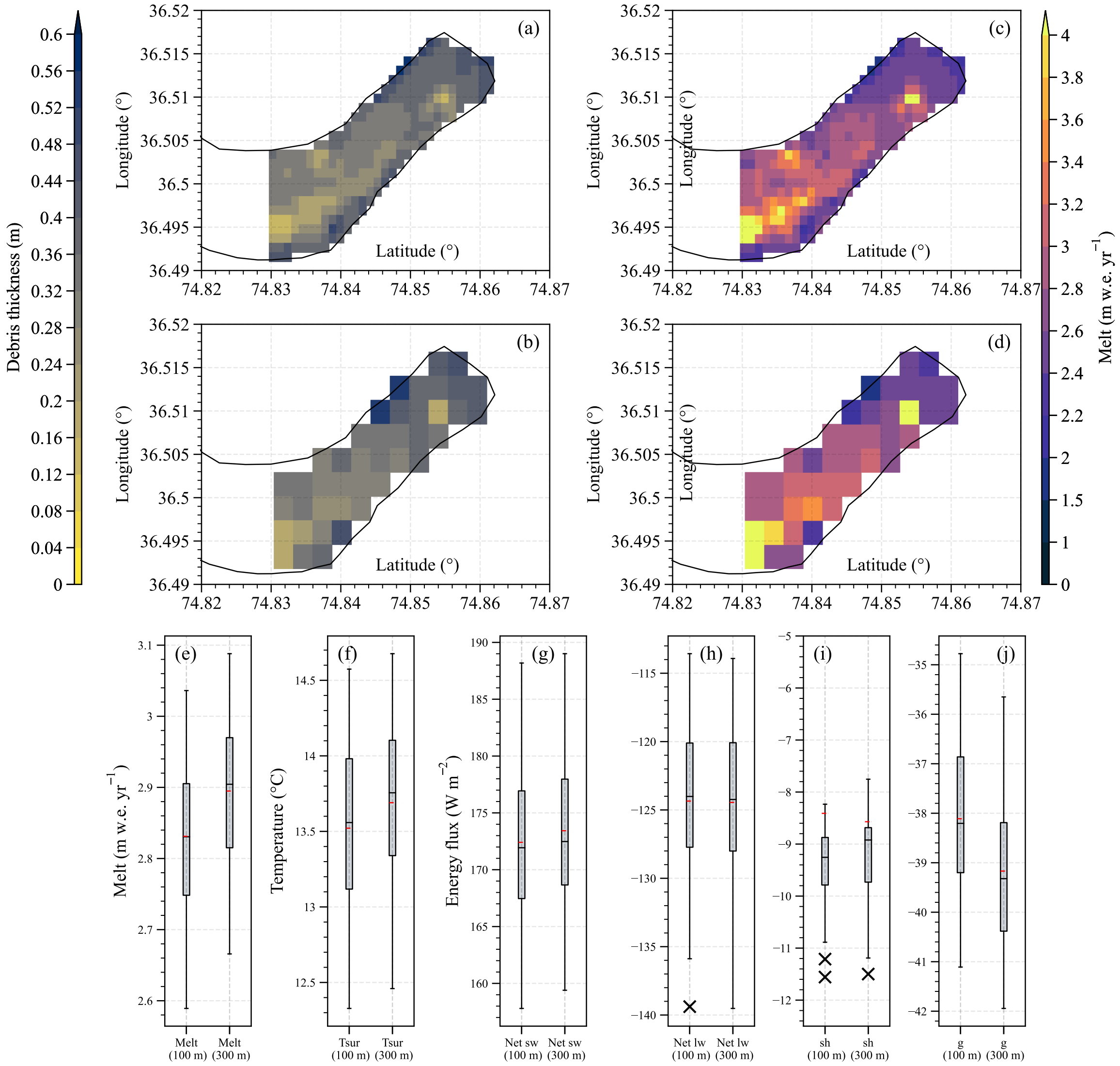

Figure S7 Comparison on subsurface melt and energy fluxes at a section of the Batura Glacier terminus simulated at two resolutions: 100 m and 300 m. (a) and (b) show the surface debris thickness at 100 meters resolution and 300 m resolution, respectively. (b) shows the surface debris thickness at 300 meters resolution. (c) and (d) depict subsurface melt at 100 m resolution and 300 m resolution, respectively. (e) to (j) present comparison boxplots for subsurface melt and various energy fluxes at both resolutions. Tsur, Net sw, Net lw, sh, and g represent surface temperature, net shortwave radiation, net longwave radiation, sensible heat flux, and conductive heat flux, respectively. The y-axis labels in (e) to (h) are consistent for ease of comparison. Red lines in (e) to (j) indicate the mean value for each variable.

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