

Postprint: Summer Ablation Modeling in the Debris-Covered Zone of Glacier No. 72, Qingbingtan, Tomur Peak

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Abstract

Debris-covered glaciers are widely distributed across western China. Since the ablation zones of such glaciers are covered by rock debris to varying degrees, their ablation patterns differ substantially from those of clean glaciers. Therefore, conducting ablation simulation studies for debris-covered glaciers is of paramount importance. This study employs on-glacier meteorological data as forcing and utilizes an energy-balance model for debris-covered glaciers to simulate energy fluxes and ablation in the debris-covered zone of Qingbingtan Glacier No. 72 on Tomur Peak, Tianshan Mountains. Based on heat conduction processes and the energy balance equation, the model computes debris surface temperature and internal temperatures within the debris layer, and estimates underlying ice ablation through the internal debris temperature. The results demonstrate that during summer 2008, the simulated ablation amounted to 0.39 m w.e., with validation against ablation stake data yielding high simulation accuracy ($R^2 = 0.92$, $RMSE = \pm 0.03 \text{ m w.e.}$). Simulated debris surface temperature and temperature at a depth of 10 cm also exhibited good agreement ($R^2 = 0.91$ and 0.60 , respectively). In the energy exchange process of the debris-covered area, net shortwave radiation constitutes the sole energy input term, while sensible heat flux represents the largest energy output term (49.7%), followed by conductive heat flux (ablation heat consumption) (25.8%), net longwave radiation (19.8%), and latent heat flux (4.6%). Precipitation heat accounts for less than 1%. Cloud cover exerts a significant influence on the meteorological and energy characteristics of the debris-covered area; under cloudy conditions, peak incoming shortwave radiation in the debris-covered area decreases from $854 \text{ W} \cdot \text{m}^{-2}$ on clear days to $587 \text{ W} \cdot \text{m}^{-2}$, downward longwave radiation and relative humidity increase, and average ablation is reduced by 12% compared to clear days. Additionally, sensitivity analysis of key debris parameters reveals that simulated ablation is most sensitive

to variations in thermal conductivity, while changes in albedo and surface roughness are likewise non-negligible.

Full Text

Simulation Study of Summer Ablation in the Debris-Covered Area of Qingbingtan Glacier No. 72 in Mt. Tomor

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Abstract

Debris-covered glaciers are widely distributed in western China. As the ablation areas of this glacier type are covered by varying degrees of rock debris, their melting conditions differ significantly from debris-free glaciers. Therefore, conducting ablation simulation studies on debris-covered glaciers is crucial. This paper uses meteorological data from the ice surface as forcing data and employs an energy balance model for debris-covered glaciers to simulate energy fluxes and ablation in the debris-covered area of Qingbingtan Glacier No. 72 in Mt. Tomor, Tianshan. Based on heat conduction processes and energy balance equations, the model calculates debris surface temperature and internal debris temperature, then estimates sub-debris melt using the internal debris temperature. The results show that the modeled ablation for the summer of 2008 was 0.39 m w.e., which achieved high simulation accuracy ($R^2 = 0.92$, $RMSE = \pm 0.03 \text{ m w.e.}$) when validated against ablation stake data. The simulated debris temperatures at the surface and inside the debris were 0.91 and 0.60, respectively). During energy exchange in the debris-covered area, net shortwave radiation was the sole energy income term, while sensible heat flux was the largest energy expenditure term (49.7%), followed by conductive heat flux (ablation heat consumption) (25.8%), net longwave radiation (19.8%), and latent heat flux (4.6%). Precipitation heat was less than 1% and can be ignored. Cloud cover had a significant impact on meteorological and energy characteristics of the debris-covered area. Under overcast conditions, the peak incoming shortwave radiation decreased from $854 \text{ W} \cdot \text{m}^{-2}$ on sunny days to $587 \text{ W} \cdot \text{m}^{-2}$, while downward longwave radiation and relative humidity increased, and the average ablation decreased by 12% compared to sunny days. Additionally, sensitivity analysis of key debris parameters indicated that the simulated ablation was most sensitive to changes in thermal conductivity, while changes in albedo and surface roughness also cannot be ignored.

Keywords: Qingbingtang Glacier No. 72; Mt. Tomor in Tianshan; debris; energy balance; melting simulation

1. Study Area Overview

Qingbingtang Glacier No. 72 originates from the upstream area of the Kumalak River, a tributary of the Aksu River, and is located on the southern side of Mt. Tomor. It is a south-facing valley-cirque glacier fed by snowfall and avalanches (Fig. 1). The glacier has an area of 5.61 km^2 , with elevations ranging from 3,560 m at the terminus to 5,986 m at the summit, and a length of approximately 7.4 km. Debris is mainly distributed at the terminus and both sides of the ablation area, covering 0.87 km^2 and accounting for 15.5% of the ablation zone. Debris thickness generally decreases with altitude, with a maximum exceeding 1.07 m. The critical debris thickness for this glacier is approximately 16 cm. Areas with debris thicker than this threshold show decreasing melt with increasing thickness, covering about 0.66 km^2 (76% of total debris area). Areas with debris thinner than 16 cm show increasing melt with debris thickness, covering 0.21 km^2 . Compared with other glaciers in the Tianshan Mountains, this glacier moves relatively fast, with an average annual surface velocity of $47 \text{ m} \cdot \text{a}^{-1}$.

2. Data and Methods

2.1 Meteorological Data Meteorological data were obtained from an automatic weather station (AWS, Davis Vantage Pro2 Plus) installed in the debris-covered area of Qingbingtang Glacier No. 72. The AWS is located on the east side of the glacier tongue at 3,950 m a.s.l., where debris thickness is 12 cm, composed mainly of gray and white granite fragments (Fig. 1). Observed meteorological elements include air temperature, relative humidity, wind speed, precipitation, and incoming/reflected shortwave radiation, recorded at 30-minute intervals. The study period spans from July 13 to August 13, 2008. Due to the complex ice surface environment, data gaps occurred during July 21-23 and August 3-5. As ablation could not be simulated during these missing periods, ablation amounts were replaced by average values. Additionally, because the radiation sensor stopped 30 minutes early on August 13, the simulation end time was correspondingly advanced by 30 minutes.

2.2 ERA5 Reanalysis Data ERA5 is the fifth-generation global atmospheric reanalysis product from ECMWF, with a horizontal resolution of $0.25^\circ \times 0.25^\circ$ and temporal resolution of 1 hour. Cloud cover factor data from July 13 to August 13, 2008, were selected to analyze meteorological and energy conditions under different weather conditions. Weather classification follows Van Den Broeke et al.'s method based on cloud cover factor: clear sky when cloud cover ≤ 0.2 ,

overcast when > 0.8 , excluding precipitation effects. Data were obtained from the Copernicus Climate Change Service (<https://cds.climate.copernicus.eu>).

2.3 Debris Temperature Data Debris temperature data are crucial parameters for energy balance modeling of debris-covered glaciers and important validation data for simulation results. During the ablation period, researchers drilled a temperature hole in the debris area at 3,950 m a.s.l. on the glacier. At this location, debris thickness is 12 cm, and 13 temperature probes were installed within the debris layer. One probe was placed approximately at the debris surface (10 cm depth) to measure surface temperature. Since surface temperature observations are easily affected by solar radiation, temperature at 10 cm depth was used to approximate surface temperature, consistent with Rounce et al.'s method for measuring debris surface temperature on Lhotse Shar Glacier in the Himalayas. Another probe was installed at 10 cm depth to measure internal debris temperature. Below the debris, ice temperature was measured at 20 cm intervals. All temperature probes are thermistors developed by the Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences (formerly the Cold and Arid Regions Environmental and Engineering Research Institute), with an accuracy of ± 0.05 °C. During field experiments, a multimeter was used to manually measure probe resistance, from which debris and ice temperatures were calculated. Six observation campaigns were conducted on July 13, 18, 23, 28, August 2, and 7.

2.4 Glacier Ablation Measurements Ablation stakes were installed in the debris area near the AWS (Fig. 1) with 12 cm debris thickness. Six detailed surveys were conducted between July 13 and August 13, measuring the vertical height from stake to glacier surface. Ablation was calculated using:

$$A = \frac{m \cdot \rho_i}{\rho_w}$$

where A is ablation (m w.e.), ρ_i is glacier ice density ($900 \text{ kg} \cdot \text{m}^{-3}$), and m is the vertical height change between stake and ice surface. The resulting ablation value for the study period was 0.40 m w.e., used as validation data for the glacier ablation simulation.

2.5 Energy Balance Model for Debris-Covered Glaciers This study uses the Debris Energy Balance (DEB) model for point-scale glacier energy and ablation simulation. This mature, physically-based model comprehensively describes energy exchange processes in debris-covered areas. Compared with degree-day models, it can quantify the influence of energy components on ablation and has achieved good simulation results on Miage Glacier in the Alps and Galongla Glacier in southeastern Tibet as an open-source model. The energy balance equation is:

$$S + L + H + LE + P = G + M$$

where S is net shortwave radiation, L is net longwave radiation, H is sensible heat flux, LE is latent heat flux, P is heat flux from precipitation, G is conductive heat flux (energy loss from debris surface to ice interface), and M is melt energy (all in $\text{W} \cdot \text{m}^{-2}$).

In this model, debris surface temperature T_s and upward longwave radiation are incorporated into the energy balance equation. T_s is both an unknown in the energy balance model and a required parameter for calculating energy fluxes. All energy fluxes except solar shortwave and downward longwave radiation can be expressed as functions of T_s . Using a numerical iteration scheme with a time step of 1 hour, the Crank-Nicolson method calculates T_s by dividing debris into multiple layers.

Since energy transfer within debris exhibits nonlinear changes and diurnal energy transfer direction may reverse, unsteady heat conduction describes temperature variations within debris:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2}$$

where α is thermal diffusivity, T is temperature at a debris layer, z is depth, t is time, k is debris thermal conductivity, ρ_d and c_d are debris density ($1,496 \text{ kg} \cdot \text{m}^{-3}$) and specific heat capacity ($948 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$), respectively.

2.5.1 Shortwave Radiation Surface shortwave radiation originates from solar radiation and is the main energy source for glacier surfaces. Cloud cover significantly affects incoming shortwave radiation, and debris albedo largely determines outgoing shortwave radiation. This study uses measured incoming/reflected shortwave radiation from the AWS as model input.

2.5.2 Longwave Radiation Longwave radiation includes upward longwave radiation emitted by the surface and downward longwave radiation emitted by the atmosphere. Since the AWS lacks longwave radiation measurements, the Stefan-Boltzmann law calculates downward and upward longwave radiation. Downward longwave radiation L_{in} is:

$$L_{in} = \sigma \epsilon_{eff} T_a^4$$

where σ is the Boltzmann constant ($5.67 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$), T_a is air temperature, and ϵ_{eff} is effective emissivity (atmospheric emissivity under cloud cover), calculated using the Unsworth-Monteith method:

$$\begin{aligned}\epsilon_{eff} &= \epsilon_{cs} \cdot (1 - c) + 0.84 \cdot c \\ \epsilon_{cs} &= 0.7 + 5.95 \times 10^{-5} \cdot e_a \cdot e^{1500/T_a}\end{aligned}$$

where ϵ_{cs} is clear-sky emissivity, c is cloud cover from ERA5 reanalysis, and e_a is sea-level vapor pressure.

Upward longwave radiation L_{out} also uses blackbody radiation law, with uncertainty depending mainly on simulated debris surface temperature:

$$L_{out} = \epsilon_d \sigma T_s^4$$

where ϵ_d is debris emissivity and T_s is debris surface temperature.

2.5.3 Turbulent Heat Fluxes Energy exchange between the lower atmosphere and underlying surface due to temperature or humidity gradients is called turbulent heat, including sensible and latent heat fluxes. Turbulent heat fluxes are important components of glacier energy balance. Calculating bulk Richardson number to determine surface stability status can effectively simulate turbulent heat fluxes. This study uses the bulk aerodynamic method, assuming turbulent heat fluxes correlate with temperature, humidity, and wind speed gradients. Sensible heat flux H and latent heat flux LE are:

$$\begin{aligned}H &= \frac{\rho_a c_a k_v^2 u (T_a - T_s)}{\Phi_m \Phi_h} \\ LE &= \frac{\rho_a L_v k_v^2 u (e_a - e_s)}{\Phi_m \Phi_v}\end{aligned}$$

where ρ_a is local air density, c_a is air heat capacity, L_v is latent heat of vaporization (2.476×10^6 J · kg⁻¹ at 283 K), k_v is von Karman constant (0.41), u is near-surface wind speed, T_a is near-surface air temperature, T_s is debris surface temperature, e_a and e_s are vapor pressures of near-surface atmosphere and debris surface, z is sensor height (2 m), z_{0t} and z_{0q} are roughness lengths for heat and water vapor (same as z_0), and Φ_m , Φ_h , Φ_v are dimensionless stability functions for momentum, heat, and moisture.

In calculating latent heat flux, debris surface relative humidity is defined as 0.2 when precipitation > 0.1 mm · h⁻¹, otherwise 0.95. Richardson number Ri describes stability:

$$Ri = \frac{gz(T_a - T_s)}{T_m u^2}$$

where g is gravitational acceleration and T_m is mean temperature of T_a and T_s .

When $Ri > 0$ (stable):

$$\Phi_m = \Phi_h = \Phi_v = (1 - 5Ri)^2$$

When $Ri < 0$ (unstable):

$$\Phi_m = \Phi_h = \Phi_v = (1 - 16Ri)^{0.75}$$

2.5.4 Precipitation Heat Heat exchange between precipitation and debris P is calculated using:

$$P = \rho_w c_w r (T_r - T_s)$$

where ρ_w is water density, c_w is water specific heat ($4.18 \times 10^3 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$), r is rainfall rate, and T_r is precipitation temperature (approximated by air temperature T_a due to lack of measurements).

2.5.5 Conductive Heat Flux Heat transfer due to temperature differences within debris is called conduction. Thermal conductivity k is a key parameter describing debris's inherent ability to conduct heat. Heat transfer rate depends on temperature gradient and debris thermal properties. Debris thermal conductivity is closely related to particle size, density, pore moisture, and temperature—higher temperature and moisture increase conductivity, transferring more energy to the ice surface. The model divides debris into equal layers (0.01 m thickness) and uses Fourier's law to calculate conductive heat flux at debris surface and ice interface, approximating each layer's temperature change as linear:

$$G_{ice} = -k \frac{T_N - T_f}{h}$$

where G_{ice} is heat flux conducted to ice surface, T_N is temperature of layer N, T_f is ice melting point temperature (ice surface temperature), and h is layer thickness.

2.5.6 Glacier Ablation Melt amount below debris simulated by the energy balance model approximates glacier ablation. Ablation a is calculated from energy available for melt M :

$$a = \frac{M}{\rho_i L_f}$$

where ρ_i is ice density and L_f is latent heat of fusion.

3. Results

3.1 Model Validation Debris surface temperature reflects energy exchange degree between debris and near-surface atmosphere. Energy at the debris surface mainly transfers downward through heat conduction, allowing sub-debris melt estimation based on surface temperature and internal conduction processes. Field-observed debris temperature provides direct validation.

Simulated surface temperature and 10 cm depth temperature were compared with measurements (Fig. 2). Despite data gaps on July 21-23 and August 3-5, results show excellent agreement for surface temperature ($R^2 = 0.91$, RMSE = 1.78 °C) and good agreement at 10 cm depth ($R^2 = 0.60$, RMSE = 0.48 °C). The lower accuracy at 10 cm arises because surface temperature is calculated first from meteorological conditions, then used to compute temperatures at different depths, accumulating surface temperature errors. Time series show large diurnal surface temperature fluctuations (often >25 °C daytime, cooling rapidly at night), while 10 cm depth temperatures near the ice have smaller diurnal ranges (daytime <5 °C). Correlation analysis shows good agreement between air and debris surface temperatures ($r = 0.55$), indicating debris temperature partly reflects near-surface air temperature variations.

Simulated cumulative ablation (0.39 m w.e.) compares well with measured values (0.40 m w.e.) (Fig. 3). Although simulated ablation is generally slightly lower, overall agreement is strong ($R^2 = 0.92$, RMSE = ± 0.03 m w.e.). Discrepancies likely arise from: (1) lack of field measurements for debris properties, with calibrated values potentially differing from actual values; (2) the model not accounting for moisture evaporation and refreezing within debris; and (3) the glacier's fast movement and strong dynamic supply. Both simulated and measured cumulative ablation show 平缓 trends during low-temperature periods (e.g., minimum temperature -3.9 °C on August 13), demonstrating temperature control on ablation.

3.2 Energy Balance Characteristics Based on meteorological data, daily average ablation was 0.55 mm w.e. The glacier remained in ablation throughout the study period, with maximum daily ablation (0.88 mm w.e.) on July 28 and minimum (0.23 mm w.e.) on August 13. Cumulative ablation showed a continuous decreasing trend, highly correlated with daily mean temperature ($r = 0.73$).

Summer energy balance characteristics show net shortwave radiation as the sole energy income term (Fig. 4). Sensible heat flux is the largest expenditure (49.7%), followed by conductive heat flux (25.8%), net longwave radiation (19.8%), and latent heat flux (4.6%). Precipitation heat (<1%) is negligible.

Net shortwave radiation shows clear diurnal variation, with daily peaks exceeding $600 \text{ W} \cdot \text{m}^{-2}$ or dropping below $400 \text{ W} \cdot \text{m}^{-2}$ depending on cloud cover. From sunrise, shortwave radiation increases continuously, peaking in early afternoon ($>600 \text{ W} \cdot \text{m}^{-2}$), then decreasing until sunset. Sensible heat flux is the largest

energy loss because solar radiation heats debris significantly above air temperature, creating convective heat exchange. Afternoon sensible heat flux losses reach $-400 \text{ W} \cdot \text{m}^{-2}$, while nighttime debris cooling creates slight sensible heat gains. Conductive heat flux, net longwave radiation, and latent heat flux remain relatively stable during daytime (losses $< -200 \text{ W} \cdot \text{m}^{-2}$). Precipitation heat is essentially zero.

3.3 Ablation Characteristics Daily ablation varied significantly, with maximum rates on July 28 (0.88 mm w.e.) and minimum on August 13 (0.23 mm w.e.). The strong correlation with temperature ($r = 0.73$) confirms that meteorological conditions, especially air temperature, control ablation patterns in debris-covered glaciers.

3.4 Cloud Cover Effects Different weather conditions significantly affect meteorological and energy characteristics (Fig. 6). Cloud cover reduces incoming shortwave radiation peaks from $854 \text{ W} \cdot \text{m}^{-2}$ on clear days to $<600 \text{ W} \cdot \text{m}^{-2}$ overcast, while increasing downward longwave radiation. Air temperature is slightly higher on clear days (1.5–6 °C difference). Relative humidity shows no clear pattern, but is generally higher in overcast conditions (average ~70%) versus clear mornings (~40%). Wind speed has two daily peaks (minimum at noon, maximum near sunset), with more variation on clear days. Precipitation occurs mainly in afternoons, with more rainfall during overcast conditions (up to $0.7 \text{ mm} \cdot \text{h}^{-1}$).

Cloud cover affects energy balance components differently (Fig. 7). Net shortwave radiation at noon exceeds $750 \text{ W} \cdot \text{m}^{-2}$ on clear days but drops to $\sim 530 \text{ W} \cdot \text{m}^{-2}$ when overcast. Average net shortwave radiation increases by 20.5% on clear days and decreases by 11.9% on overcast days compared to all conditions. Although cloud cover reduces net shortwave income and sensible heat expenditure, their temporal patterns remain similar. Overcast conditions reduce net longwave radiation, latent heat flux, and conductive heat flux by ~25% compared to clear skies. Average ablation is 0.58 mm w.e. on clear days versus 0.51 mm w.e. overcast—a 12% reduction. Thus, cloud cover significantly impacts flux magnitudes but not their temporal patterns.

4. Discussion

4.1 Sensitivity Analysis Debris properties are important uncertainty sources in energy balance modeling. Sensitivity analysis identifies key parameters affecting ablation simulation. In these tests, debris albedo ($\alpha = 0.086$) was calculated from AWS shortwave radiation measurements, while other parameters were calibrated from literature [12, 28]. We selected debris thermal conductivity (k), surface roughness (z_0), emissivity (d), and albedo (α) as sensitivity parameters.

For Qingbingtan Glacier No. 72, baseline $k = 0.94 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. Increasing k by 0.2 and $0.4 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ increased ablation by 17.8% and 35.7%, respectively. Baseline roughness $z_0 = 0.016 \text{ m}$; increasing by 0.01 and 0.02 m decreased ablation by 18.4% and 38.3%. Emissivity $d = 0.94$; increasing by 0.01 and 0.03 decreased ablation by 4.6% and 7.7%. Albedo $\alpha = 0.086$; increasing by 0.02 and 0.03 decreased ablation by 8.2% and 11.5%.

All parameters except conductivity show negative correlation with ablation. Thermal conductivity is the most sensitive parameter. Albedo and roughness also show significant sensitivity, though their variation range in debris areas is limited. Emissivity changes have minimal impact. Therefore, debris-covered glacier simulations should prioritize field observations of thermal conductivity, plus careful selection of roughness and albedo values, as small changes substantially affect results. Future work should strengthen field measurements to reduce uncertainty.

4.2 Comparison with Other Debris-Covered Glaciers To better understand energy balance characteristics, we compared different mountain glaciers (Table 4). West Qiongtailan and Keqikare glaciers in the Tomor region share similarities with Qingbingtan No. 72: large area, extensive ice cliffs and supraglacial lakes. West Qiongtailan Glacier ($>100 \text{ km}^2$, terminus $\sim 4,000 \text{ m}$) shows significant differential ablation, with net radiation accounting for 80% of energy income, sensible heat 10.5%, and condensation latent heat only 9.5%. At 4,200 m on Keqikare Glacier, June-August mean temperature is $\sim 5^\circ \text{C}$ (maximum 20°C), with strong solar radiation and 70% of annual precipitation during these months, reducing energy exchange. Han et al. [30] simulated ablation energy of $123 \text{ W} \cdot \text{m}^{-2}$ for this glacier.

Galongla Glacier in southeastern Tibet shows similar energy flux distribution to Qingbingtan No. 72, with differences only in net shortwave and latent heat fluxes, likely due to lower latitude (more shortwave radiation) and East Asian monsoon influence (higher moisture content). Compared with Qingbingtan No. 72, Miage Glacier in the Alps receives more solar radiation but has $>5 \text{ W} \cdot \text{m}^{-2}$ greater net longwave radiation loss and huge conductive heat flux consumption, resulting in lower available melt energy. Lirung Glacier in the Himalayas (terminus $\sim 4,000 \text{ m}$) has much higher ablation rates. Karakoram glaciers at higher latitudes receive significantly less shortwave radiation; Collier et al. [43] simulated positive sensible and conductive heat fluxes there, unlike other point-scale studies showing energy losses for all terms except net shortwave, indicating that model scale and spatial resolution importantly affect results.

Overall, regional glacier ablation depends on local circulation and surface meteorological conditions, while different energy balance models and parameterization schemes also affect simulation accuracy.

5. Conclusions and Outlook

This study simulated ablation of Qingbingtan Glacier No. 72 in Mt. Tomor, a region with abundant ice and snow water resources (average annual runoff $\sim 63.4 \times 10^8 \text{ m}^3$, $\sim 70\%$ from melt) and numerous debris-covered glaciers. Differential ablation from debris cover challenges mass balance and runoff assessment. Using hourly AWS data and a debris energy balance model, we simulated sub-debris melt and validated results with field measurements. Key conclusions:

- 1) Simulated ablation was 0.39 m w.e., matching measured ablation (0.40 m w.e.) with good accuracy ($R^2 = 0.92$, $\text{RMSE} = \pm 0.03 \text{ m w.e.}$). Simulated debris surface and internal temperatures agreed well with observations.
- 2) In the debris-covered area, net shortwave radiation was the sole energy income term and main energy source; all other terms were losses. Sensible heat flux was the largest expenditure (49.7%), followed by conductive heat flux (25.8%), net longwave radiation (19.8%), and latent heat flux (4.6%). Precipitation heat ($< 1\%$) was negligible.
- 3) Different weather conditions significantly affected meteorological and energy variations but not their temporal patterns. Cloud cover strongly influenced incoming shortwave radiation, downward longwave radiation, and relative humidity. Overcast conditions reduced net shortwave radiation flux and other radiation fluxes by $\sim 25\%$ compared to clear skies, decreasing average ablation by 12%.
- 4) Sensitivity tests showed simulated ablation was most sensitive to thermal conductivity changes; albedo and surface roughness changes were also important, while emissivity had minimal impact.

This study only addressed point-scale ablation simulation. Since meteorological and topographic conditions vary greatly across glaciers, future work should: (1) improve spatiotemporal characterization of meteorological elements to optimize parameterization schemes at larger scales; (2) enhance field observations and modeling of debris thickness and thermal conductivity to better drive ablation models; and (3) develop glacier dynamic parameterization schemes coupled with energy balance models to study glacier dynamics and motion impacts on ablation.

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References

- [1] Shi Yafeng. Estimation of the water resources affected by climatic warming and glacier shrinkage before 2050 in West China[J]. Journal of Glaciology and Geocryology, 2001, 23(4): 333-341.
- [2] Yao Tandong, Liu Shiyin, Pu Jianchen, et al. Recent recession of High Asian

- glaciers and their impacts on water resources in Northwest China[J]. *Science in China Series D Earth Sciences*, 2004, 34(6): 535-543.
- [3] Bates B, Kundzewicz Z W, Wu S, et al. *Climate Change and Water*. Technical Paper VI[M]. Intergovernmental Panel on Climate Change (IPCC), 2008.
- [4] Liu Shiyin, Zhang Yong, Liu Qiao, et al. *Study on the Impact of Climate change on Glacier and Its Risk*[M]. Beijing: Science Press, 2017.
- [5] Östrem G. Ice melting under a thin layer of moraine, and the existence of ice cores in moraine ridges[J]. *Geografiska Annaler*, 1959, 41(4): 228-230.
- [6] Nakawo M, Young G J. Field experiments to determine the effect of a debris layer on ablation of glacier ice[J]. *Annals of Glaciology*, 1981, 2: 85-91.
- [7] Nicholson L, Benn D I. Calculating ice melt beneath a debris layer using meteorological data[J]. *Journal of Glaciology*, 2006, 52(178): 463-470.
- [8] Evatt G W, Abrahams I D, Heil M, et al. Glacial melt under a porous debris layer[J]. *Journal of Glaciology*, 2015, 61(229): 825-836.
- [9] Giese A, Boone A, Wagnon P, et al. Incorporating moisture content in surface energy balance modeling of a debris-covered glacier[J]. *The Cryosphere*, 2020, 14(5): 1555-1577.
- [10] Rounce D R, Quincey D J, McKinney D C. Debris-covered glacier energy balance model for Imja-Lhotse Shar Glacier in the Everest region of Nepal[J]. *The Cryosphere*, 2015, 9(6): 2295-2310.
- [11] Han Haidong, Wang Jian, Wei Junfeng, et al. Backwasting rate on debris-covered Koxkar glacier, Tuomuer mountain, China[J]. *Journal of Glaciology*, 2010, 56(196): 287-296.
- [12] Yang Wei, Yao Tandong, Zhu Meilin, et al. Comparison of the meteorology and surface energy fluxes of debris-free and debris-covered glaciers in the southeastern Tibetan Plateau[J]. *Journal of Glaciology*, 2017, 63(242): 1090-1104.
- [13] Zhang Yong, Fujita K, Liu Shiyin, et al. Distribution of debris thickness and its effect on ice melt at Hailuoguo Glacier, southeastern Tibetan Plateau, using in situ surveys and ASTER imagery[J]. *Journal of Glaciology*, 2011, 57(206): 1147-1157.
- [14] Zhang Yong, Liu Shiyin. Research progress on debris thickness estimation and its effect on debris-covered glaciers in western China[J]. *Acta Geographica Sinica*, 2017, 72(9): 1606-1620.
- [15] Xie Changwei, Ding Yongjian, Liu Shiyin, et al. Runoff change on the South slopes of Mount Tomur and its response to climatic variation[J]. *Journal of Glaciology and Geocryology*, 2005, 27(2): 269-275.
- [16] Chen Yaning, Li Zhi, Fan Yuting, et al. Research progress on the impact of climate change on water resources in the arid region of Northwest China[J]. *Acta Geographica Sinica*, 2014, 69(9): 1295-1304.

- [17] Shi Yafeng. China Concise Glacier Inventory[M]. Shanghai: Shanghai Popular Science Press, 2005.
- [18] Mountaineering Expedition of Chinese Academy of Science. Glaciers and Meteorology in the Tumor Region of the Tianshan Mountains[M]. Urumqi: Xinjiang People's Press, 1985.
- [19] Aizen V B, Aizen E M, Melack J M. Precipitation, melt and runoff in the northern Tien Shan[J]. Journal of Hydrology, 1996, 186(1): 97-117.
- [20] Li Zhongqin, Li Kaiming, Wang Lin. Study on recent glacier changes and their impact on water resources in Xinjiang, Northwestern China[J]. Quaternary Sciences, 2010, 30(1): 96-106.
- [21] Wang Puyu, Li Zhongqin, Cao Min, et al. Variation of Qingbingtan Glacier No.72 in Mt. Tuomuer region during past 45 years[J]. Scientia Geographica Sinica, 2010, 30(6): 962-967.
- [22] Wang Puyu, Li Zhongqin, Wang Wenbin, et al. Changes of six selected glaciers in the Tomor region, Tian Shan, Central Asia, over the past 50 years, using high resolution remote sensing images and field surveying[J]. Quaternary International, 2013, 311: 123-133.
- [23] Wang Puyu, Li Zhongqin, Li Huilin, et al. Characteristics of a partially debris-covered glacier and its response to atmospheric warming in Mt. Tomor, Tien Shan, China[J]. Global and Planetary Change, 2017, 159: 11-24.
- [24] Fang Xiaoyu, Li Zhongqin, Bernd Wuennemann, et al. Physical energy balance and statistical glacier melting models comparison and testing for Shiyi Glacier, Heihe River Basin, Qilian Mountains, China[J]. Journal of Glaciology and Geocryology, 2015, 37(2): 336-350.
- [25] Che Yanjun, Zhang Mingjun, Li Zhongqin, et al. Understanding the mass balance characteristics of Qingbingtan Glacier No. 72 during the period of 2008-2014[J]. Journal of Glaciology and Geocryology, 2020, 42(2): 318-331.
- [26] Wang Puyu, Li Zhongqin, Li Huilin, et al. Ice surface elevation change and velocity of Qingbingtan glacier No. 72 in the Tomor region, Tianshan Mountains, Central Asia[J]. Journal of Mountain Science, 2011, 8(6): 855-864.
- [27] Huai Baojuan, Li Zhongqin, Sun Meiping, et al. Glaciers change in the Tailan River watershed in the last 40 years[J]. Scientia Geographica Sinica, 2014, 34(2): 229-236.
- [28] Cao Min, Li Zhongqin, Li Huilin. Features of surface flow velocity on the Qingbingtan Glacier No. 72, Tianshan Mountains[J]. Journal of Glaciology and Geocryology, 2011, 33(1): 21-29.
- [29] Kou Youguan, Ding Liangfu, Li Wenzheng, et al. Glacial meteorology on Mt. Tuomuer[J]. Journal of Glaciology and Geocryology, 1980, 2(4): 11-14.

- [30] Han Haidong, Liu Shiyin, Ding Yongjian, et al. Near surface meteorological characteristics on the Koxkar Baxi Glacier, Tianshan[J]. *Journal of Glaciology and Geocryology*, 2008, 30(6): 967-975.
- [31] Han Haidong, Ding Yongjian, Liu Shiyin. Estimation and analysis of heat balance parameters in the ablation season of debris-covered Kerqikaer Glacier, Tianshan Mountains[J]. *Journal of Glaciology and Geocryology*, 2005, 27(1): 88-94.
- [32] Van Den Broeke M, Reijmer C, Van As D, et al. Daily cycle of the surface energy balance in Antarctica and the influence of clouds[J]. *International Journal of Climatology*, 2006, 26(12): 1587-1605.
- [33] Reid T D, Brock B W. An energy balance model for debris-covered glaciers including heat conduction through the debris layer[J]. *Journal of Glaciology*, 2010, 56(199): 903-916.
- [34] Idso S B. A set of equations for full spectrum and 8-to 14- m and 10.5-to 12.5- m thermal radiation from cloudless skies[J]. *Water Resources Research*, 1981, 17(2): 295-304.
- [35] Unsworth M H, Monteith J L. Long wave radiation at the ground I. Angular distribution of incoming radiation[J]. *Quarterly Journal of the Royal Meteorological Society*, 1975, 101(427): 13-24.
- [36] Brutsaert W. *Evaporation into the Atmosphere: Theory, History and Applications*[M]. New York: Springer, 1982.
- [37] Oke T R. *Boundary Layer Climates*[M]. 2nd ed. New York: Routledge, 1987.
- [38] Moore R D. On the use of bulk aerodynamic formulae over melting snow[J]. *Hydrology Research*, 1983, 14(4): 193-206.
- [39] Xie Zichu, Liu Chaohai. *Introduction to Glaciology*[M]. Shanghai: Shanghai Science Popularization Press, 2010.
- [40] Brock B W, Mihalcea C, Kirkbride M P, et al. Meteorology and surface energy fluxes in the 2005-2007 ablation seasons at the Miage debris-covered glacier, Mont Blanc Massif, Italian Alps[J]. *Journal of Geophysical Research: Atmospheres*, 2010, 115(D9106): 1-16.
- [41] Strasser U, Corripio J, Pellicciotti F, et al. Spatial and temporal variability of meteorological variables at Haut Glacier d'Arolla (Switzerland) during the ablation season 2001: Measurements and simulations[J]. *Journal of Geophysical Research: Atmospheres*, 2004, 109(D03103): 1-18.
- [42] Steiner J F, Pellicciotti F, Buri P, et al. Modelling ice cliff backwasting on a debris-covered glacier in the Nepalese Himalaya[J]. *Journal of Glaciology*, 2015, 61(229): 889-907.

[43] Collier E, Maussion F, Nicholson L I, et al. Impact of debris cover on glacier ablation and atmosphere-glacier feedbacks in the Karakoram[J]. The Cryosphere, 2015, 9(4): 1617-1632.

[**Figure 1: see original paper**] Map of study area
[**Figure 2: see original paper**] Simulated and measured debris temperature at surface and depth of 10 cm
[**Figure 3: see original paper**] Simulated and measured glacier melt
[**Figure 4: see original paper**] Mean diurnal variation of debris surface heat fluxes components
[**Figure 5: see original paper**] Hourly variation of debris surface heat fluxes components
[**Figure 6: see original paper**] Effects of different weather conditions on meteorological elements
[**Figure 7: see original paper**] Effects of different weather conditions on radiation fluxes

**** Meteorological sensors and their indicators of the automatic weather station
**** Mean fluxes and variation under different weather conditions
**** Sensitivity analysis of debris parameters
**** Surface heat fluxes components of debris-covered glaciers in different regions

Note: Figure translations are in progress. See original paper for figures.

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