The energy and mass balance of a continental glacier: Dongkemadi Glacier in central Tibetan Plateau

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Understanding glacier mass balance (MB) change under global warming is important to assess the impact of glacier change on water resources. This study evaluated the applicability of a modified distributed surface energy balance model (DSEBM) with 3–h temporal and 100-m spatial resolution to the alpine Dongkemadi Glacier (DKMD) in the central Tibetan Plateau region, analyzed the causes of glacier MB variations with respect to energy balance, and evaluated MB changes under various climate scenarios. Results showed that: (i) the modified model can describe surface energy and MB of XDKMD well; (ii) net shortwave and longwave radiation, accounting for more than 80% of total heat flux, dominated the glacier energy balance during both summer and winter months; (iii) summer MB spatial patterns dominated annual MB, consistent with the fact that DKMD is a summer accumulation type glacier; and (iv) effect of increase in air temperature on glacier MB is higher than that of decrease in air temperature. The sensitivity of MB revealed by the modified DSEBM can help to understand MB changes influenced by the climate changes and to regulate water management strategies to adapt to climate changes at the catchment scale.

Glaciers are sensitive climate indicators1, and have been shrinking globally for the past decades with some localized exceptions (e.g., eastern Pamir Plateau and central Karakoram)1–3. Due to that glaciers store important water resources in the form of snow and ice (~75% of the world’s freshwater), contributing significantly to runoff, especially in mountainous areas, changes of glaciers exert a considerable influence on mountainous watershed hydrology, and indirectly have a significant and lasting impact on local and downstream ecosystems and populations4–10. Because of environmental lapse rates and orographic lifting (and associated cloudiness)11, many high-elevation catchments are energy-limited where much of the globe’s important fresh water resources are conserved12,13. The impacts of climate warming could vary considerably between different glaciers14–17, inducing different hydrological responses in glacierized mountainous basins.

The Tibetan Plateau and its surrounding area contain the largest number of the glaciers (with an area of ~100,000 km²) outside the Polar Regions14, and 78% of them are continental14, which has been regarded as the Asian Water Tower and supporting 1.4 billion people10. Evidence showed that most of the glaciers (excluding the Karakoram) are retreating influenced by the climate changes on the Tibetan Plateau14. Glacier changes on the Tibetan Plateau could have affected the water discharge of large rivers3,19,20, glacial lake level and area21–23, and glacial lake outburst floods and debris flows24–26. In this context, the characteristics and changes in energy and mass balance of glacier on the Tibetan Plateau have drawn great attention to describe the melt processes which is used to explain the changes in glaciers27. An integrated assessment of glacier status (area, length and elevation) and in situ measurement have been conducted to understand the glacier status and mass balance on and around the Tibetan Plateau. So far 15 glaciers have undergone continuous mass balance observation14.

Based on the in situ observations of meteorology and MB on glacier surface and improvements in the understanding of physical processes of ablation and accumulation, process-based studies at point scale are crucial for process understanding and can shed light on the physics of the interaction between glaciers and climate28,29.

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Promoted by increased availability of digital terrain models and computational power, the distributed surface energy balance model (DSEBM) that takes the spatial heterogeneity of the melt process into account was developed. Physical process based distributed modelling can reveal the most important variables and water balance components, as well as the locations that should be monitored. Up to now, few studies provided comprehensive information of glacier mass and energy balance and its sensitivity to climate change, especially on the Tibetan Plateau (Table S1). Consequently, our objectives are: (i) to evaluate the applicability of the modified DSEBM model improved in the albedo and ground heat flux calculations; (ii) to understand and determine the drivers of glacier MB change; and (iii) to evaluate glacier MB under various climate scenarios and its sensitivity in DKMD Glacier in the central Tibetan Plateau (Fig. 1). The above three objectives will further improve the understanding of the mechanisms of change, provide a more comprehensive and systematic knowledge of the DKMD Glacier, and lay a foundation for investigating future changes in the ablation and hydrology of DKMD Glacier under a changing climate. This study will also contribute to the understanding of the overall glacier change on the Tibetan Plateau.

Results

Model calibration and validation in XDKMD. The calibrated parameters and their values used in DSEBM are provided in Table S2. The albedo parameters \(a_1 \ldots a_4, b_0\) and \(b_1\) were calibrated using local observations and hence differ from those for Qiyi Glacier where the formulas were developed. The air temperature lapse rate \((-0.65^\circ C/100\ m)\) was first calculated using gridded data for this area and then locally calibrated. The precipitation gradient with elevation was 0.01 mm/(3–h 100 m), which first adopted the value for Nyainqentanglha region (a sub-region of Tibetan Plateau including DKMD Glacier) and then was locally calibrated.

The albedo simulation was generally acceptable for the 1993 calibration period, although it was a little low for September (Fig. 2; RMSE = 0.05 mm w.e., \(R^2 = 0.23\)). The relative error was only 8.10%. Albedo decreased when air temperature increased as shown in Eqs (9–10) and Table S2. The underestimated albedo in September was caused by a rise in air temperature, which was from \(-6.9^\circ C\) on September 3 to \(-2.5^\circ C\) on September 12. The underestimation of albedo demonstrates the importance of the quality of meteorological forcing data. MB simulations at all stakes situated from 5480 m to 5690 m AMSL were acceptable for the 1993 calibration period (Fig. 3a; NS = 0.90, \(R^2 = 0.93\) and RMSE = 67.19 mm w.e.). During the 1992 validation year, the simulated MB was slightly higher than observed values at the top two stakes (at 5680 m and 5690 m AMSL) and lower at the bottom two stakes (at 5480 m and 5510 m AMSL) (Fig. 3b). Generally, the validation period simulation was reasonably good (NS = 0.80, \(R^2 = 0.93\) and RMSE = 71.14 mm w.e.).
Mass and surface energy balance in the entire DKMD. Taking 1993 MB for an example (Fig. 4), most of the DKMD Glacier experienced accumulation. MB for the entire glacier was 157, 68 and 88 mm w.e. for the whole year, summer and winter, respectively. Correspondingly, ELA was 5538, 5560 and 5391 m, respectively.

Figure 2. Variation of daily albedo. Red dots are in situ field observations made at AWS located at 5600 m shown on Fig. 1(c) and black line is simulations. The regression equation between observed and simulated albedo, $R^2$, RMSE and relative error (RE) were presented. RE calculated by $(\text{RMSE/mean}) \times 100\%$. The mean is of observed albedo.

Figure 3. Comparison between simulated and observed glacier MB at 19 stakes on the XDKMD Glacier: (a) calibration period 1993; (b) validation period 1992. The location of the stakes is shown in Fig. 1(c).

Figure 4. Spatial distributions in 1993 (a) annual, (b) summer, and (c) winter glacier MB of the DKMD Glacier. Black cells denote equilibrium lines. This figure was plotted using the Generic Mapping Tools (GMT) V4.5.0 https://www.soest.hawaii.edu/gmt/).
In winter, almost the entire glacier experienced accumulation and MB varied little spatially (Fig. 4c), while in summer (Fig. 4b) and over the whole year (Fig. 4a), MB varied substantially, from about −1.4 m w.e. at the glacier tongue to greater than 0.8 m w.e. at high elevations. The spatial pattern of annual MB was similar with summer.

Variabilities of daily energy components are shown in Fig. 5. Net shortwave radiation ($S_{net}$) was directed towards the surface and varied largely during the year, with high values in summer (65 W m$^{-2}$ in average) and low values in winter (34 W m$^{-2}$ in average) (Table 1). Besides solar altitude, glacier surface albedo also played a main role in seasonal variation of $S_{net}$. For the entire DKMD Glacier, albedo was 0.75 on average in winter and 0.54 on average in summer. Net longwave radiation ($I_{net}$) varied less than $S_{net}$ during a year (Fig. 5a), with an average of 39 W m$^{-2}$ in summer and 42 W m$^{-2}$ in winter, and was directed away from glacier surface. The reason is that incoming and outgoing longwave radiations have similar seasonal patterns and outgoing longwave radiation

|          | Winter (Oct. 7–May 4) | Summer (May 5–Oct. 6) | Year (Oct. 7–Oct. 6) |
|----------|------------------------|------------------------|----------------------|
|          | W m$^{-2}$ | %        | W m$^{-2}$ | %        | W m$^{-2}$ | %        |
| $S_{net}$ | 34↑       | 35↓       | 65↑       | 55↓       | 48↑       | 45↓       |
| $I_{net}$ | 42↑       | 43↑       | 39↑       | 32↑       | 41↑       | 38↑       |
| $Q_H$    | 15↑       | 15↑       | 8↑        | 7↑        | 12↑       | 11↑       |
| $Q_L$    | 6↑        | 6↑        | 5↑        | 5↑        | 0         |
| $Q_G$    | 0.9↓      | 1↓        | 1.2↑      | 1↑        | 0.1↓      | 0         |
| $Q_M$    | 0.0       | 0         | 0.2↓      | 0         | 0         |
| Sum      | 98        | 100       | 103       | 100       | 106       | 100       |

Table 1. Energy components and the percentage of each energy component in relation to the sum of all energy components in 1993. ↑ is energy flux directed away from the surface; ↓ is energy flux directed towards the surface.

Figure 5. Daily energy components of DKMD Glacier in 1993. (a) Net shortwave radiation $S_{net}$, net longwave radiation $I_{net}$ and net radiation $R_n$; (b) Turbulent sensible heat flux $Q_H$ and turbulent latent heat flux $Q_L$; (c) Ground heat flux $Q_G$ and the melting component $Q_M$.
is much higher. Turbulent $Q_{th}$ directed towards the glacier surface indicates that heat was transferred from air to glacier surface. $Q_{th}$ was higher and more varied in winter than in summer, because of the larger difference between air temperature and surface temperature and the higher wind speed in winter than in summer (Fig. 5b).

As shown in Table 1 the radiation heat flux ($S_{net}$ and $L_{net}$) was the most important component of the energy balance and accounted for 83% of the annual heat flux together. The ratio of $S_{net}$ to total energy was higher in summer while that of $L_{net}$ was higher in winter. Therefore, $R_{n}$ contributed towards causing glacial melt in the summer but reduced melting in the winter. Turbulent $Q_{th}$ and $Q_{s}$ accounted for 11% and 5% of the annual heat flux, respectively. $Q_{th}$ contributed a little to the seasonal variation of energy. The contribution of $Q_{th}$ and $Q_{s}$ can both be neglected for annual heat flux.

**Table 2.** Simulated changes of surface MB under different scenarios.

| Scenarios | Temperature (°C) | Precipitation (%) | Change of MB (m w.e.) |
|-----------|------------------|-------------------|----------------------|
| 1         | −1               | −20               | 0.00                 |
| 2         | −1               | 0                 | 0.23                 |
| 3         | −1               | 20                | 0.45                 |
| 4         | 0                | −20               | −0.23                |
| 5         | 0                | 20                | 0.22                 |
| 6         | 1                | −20               | −0.56                |
| 7         | 1                | 0                 | −0.32                |
| 8         | 1                | 20                | −0.11                |

**Sensitivity of mass balance in the entire DKMD.** The response of MB to various scenarios of climate change showed (Table 2): (i) to some extent, increasing precipitation offset effects of increasing air temperature, and vice versa; (ii) for a certain magnitude, wetting and drying effects are roughly equivalent. E.g., when temperature remains unchanged, 20% decrease (or increase) in precipitation will cause 0.23 m w.e. decrease (or 0.22 m w.e. increase) in MB; and (iii) for a certain magnitude, warming effect is higher than cooling effect. E.g., when precipitation remains unchanged, 1 °C increase in air temperature will cause 0.33 m w.e. decrease in MB, which is much higher than effect of 1 °C decrease (0.23 m w.e.). Therefore, effect of 1 °C increase can be offset by a 20% decrease in precipitation, while to offset 1 °C warming, about a 30% increase in precipitation is required. The important reason is that the ratio of snow to precipitation will decrease/increase, when air temperature increase/decrease.

**Discussion**

**Glacier mass and surface energy balance.** Summer and annual MB spatial patterns were similar, indicating the summer MB change dominance in annual MB change. This was because most precipitation (85% of annual total amount) and melting occurred in summer (see section 2.1). The similar MB for summer and winter was due to strong melting consuming most of the precipitation in summer. The similar spatial patterns of MB in summer and the whole year proved that DKMD is a summer accumulation glacier, and is much more sensitive to air temperature change in contrast with winter accumulation glaciers. This is because in summer air temperature is near or above 0 °C whereas in winter air temperature is much lower than 0 °C (see section 2.1). The slight increase in air temperature in summer will facilitate the glacier melt greatly compared to the effects of equivalent absolute increase of air temperature in winter.

Seasonal variations in the melt rate of DKMD Glacier were controlled by the seasonality of the energy balance (Fig. 5c). Glacier melting occurred in summer, and energy for melting $Q_{th}$ was mainly provided by $S_{net}$ (Fig. 5a,c). Turbulent heat flux and $Q_{s}$ also provided energy for melting, but their contributions were very little. Over all, $Q_{th}$ consumed energy during the summer period, although condensation released limited energy. In winter, $L_{net}$ dominated the radiation balance and led to negative $R_{n}$. Although the positive turbulent heat flux, i.e. $Q_{th}$ and $Q_{s}$, compensated negative heat flux to some extent, not enough energy was available for melting.

**Sensitivity of MB to climate changes.** As shown in Table 2, MB change reflected the complex influence of climate changes in DKMD. For DKMD Glacier, MB changed −0.21 m w.e. during melting season when air temperature increases 1 °C (in the region near ELA). Consistent with our result, a similar result were also reported by Zhang et al. with a MB change of −0.18 m w.e.. Precipitation and air temperature are two key factors affecting glacier by controlling accumulative and melting processes, respectively. For precipitation, change of MB from precipitation −20% to actual conditions is roughly equivalent to that from actual conditions to precipitation +20%, due to their similar effects on glacier surface (e.g., snow conditions and albedo), in addition to direct effect of precipitation change. Interestingly, the sensitivity of MB to air temperature varies with increasing air temperature (shown in Table 2), that is to say, absolute MB change increased with the increase in temperature.
when precipitation change kept constant (e.g., when precipitation remains changed, the absolute change of MB is 0.33 m w.e. from actual conditions to temperature +1 °C, which is higher than that from temperature −1 °C to actual conditions (0.23 m w.e.). The reason is that the altered glacier surface due to melting caused by warming has lower albedo and then obtains more energy for melting. Furthermore, historical observation from a nearby meteorological station (Tuotuohe) reveals that air temperature increased 1.37 °C and precipitation increased 13% in the past 50 years. This means that MB will most likely decrease but with high annual variability in the future, since increasing precipitation can not totally offset effect of increasing air temperature in the DKMD glacier.

Effects of warming on MB of DKMD Glacier in contrast with Qiyi Glacier. Due to different ambient atmosphere conditions, sensitivity of glacier MB accordingly exhibited different patterns. DKMD Glacier (located in inner Tibetan Plateau) exhibited lower sensitivity to climate change than other glaciers when comparing entire glaciers, and was relative stationary. E.g., 1 °C warming will cause MB to decrease less than 0.25 m w.e. for DKMD Glacier, while will cause a MB decrease of more than 1.00 m w.e. for Qiyi Glacier (See Fig. 1a for location, a continental glacier located in middle Qilian Mountain on northeastern TP) during the two periods July 1 to October 9 and June 30 to September 5. While, MB of DKMD Glacier is more sensitive than Qiyi Glacier to 1 °C warming in summer in comparison made in the regions near ELA of each glacier, which divides the accumulation and ablation areas and is generally considered as the most sensitive one to climate change among the glacier parameters. The reason for the contradiction between the two comparisons lies in the compared regions (partial glacier or entire glacier), that is to say, the ratio of accumulation area to total glacier area plays a vital role. The accumulation area covers about half of DKMD Glacier, which is much larger than Qiyi Glacier with accumulation area ratio of about 15%. From this perspective, stability of DKMD Glacier induced by high ratio of accumulation area alleviates the response of glacier MB to climate warming.

Study area, methods and data. Study area. As one of the only two glaciers with relatively long-term MB observational studies on Tibetan Plateau (See Supplementary Information), the DKMD Glacier, situated in the mid-Tanggula Mountains, central Tibetan Plateau region, is an alpine glacier that comprises part of the headwaters of the Yangtze River (Fig. 1a). The entire DKMD Glacier has an area of 15.87 km² in 2010, extending from 5278 m to 6087 m AMSL. The DKMD Glacier is composed of the south facing Da Dongkemadi Glacier (Da DKMD, 14.14 km², and 5278–6087 m AMSL) and the southwest facing XDKMD Glacier (1.73 km², and 5372–5912 m AMSL) (Fig. 1b). Both Da DKMD and XDKMD have a similar elevation range, topography and climatology which justify the evaluations conducted on the XDKMD and the application of the model to the entire DKMD. The headwater region of the Yangtze River is under the influence of the Westerlies between October and April which results in an average air temperature of −11.6 °C, 20% of the annual total precipitation, and an average wind speed of 4.3 m s⁻¹. The region is subjected to monsoon influences between May and September with an average air temperature of about −4 °C, 80% of the annual total precipitation, and average wind speed of 3.4 m s⁻¹.

Based on 1992–1993 Aanderaa automatic weather station (AWS) observations at 5600 m on XDKMD which is also the equilibrium line altitude (ELA) (Fig. 1c), the annual mean daily air temperature is approximately −10 °C with an annual range of −26.5 to 2.7 °C, changing dramatically with seasons. Only 38 d a⁻¹ had daily mean air temperatures exceeding 0 °C, mostly occurring in August. Annual precipitation at 5500 m AMSL is approximately 909 mm, 85% of which occurred between May–September.

Methods. The DSEBM model is a fully distributed surface energy balance model. Combined with snowfall, this model can indirectly generate mass balance by converting its energy available for melting into melt water equivalent. It computes each energy component and its contribution to glacier ablation as follows:

\[
S \downarrow (1 - \alpha) + L \downarrow + L \uparrow + Q_R + Q_L + Q_G + Q_K + Q_M = 0
\]

where \(S\downarrow\) is incoming solar radiation; \(\alpha\) is albedo; \(L\downarrow\) is incoming longwave radiation; \(L\uparrow\) is outgoing longwave radiation; \(Q_R\) is sensible heat flux; \(Q_L\) is latent heat flux; \(Q_G\) is ground heat flux in ice or snow; \(Q_K\) is energy supplied by rain; and \(Q_M\) is energy available for melt. The effects of subsurface melting are not considered. Energy fluxes directed towards the glacier surface are positive. Units are W m⁻². \(Q_M\) is converted into melt water equivalent and corrected for the mass transfer by sublimation or condensation, hence referred to as ablation. Then combined with snowfall converted to water equivalent, mass balance is obtained.

The computations of \(L\downarrow, Q_R, Q_L\) and \(Q_K\) in Eq. (1) follow Hock & Holmgren. Ground heat flux was calculated using a temperature profile \((\partial T/\partial z)\) during a given time span, instead of linear interpolation during the entire melting period. Albedo was computed using a more feasible method developed on Tibetan Plateau by Jiang et al. The freezing process was calculated using a simplified method. The detailed computation of the above energy component and parameter are in Supplementary Information. The air temperature used to divide snowfall and rainfall is adopted from Cuo et al. Precipitation is pure rainfall when air temperature \(> = 3.4 °C\), and pure snowfall when air temperature \(< = 1.6 °C\). Within the range 1.6–3.4 °C, the proportions of snowfall and rainfall are obtained from linear interpolation.

On account of the availability of detailed observations of albedo and MB for the XDKMD Glacier, model applicability is tested on the XDKMD Glacier (Fig. 1). After the test, the model is applied to the entire DKMD Glacier. To assess the response of MB to various scenarios of climate change, eight scenarios were created with air temperature change (±1 °C) and precipitation change (±20%).
Data. Data included observed meteorological forcing, glacier surface MB, albedo, and elevation records. Meteorological forcing data included air temperature, wind speed, relative humidity, precipitation, incoming shortwave radiation, and incoming longwave radiation. MB and albedo were used to calibrate and evaluate the model. The model was run at a 3-h time interval but evaluated at a daily time step. Glacier surface mass balance was calculated for the simulation period 1992–1993, which was justified by the slow glacier change before 1990s and dramatic change after 1990s.[25] The 0.003768° (400 m) glacier map from the GLIMS database was also converted to a 100 m map to match the model DEM resolution and to obtain the spatial distribution of the glacier in the model. The glacier map was based on materials in 1970 and therefore correlated according to the field trip in 1993.

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Author Contributions
L.L. and L.C. designed the project and collected data. L.L. performed the simulation and wrote the paper. All authors discussed the results and commented on the manuscript.

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