Development of a Water and Enthalpy Budget-based Glacier mass balance Model (WEB-GM) and its preliminary validation

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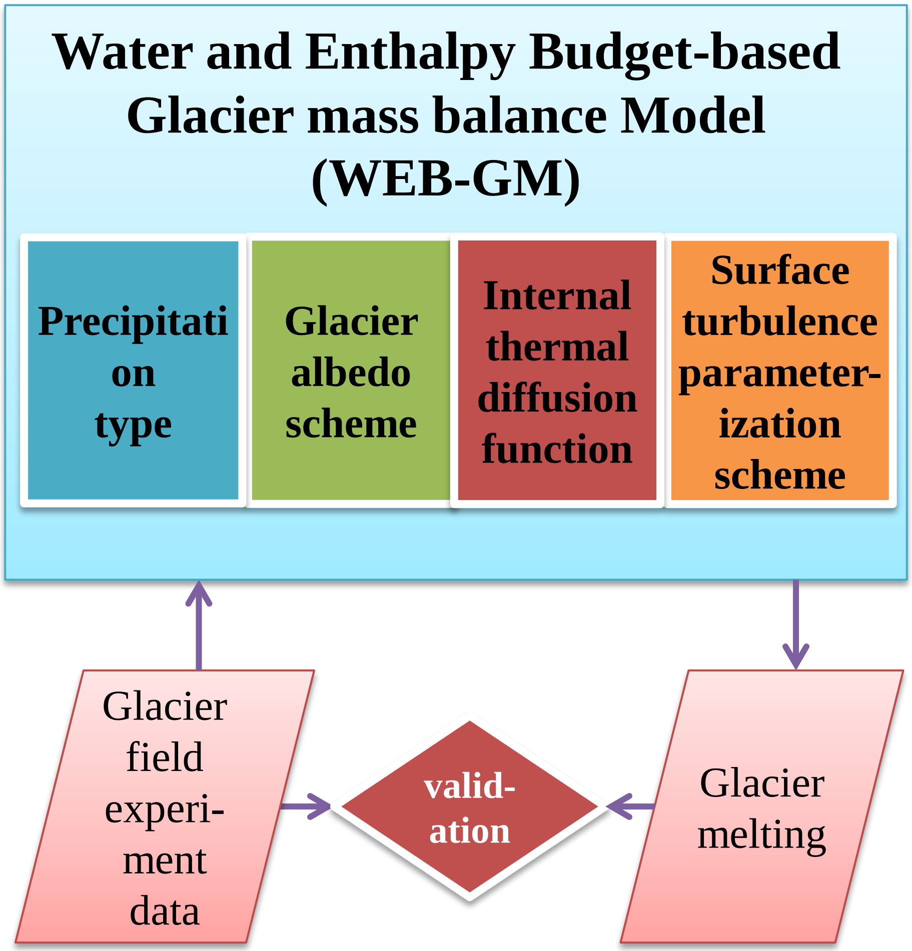
Introduction

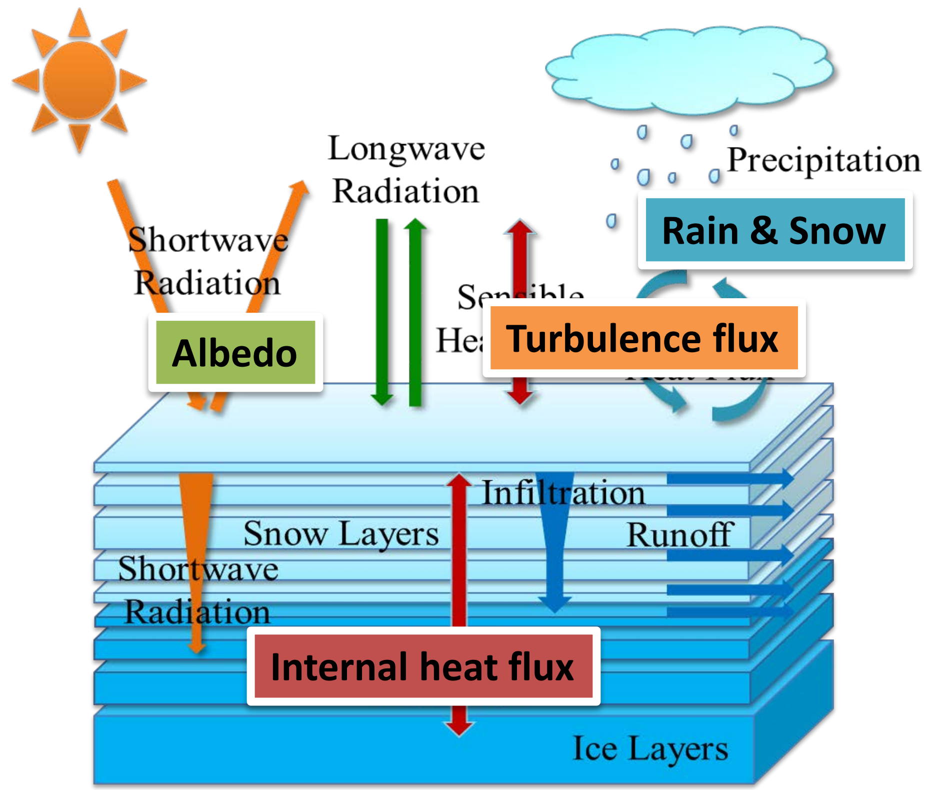
- Glacier mass balances have crucial impacts on the hydrological cycle and play an important role in stabilizing seasonal river hydrographs. Meanwhile, glacier melting can also induce local disasters such as downstream lake outbursts.
- Therefore, it is very important to understand glacier mass balances and to predict their changes.
- However, the harsh environmental conditions on mountainous glaciers limit direct observations of glacier mass balances. Numerical modeling provides an alternative and effective way to estimate glacier melting and mass balances.
- This study develops an energy budget-based glacier mass balance model.

Outline

- Model Structure
- Parameterizations
  - Surface Albedo
  - Precipitation Type Discrimination
  - Surface Turbulent Heat Flux
- Model Validation
- Sensitivity Analysis
- Comparison of simulation between two glaciers

Model Structure





Enthalpy: $H_j^k = (m_{i,j}^k c_i + m_{l,j}^k c_l)T_j^k - m_{i,j}^k L_{li}$

Reference: enthalpy of liquid water at 0°C is 0, so that the energy transfer due to liquid water movement could be simplified.

➢ *Surface Layer Energy Balance*

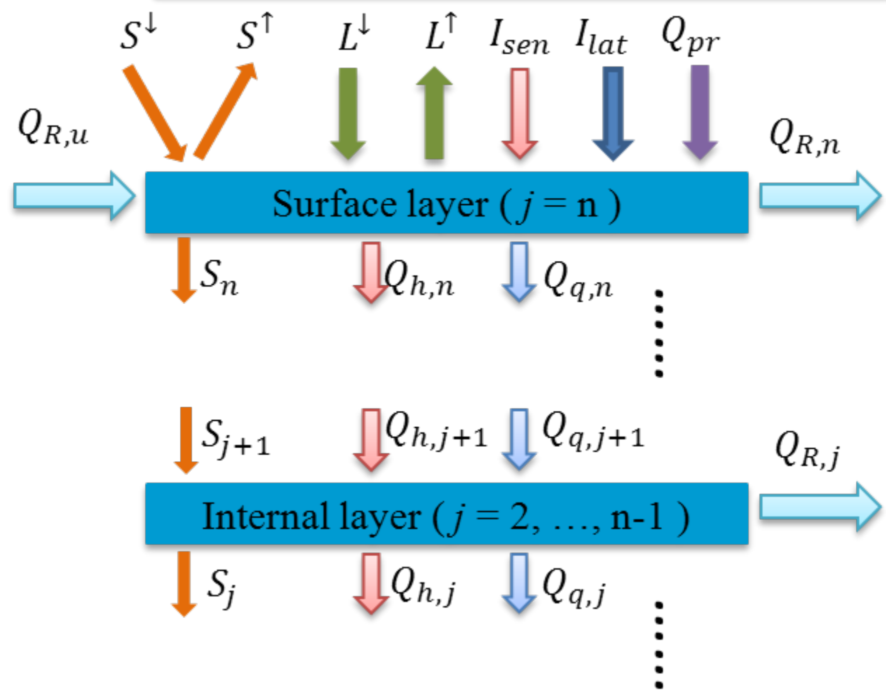
$$\frac{\partial H_n}{\partial t} = \Delta S_n + \Delta L_n + I_{lat} + I_{sen} - Q_{h,n}$$

- Enthalpy Variation → $\frac{\partial H_n}{\partial t}$
- Net Shortwave Radiation → ΔS_n
- Net Longwave Radiation → ΔL_n
- Latent Heat Flux → I_{lat}
- Sensible Heat Flux → I_{sen}
- Heat Flux Exchange between Layers → $Q_{h,n}$

➢ *Internal Layer Energy Balance*

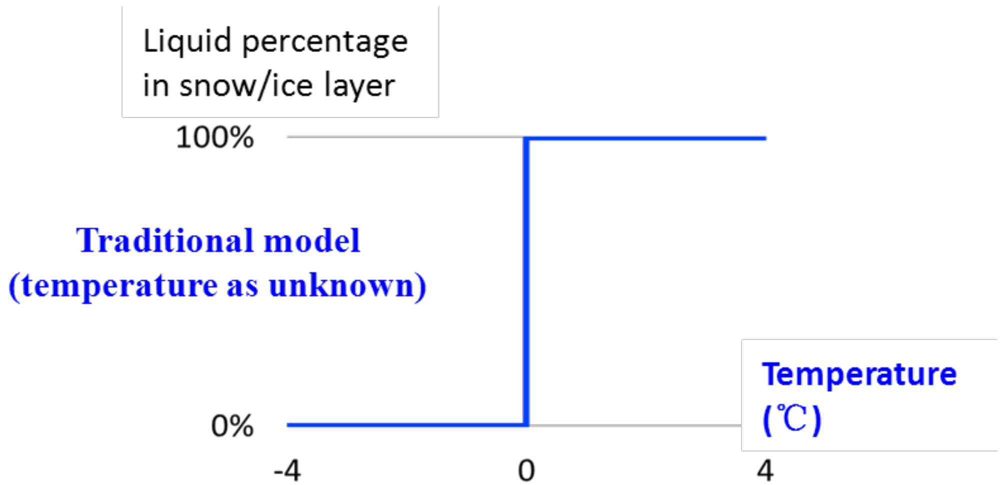
$$\frac{\partial H_j}{\partial t} = \Delta S_j + \Delta Q_{h,j}$$

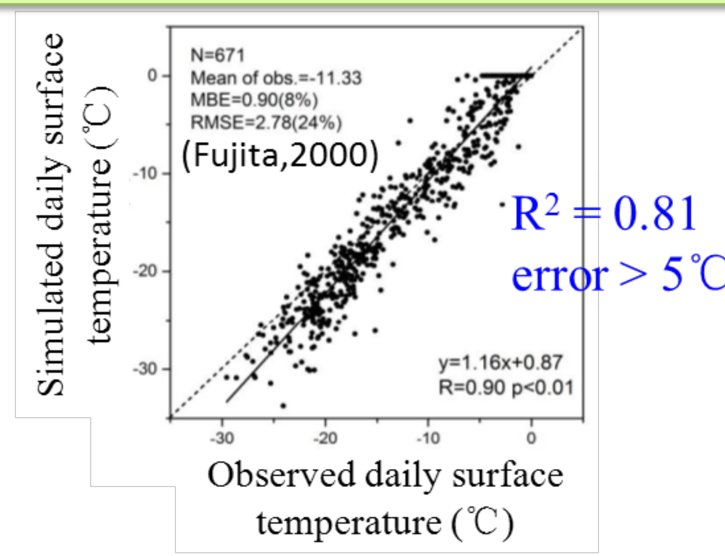
- Enthalpy Variation → $\frac{\partial H_j}{\partial t}$
- Net Shortwave Radiation → ΔS_j
- Heat Flux Exchange between Layers → $\Delta Q_{h,j}$

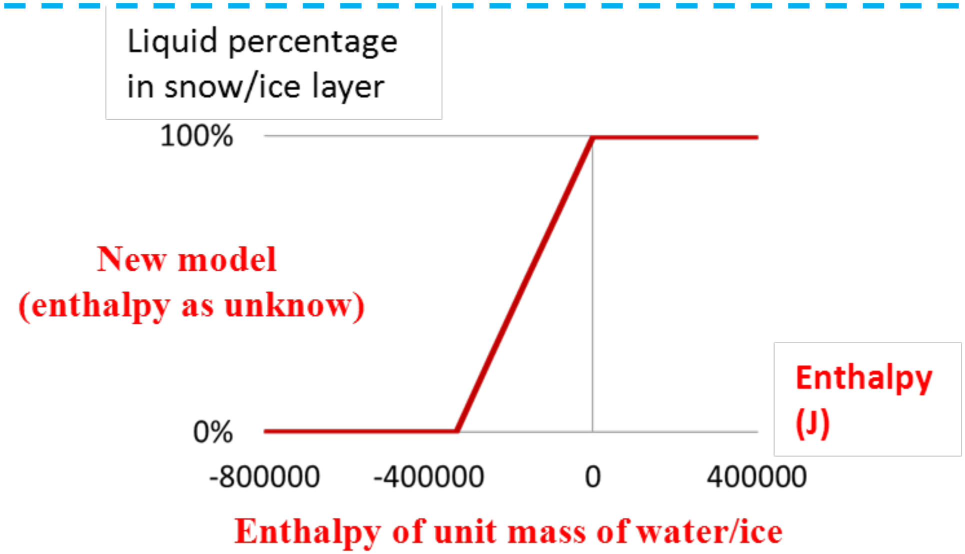


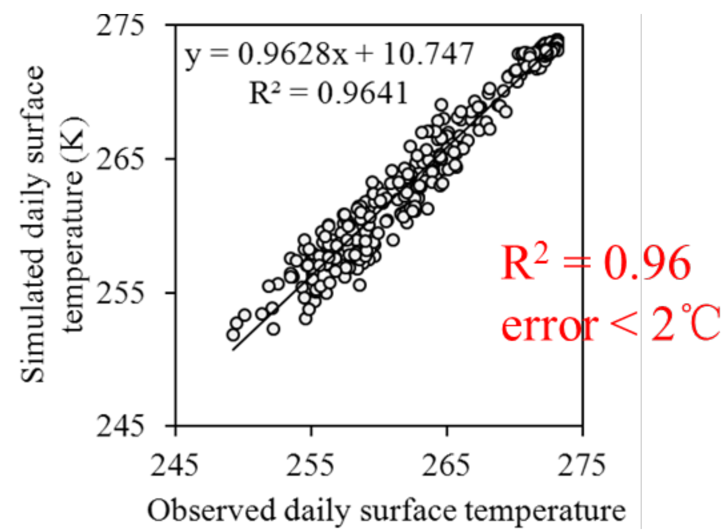
Enthalpy is used rather than temperature as unknown in energy balance equation, which could simplify calculation and improve simulation accuracy.

An enthalpy budget based glacier mass balance model is developed









Enthalpy is used rather than temperature as unknown in energy balance equation, which could simplify calculation and improve simulation accuracy.

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A new albedo scheme considering sleet and shallow snow is implemented in the new model

Inputs:
Albedo before snowfall, snowfall,rainfall, snow density, cloud fration ,sun angle

New snowfall

$$\alpha_r^t = \alpha_0^t \cdot (1 - e^{-K \cdot M_{sn}}) + \alpha_b^{t-1} \cdot e^{-2K \cdot M_{sn}}$$

$$\alpha_s^t = \begin{cases} (\alpha_r^t - \alpha_b^{t-1}) \cdot \dfrac{\frac{p_s}{p_r} - 50\%}{50\%} + \alpha_b^{t-1} & ,\text{for } 50\% < \dfrac{p_s}{p_r} < 100\% \\ \alpha_b^{t-1} & ,\text{for } \dfrac{p_s}{p_r} \le 50\% \end{cases}$$

$$\alpha_b^t = \alpha_s^t \cdot f_{sn} + \alpha_b^{t-1} \cdot (1 - f_{sn})$$

Snow particle diameter, snow mass, solid percentage of precipitation, snow depth

Snow aging

non-melting: (Baker, 1990)

$$\alpha_b^t = \alpha_b^{t-1} - \frac{\tau_a \cdot \Delta t}{86400}$$

melting: (Verseghy, 1991)

$$\alpha_b^t = (\alpha_b^{t-1} - \alpha_{min}) \cdot e^{-\frac{0.24 \times \Delta t}{86400}} + \alpha_{min}$$

Cloud effect

$$\Delta\alpha_c^t = 0.00449 + 0.097 \times C^3$$

C: cloud fraction (Petzold, 1977)

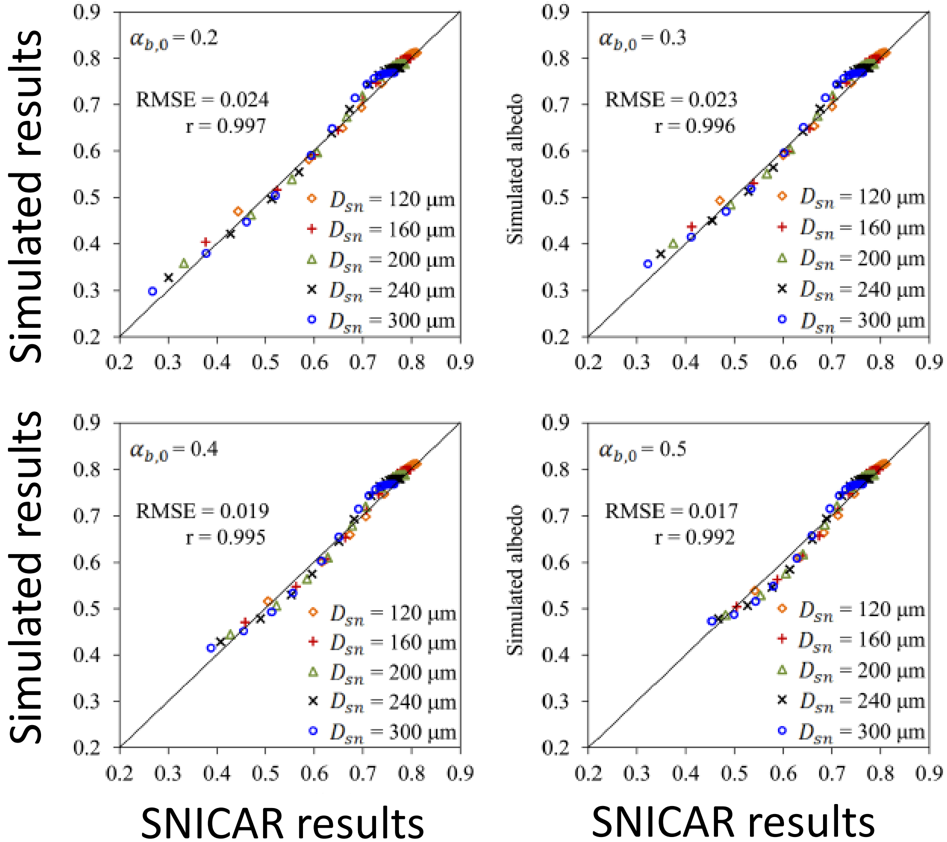
Sun elevation angle

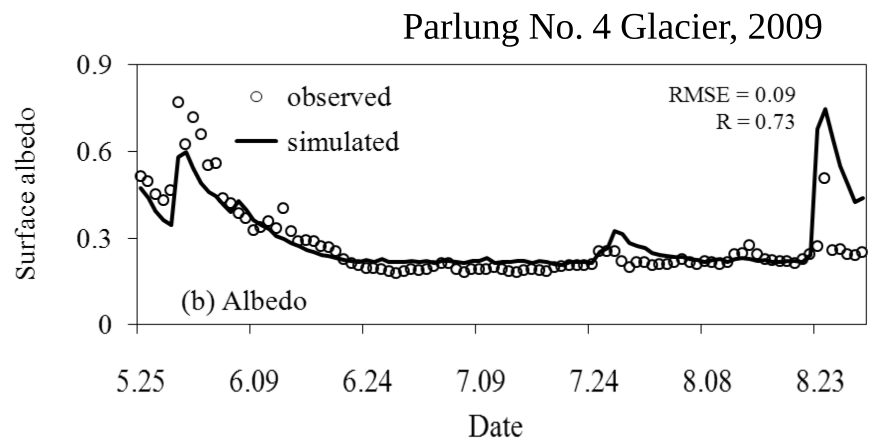
$$\Delta\alpha_\beta^t = -0.019 + 0.248 e^{-\frac{\beta}{15.5}}$$

β: sun elevation angle (degrees) (Petzold, 1977)

Albedo: $\alpha^t = \alpha_b^t + \Delta\alpha_c^t + \Delta\alpha_\beta^t$

A new albedo scheme considering sleet and shallow snow is implemented in the new model





Simulated albedo is close to the observation at Parlung No. 4 Glacier during 25 May-29 Aug. 2009

Simulated albedo by new scheme is highly related to the SNICAR results

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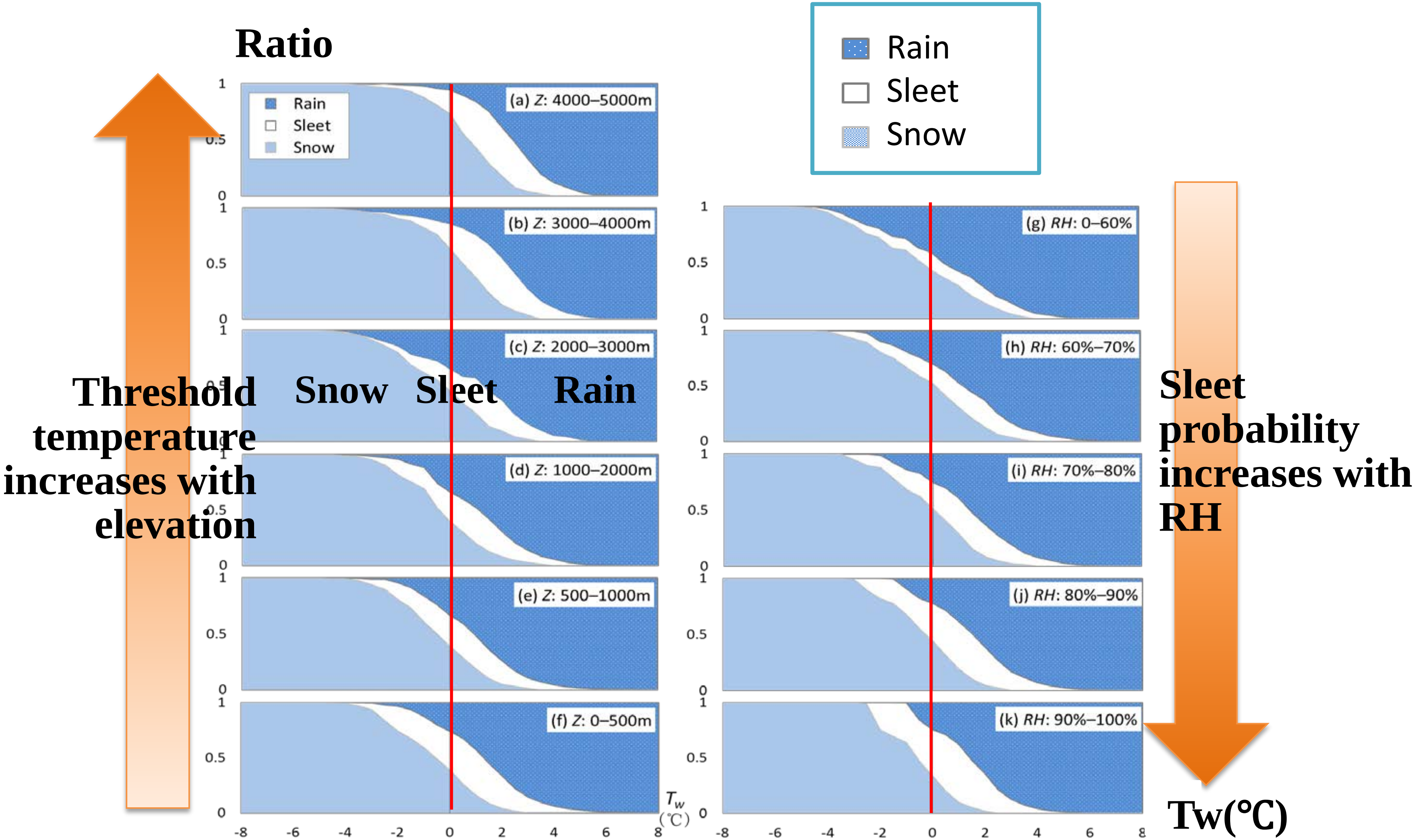
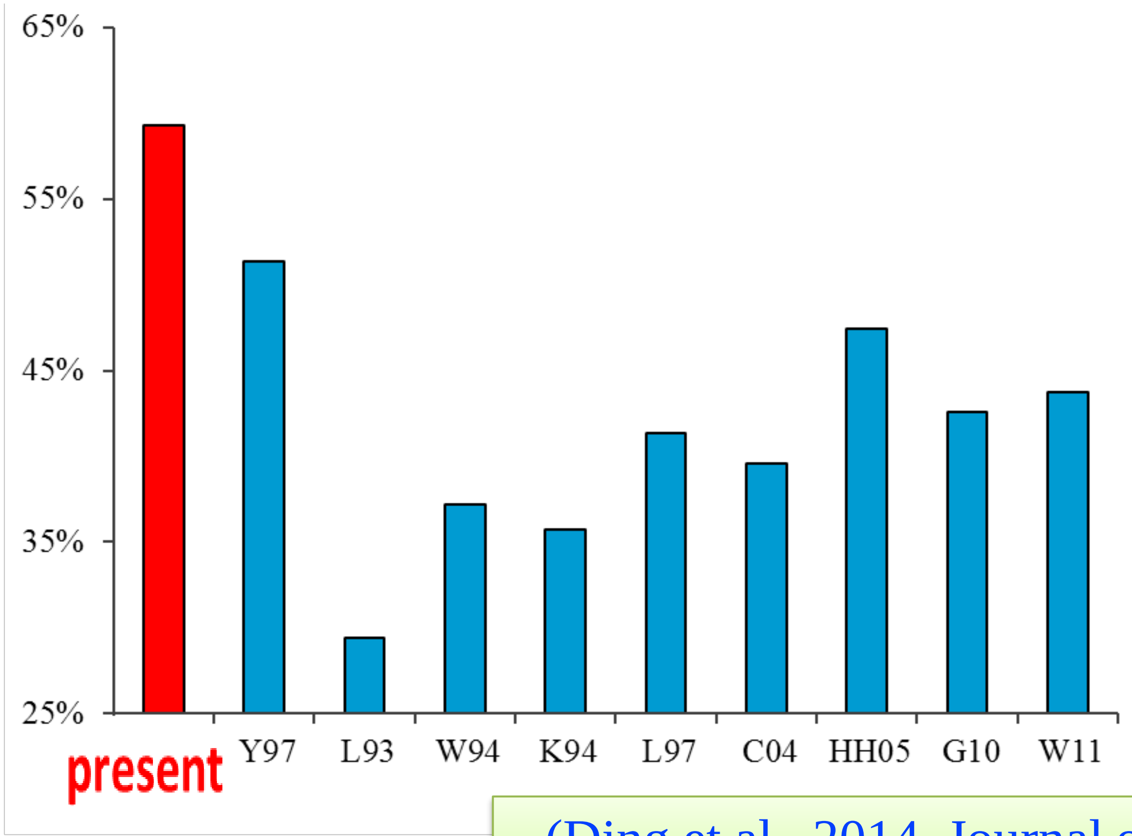
Precipitation types are highly dependent on Tw, RH, and elevation



The accuracy of the new parameterization to discriminate snow, sleet and rain, comparing with other schemes

Accuracy of precipitation type discrimination



(Ding et al., 2014, Journal of Hydrology)

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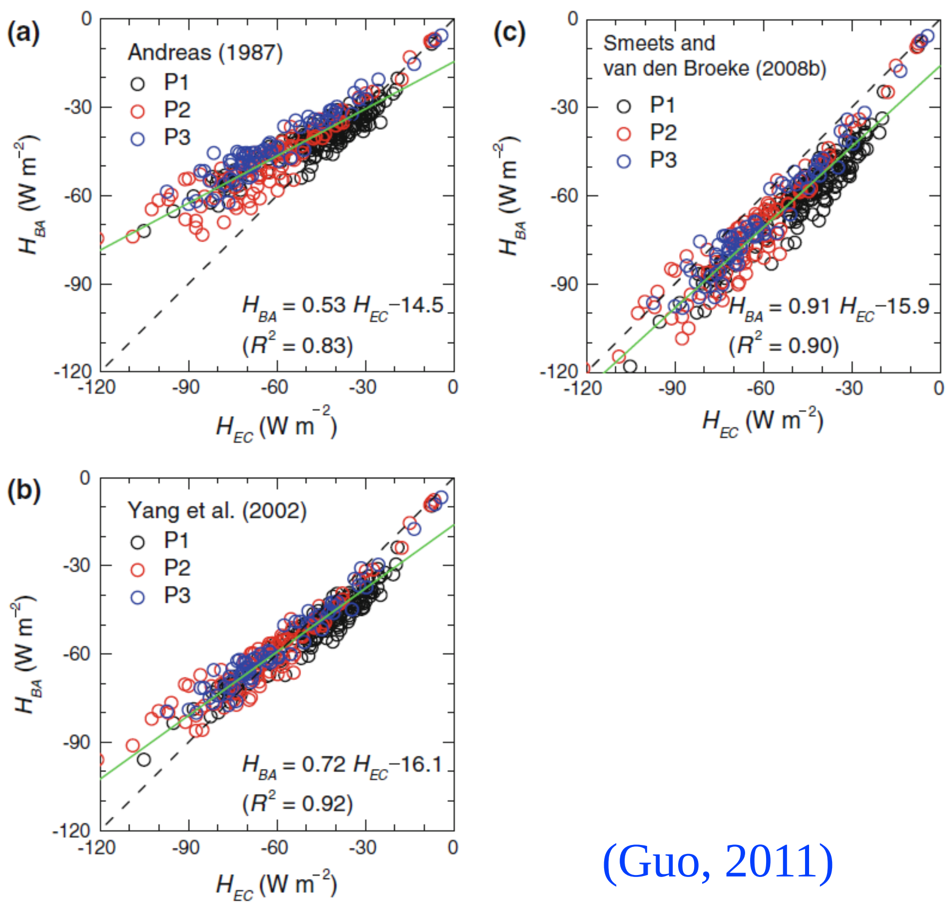
Heat transfer parameterization

- Yang et al. (2008) developed a parameterization for sensible heat flux, based on the Monin-Obhukov similarity theory.

Thermal roughness length:

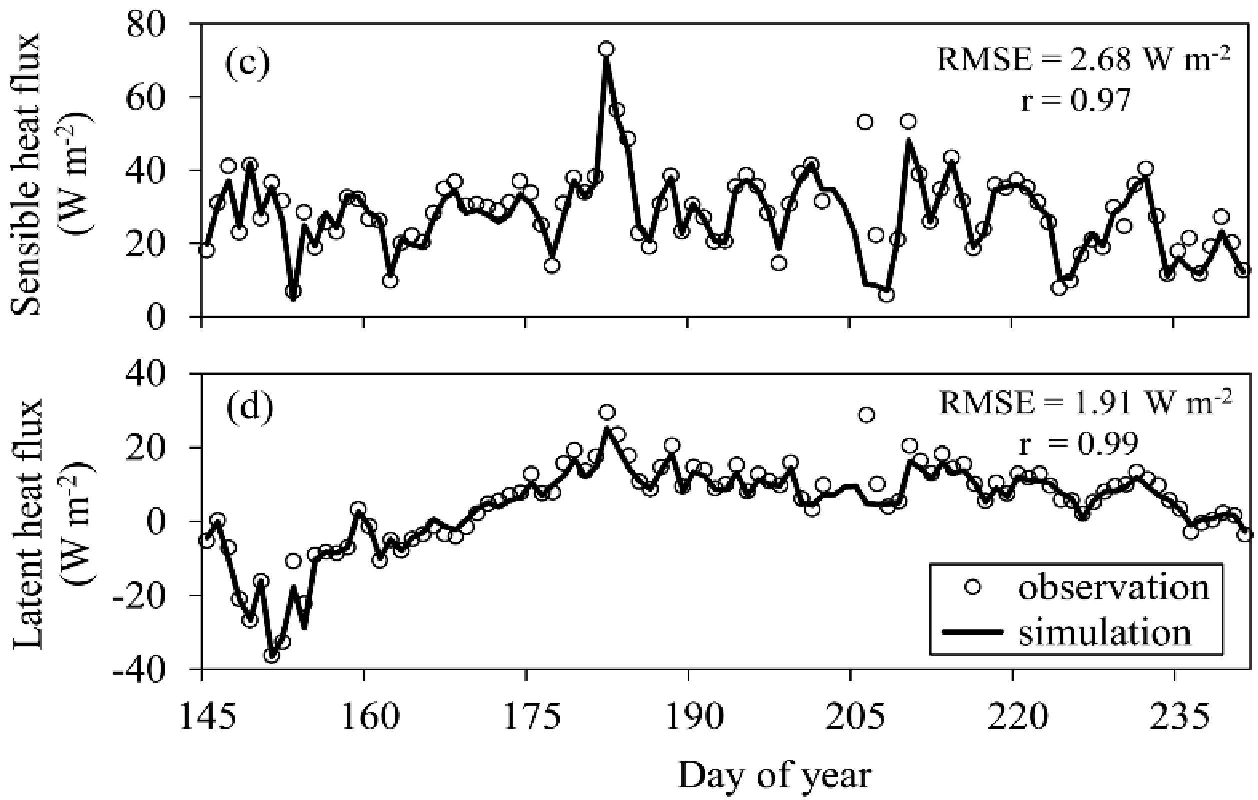
$$z_{h0} = \frac{70\nu}{u_*} \exp(-\beta u_*^{1/2} |\theta_*|^{1/4})$$



(Guo, 2011)

Guo (2011) compared Yang (2008) scheme with Andreas (1987) scheme and Smeets & van den Broeke (2008) scheme, based on the observation data at a glacier at Southeast Tibetan Plateau, and found Yang (2008) scheme performs better.

A turbulent heat flux parameterization suitable for glacier surface is implemented in the model.



Parlung No. 4 Glacier 2009

Simulated sensible heat and latent heat flux are close to observation at Parlung No. 4 Glacier during during 25 May-29 Aug. 2009

The development of the WEB-GM is published in Water Resources Research (Ding et al., 2017)

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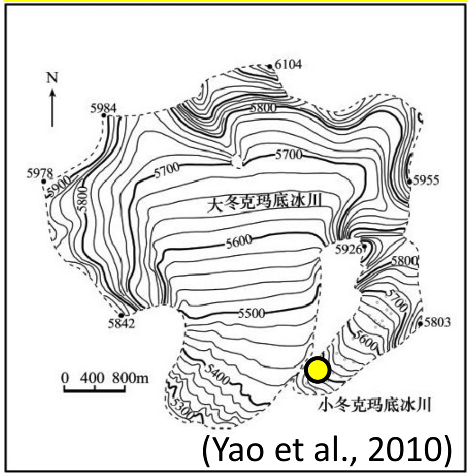
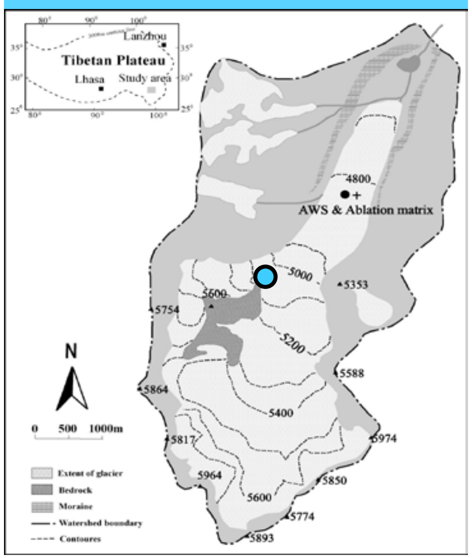
Study Area

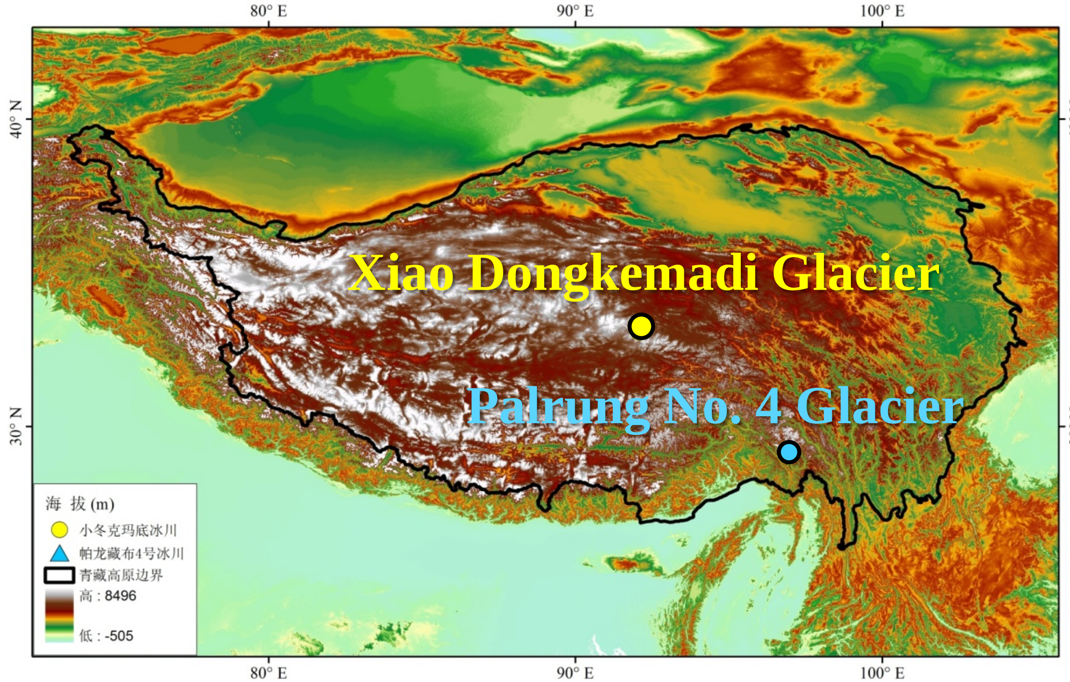
Xiao Dongkemadi Glacier



(Yao et al., 2010)

Parlung No. 4 Glacier





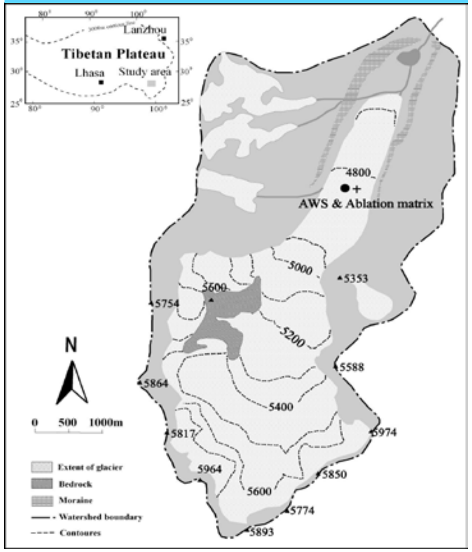
- **Parlung No. 4 Glacier**
  - Area: ~11.7 km^2
  - Length: ~8 km
  - Elevation: 4650 m - 5964 m
- **Surface Energy Budget Station**
  - Elevation: 4804 m
  - In ablation zone about 1500m near the end of the glacier

- **Xiao Dongkemadi Glacier**
  - Area: ~1.767 km^2
  - Length: ~2.8 km
  - Elevation: 5275 - 5926 m
- **Surface Energy Budget Station**
  - Elevation: 5438 m
  - In the ablation zone

Field Experiment for glacier surface mass balance and energy budget

Glacier mass balance measurement

Parlung No. 4 Glacier

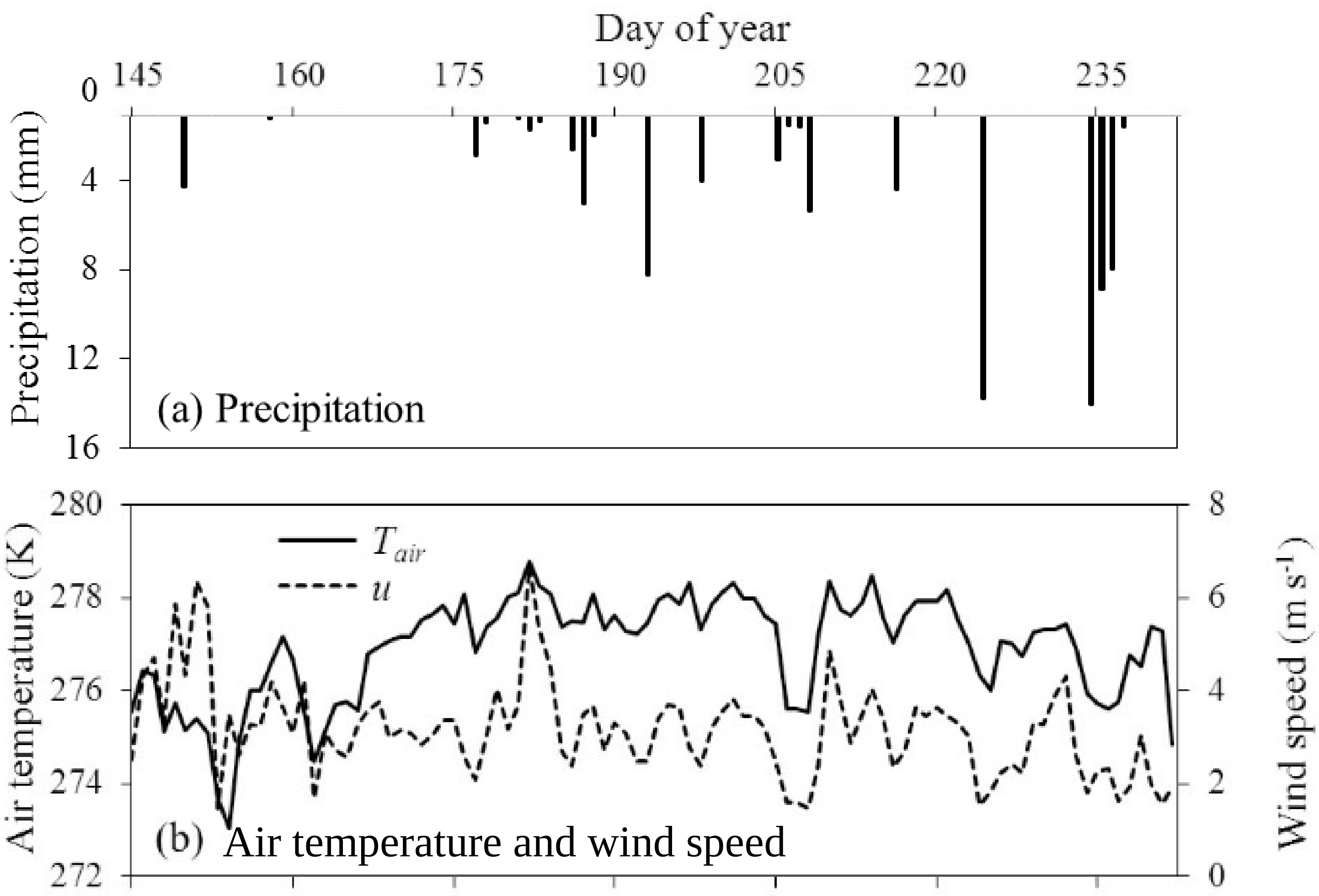


Meteorological and radiation observation

Precipitation gauge

Observations

Parlung No.4 Glacier
25 May – 29 Aug. 2009
4804 m .a.s.l.



Total precipitation: 148.4 mm w.e.

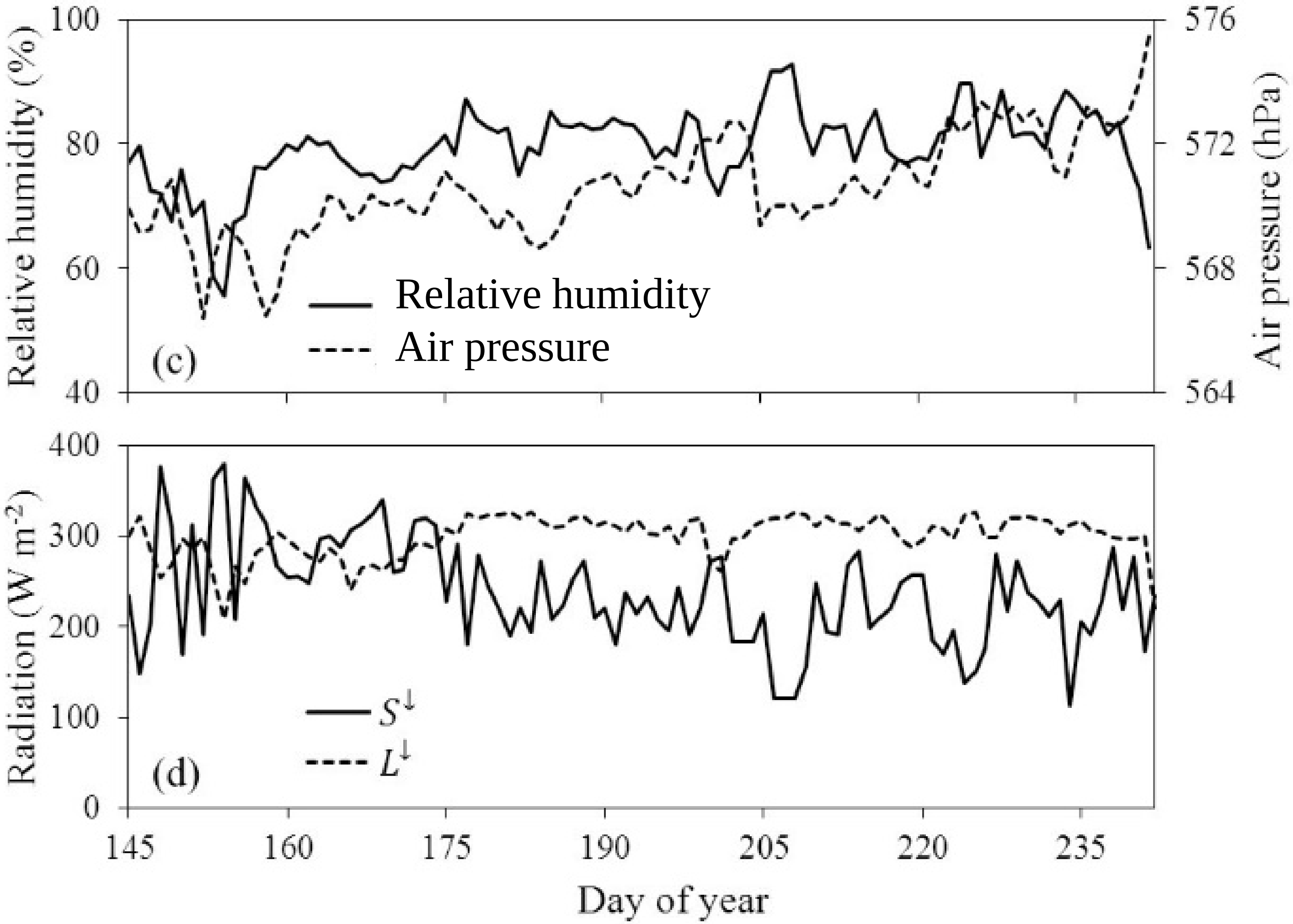
Mean air tempature: 276.9K

Mean wind speed: 3.2 m s^{-1}

Mainly katabatic wind

Observations

Parlung No.4 Glacier
25 May – 29 Aug. 2009
4804 m .a.s.l.



Mean relative humidity: 79%

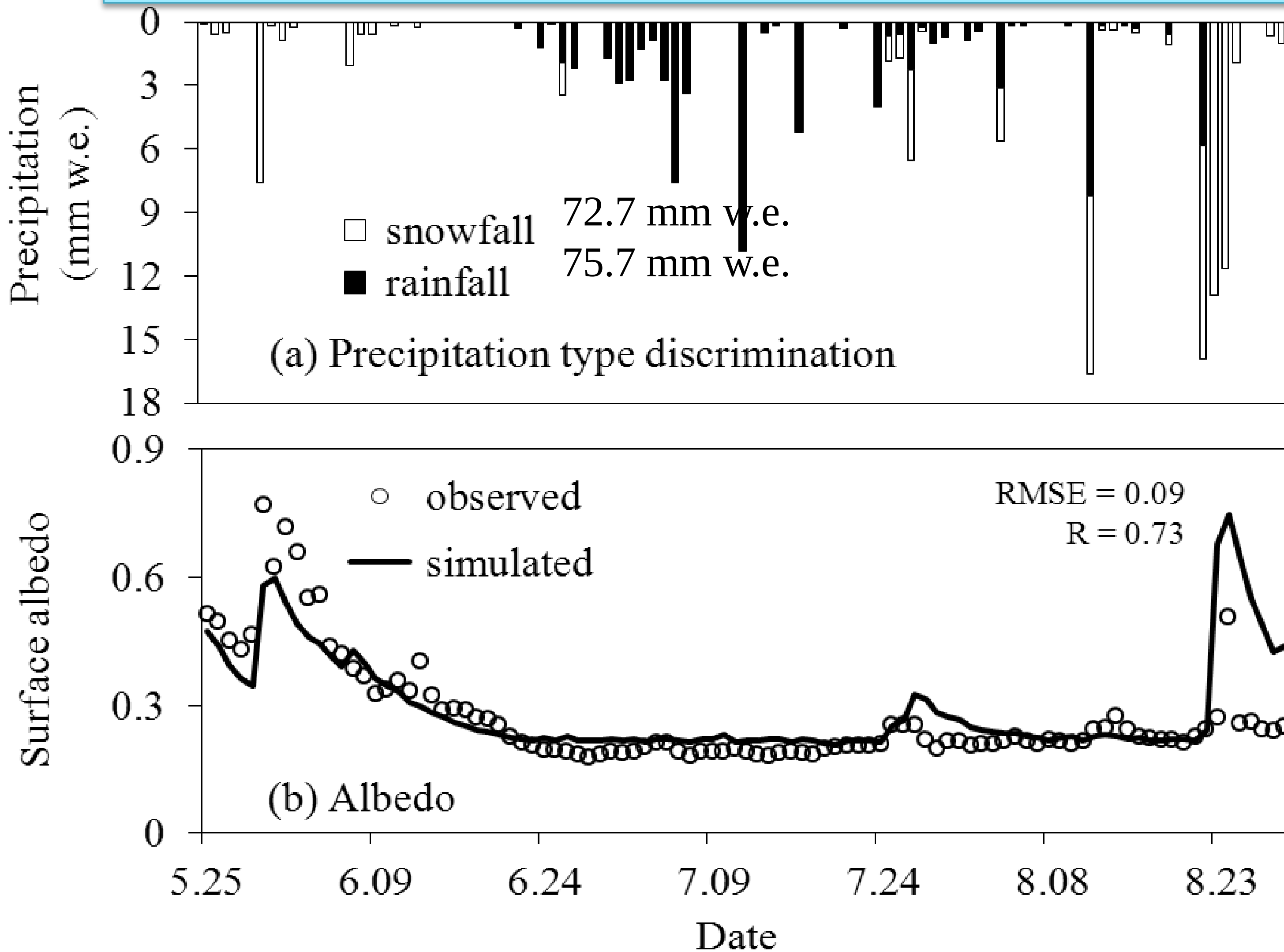
Mean air pressure: 570.6 hPa

Downward solar radiation：237.0 W m^{-2}

Downward longwave radiation：299.1 W m^{-2}

Model evaluation 1

Validations based on the field observation at the two glaciers



Simulation results

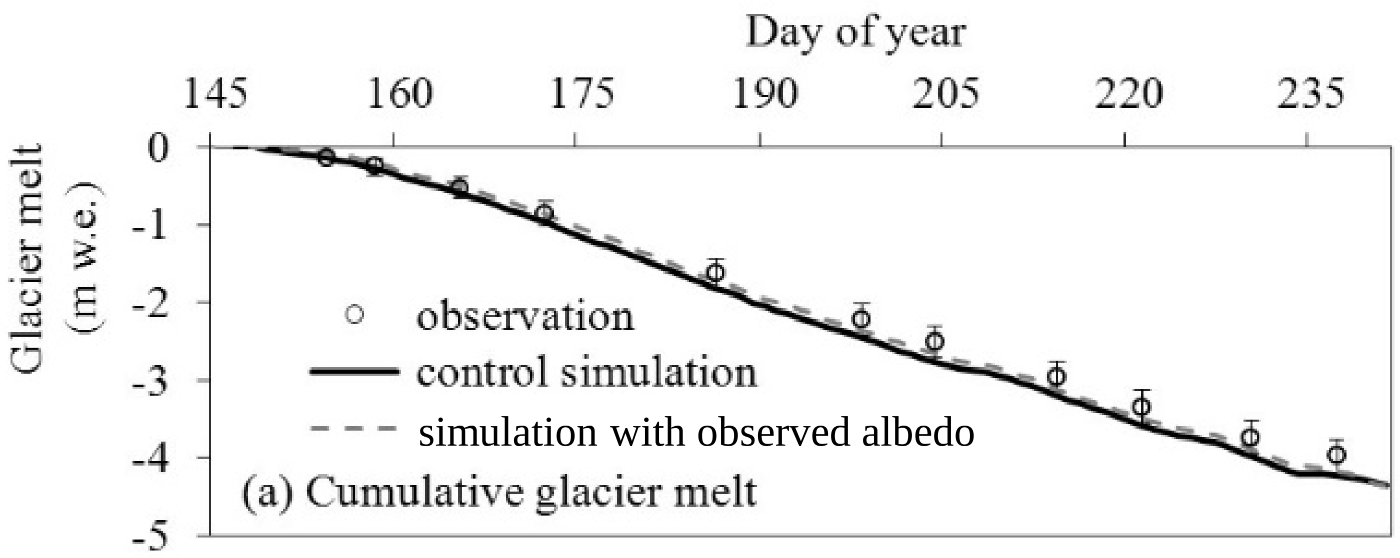
Parlung No.4 Glacier

25 May – 29 Aug. 2009

4804 m .a.s.l.

Model evaluation 1

Validations based on the field observation at the two glaciers



Simulation results

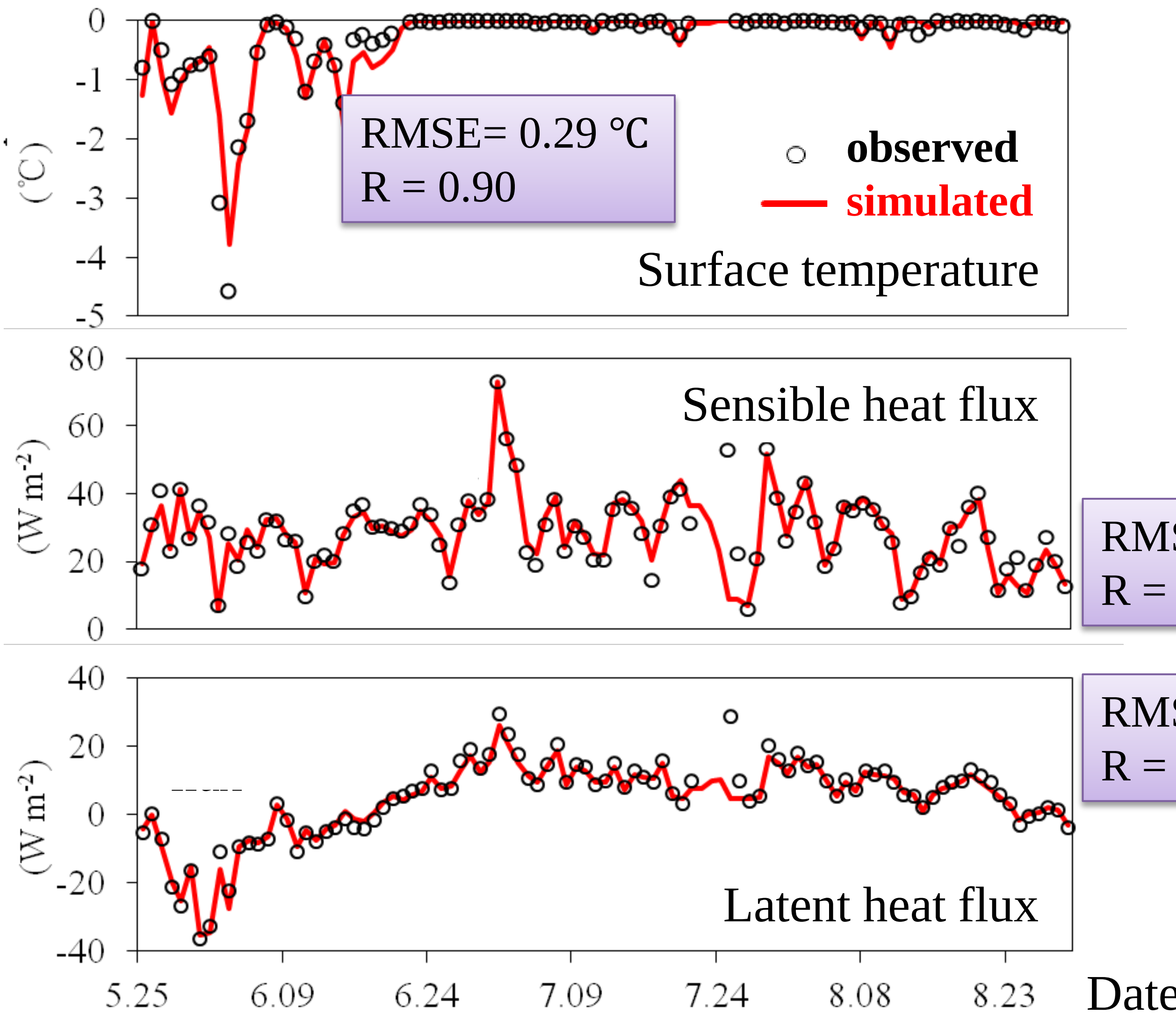
Parlung No.4 Glacier
25 May – 29 Aug. 2009
4804 m .a.s.l.

From 3 June to 25 August:

- The simulated accumulative glacier melt was 4.09 m w.e. (the black solid line)
- The observed one was 3.84 m w.e. (the circle)
- The difference is approximately 6% (i.e., 0.24 m w.e.)

Model evaluation 1

Validations based on the field observation at the two glaciers



RMSE= 2.68 W m^{-2}
R = 0.97

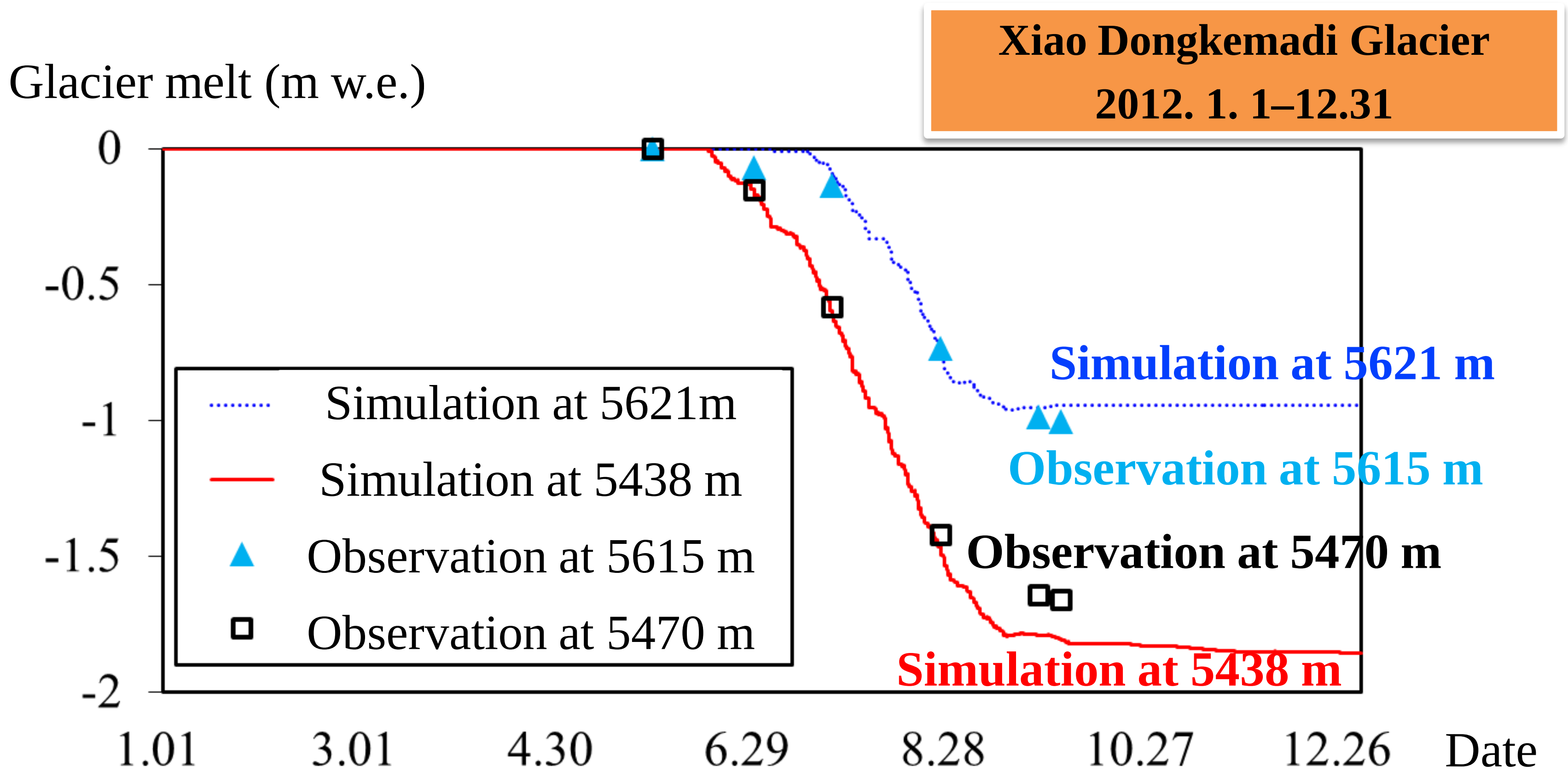
RMSE= 1.91W m^{-2}
R = 0.99

Simulation results

Parlung No.4 Glacier
25 May – 29 Aug. 2009
4804 m .a.s.l.

Model evaluation 2

Validations based on the field observation at the two glaciers



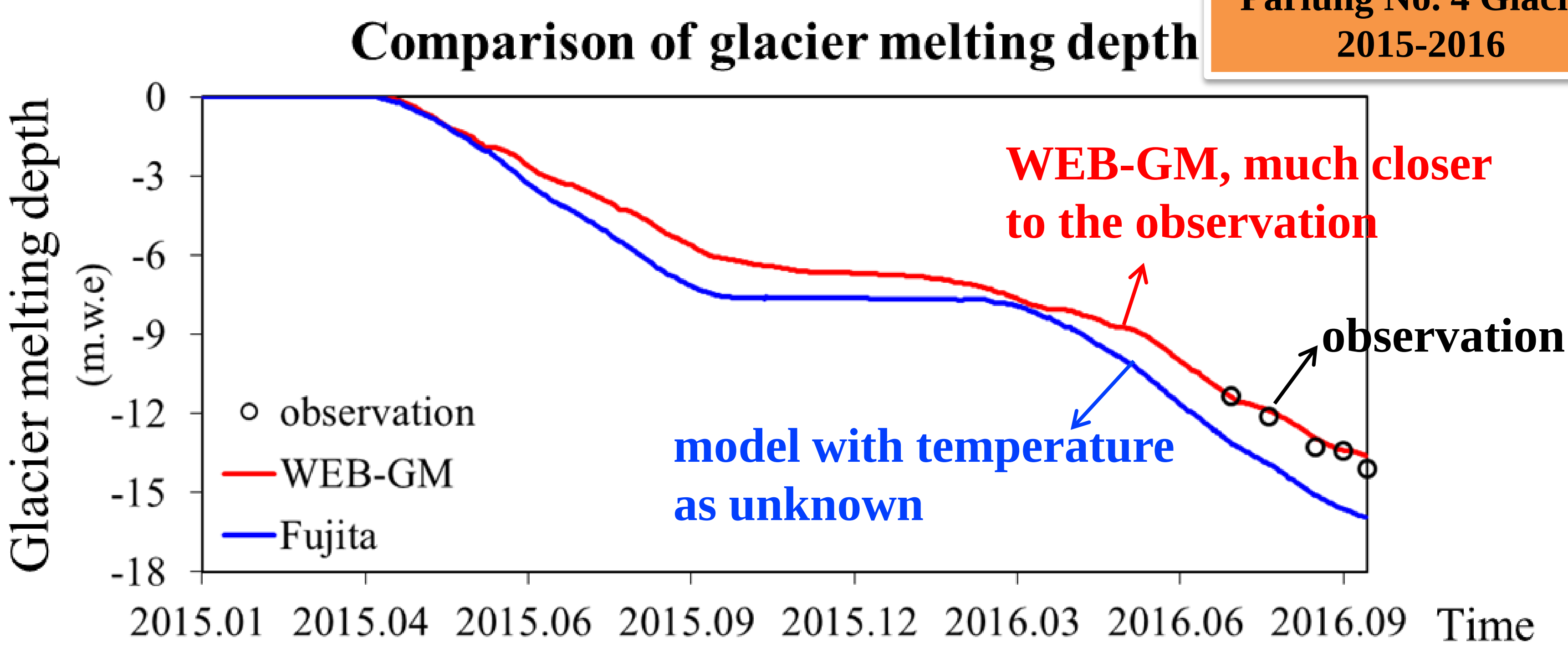
Simulations at Xiao Dongkemadi Glacier further prove the reliability of WEB-GM.

Model evaluation 3

Comparing with a traditional energy budget-based glacier mass balance model, this enthalpy-based model shows a superior capacity in simulation accuracy.

- Temperature is used as unknown of the energy balance equation in the traditional energy budget-based model (*Fujita and Ageta*, 2000).
- Enthalpy is used as unknown of the energy balance equation in the new model (WEB-GM).

Parlung No. 4 Glacier 2015-2016

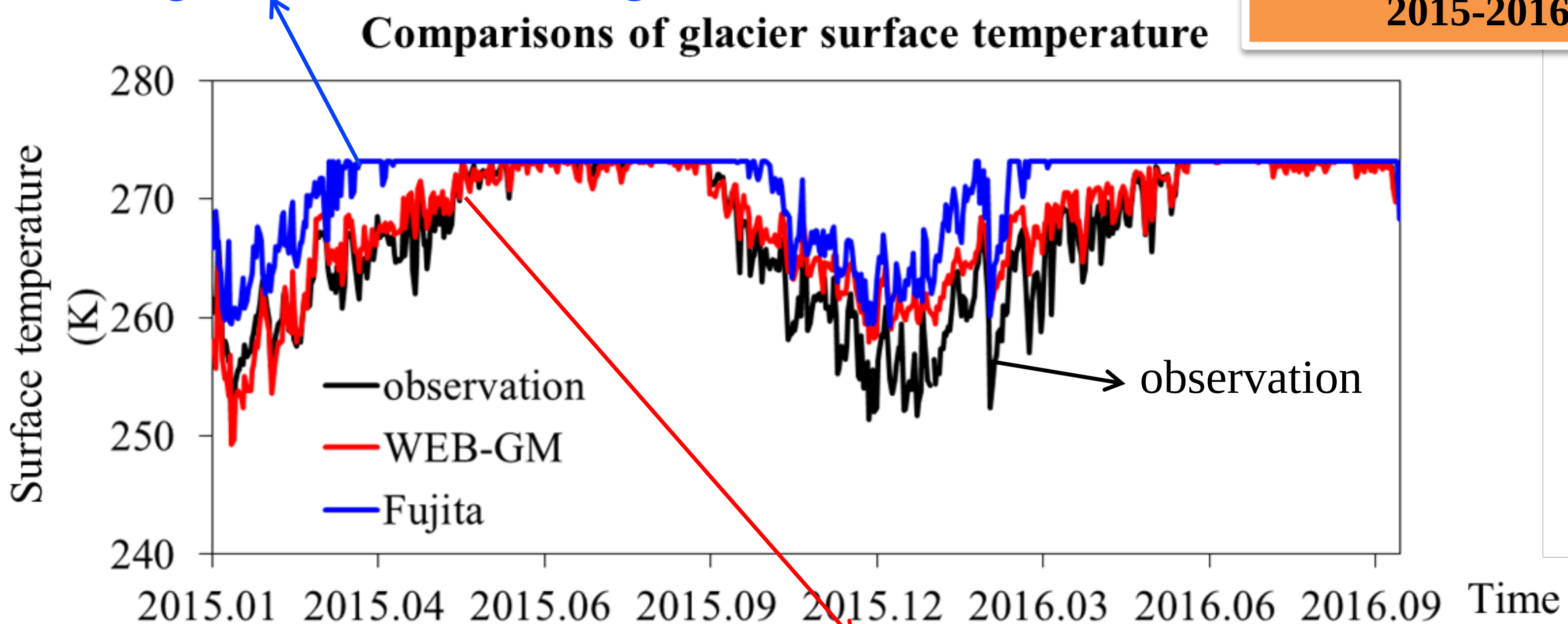


Model evaluation 3

Comparing with a traditional energy budget-based glacier mass balance model, this enthalpy-based model shows a superior capacity in simulation accuracy.

The surface temperature simulated by the temperature-based model stayed near 273.15 K during late March to middle October.
The melting season was much longer than observation.

Parlung No. 4 Glacier 2015-2016



The period that surface temperature being approximately 273.15 K by WEB-GM was similar with observation, which was from middle June to late September. Also, the simulated surface temperature was closer to observation.

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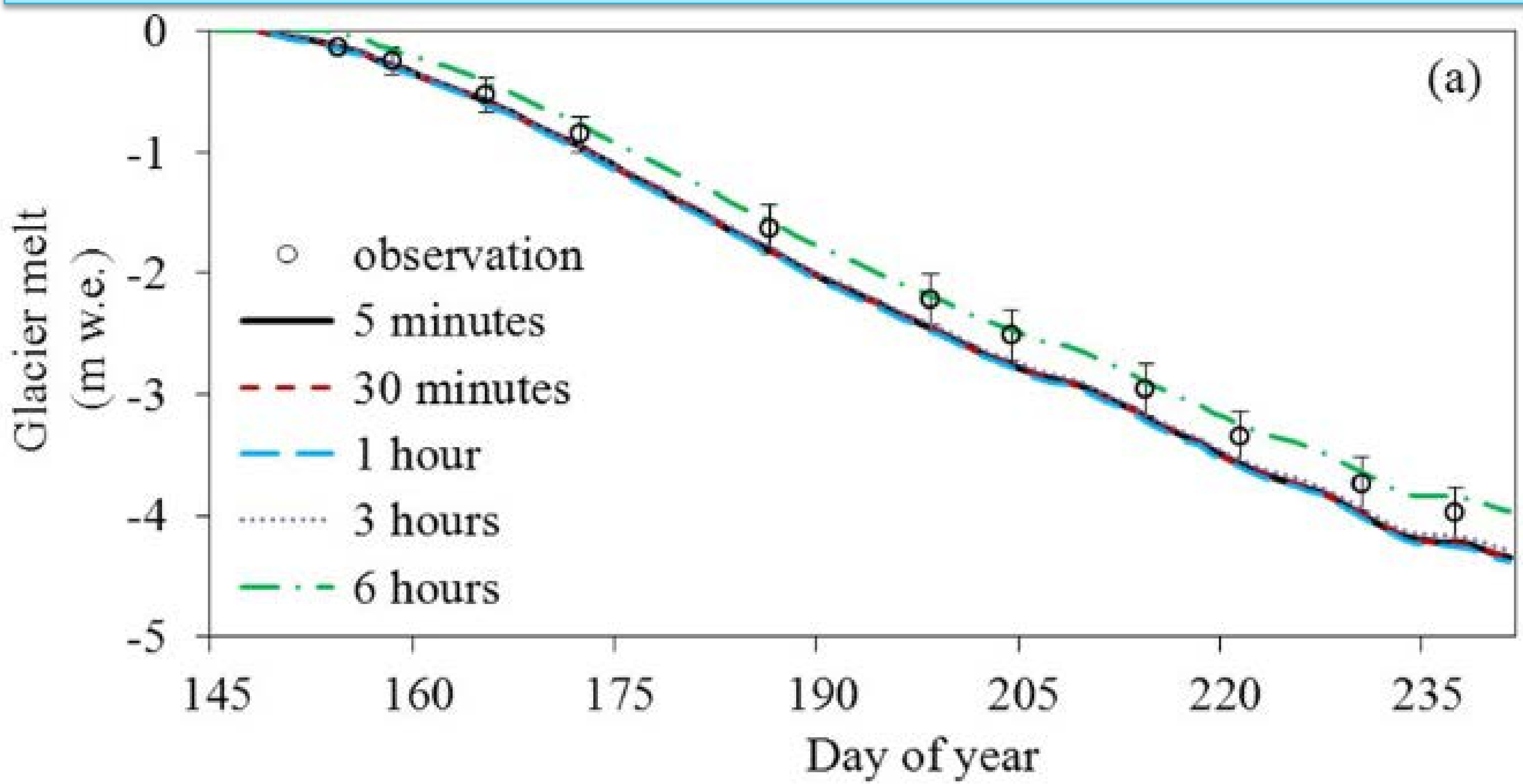
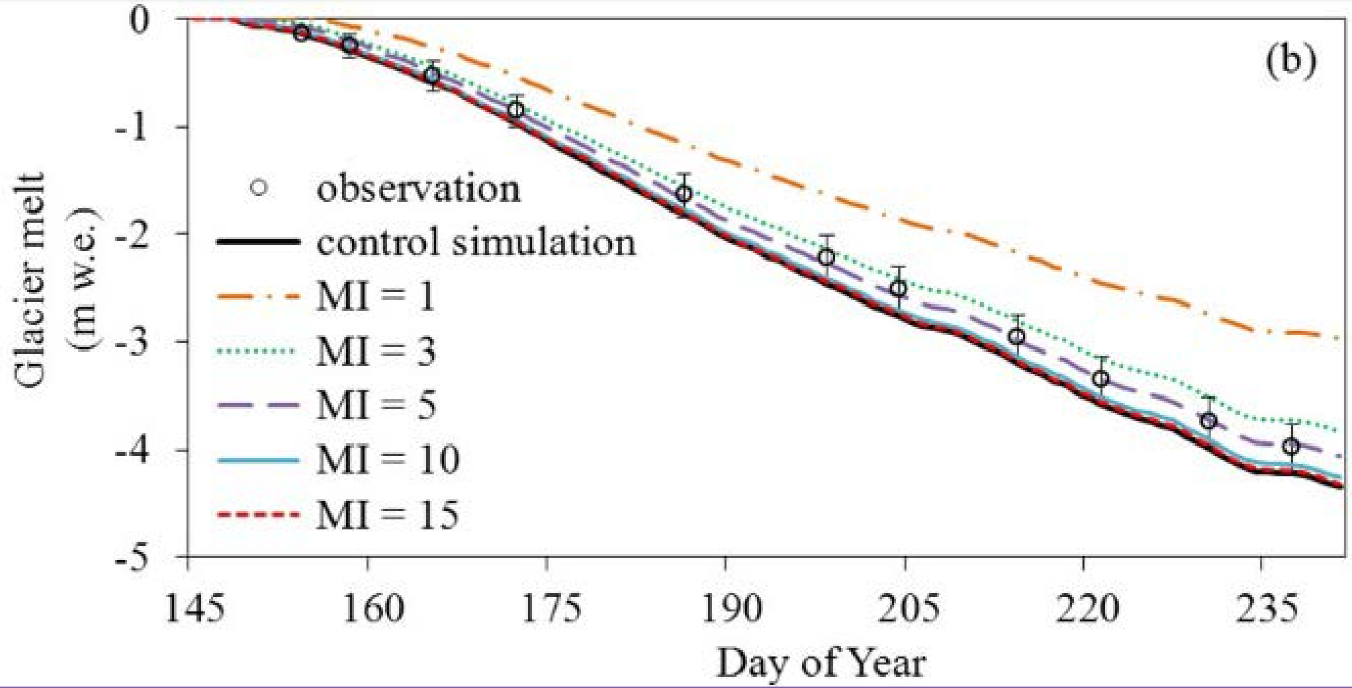
Sensitivity to temporal resolutions of forcing data



• When the simulation time step is no greater than 3 hours, the simulation results are not sensitive to the input data.

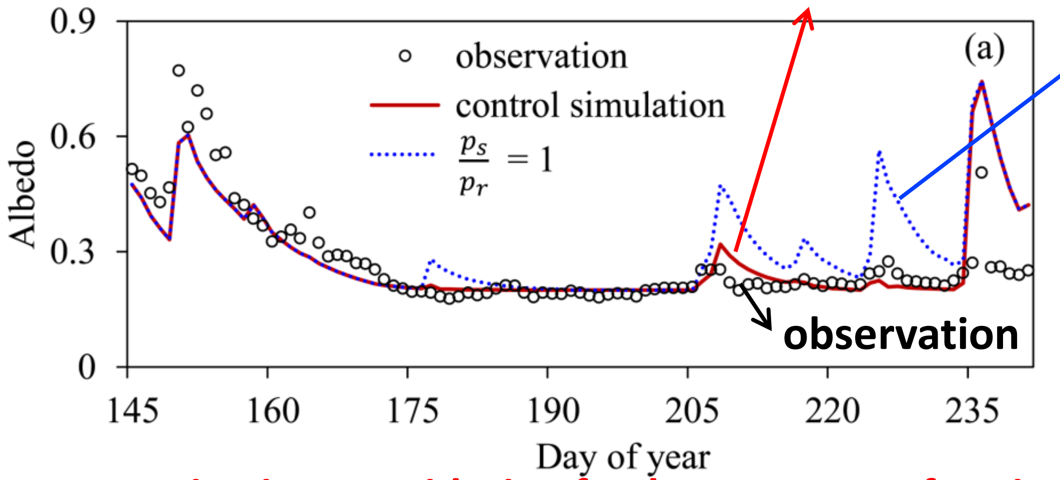
Sensitivity to maximum number of iterations of the energy budget calculation



- The solution of the energy budget equations is obtained through numerical iteration. The mean iteration number for the standard case was only 9. When the MI was set to 15, the difference was negligible.
- One run for the total 98 days cost about 7 s on PC at a 30 min time step.
- Therefore, the model was not time consuming.

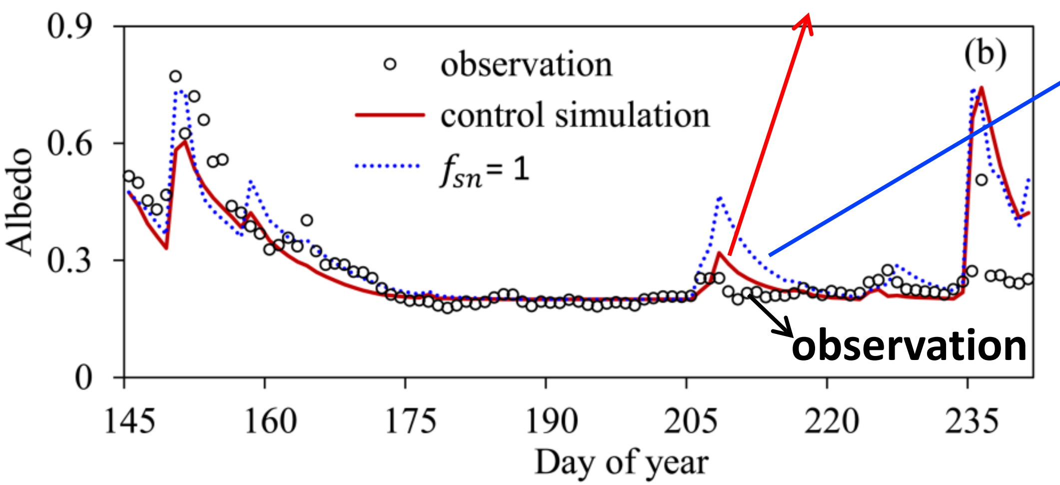
Sensitivity to the albedo scheme

Parameterization consider solid fraction in sleet



Assuming precipitation being fully solid ($\frac{p_s}{p_r} = 1$) would induce obvious deviations in simulated albedo

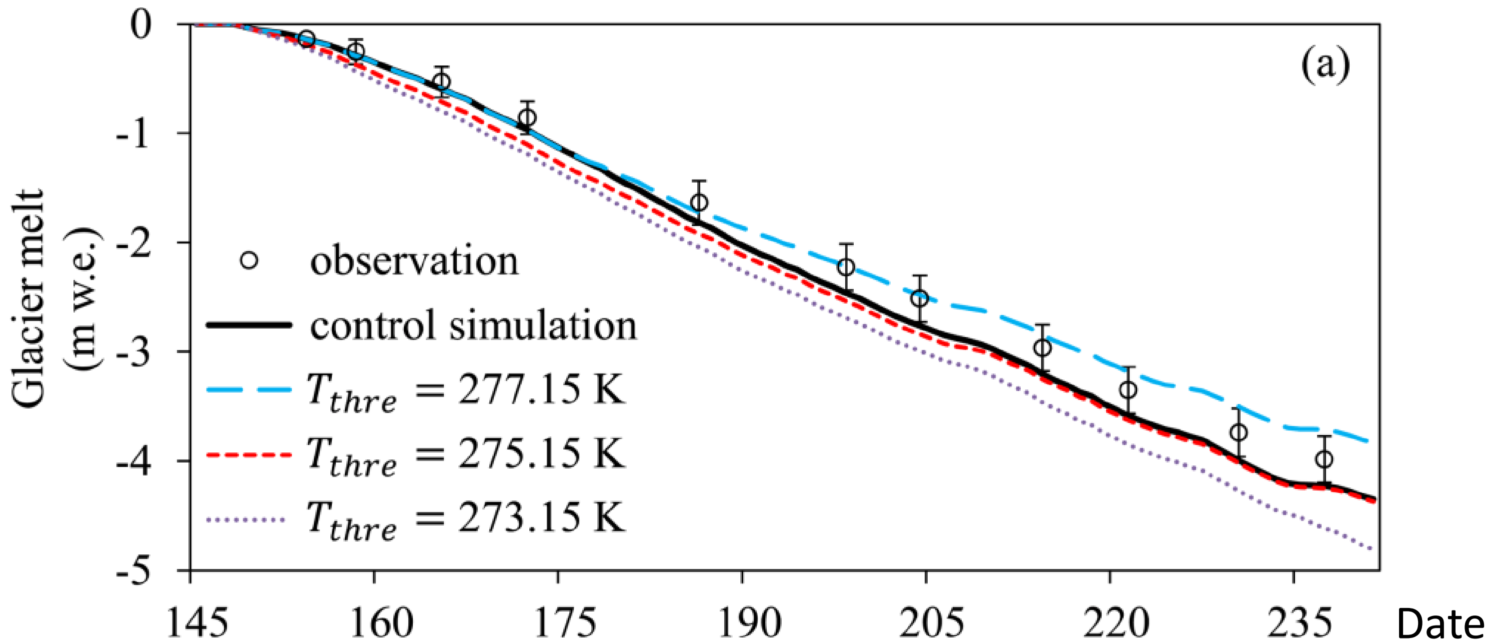
Parameterization considering fresh snow cover fraction



Assuming to be covered uniformly (f_{sn} = 1) would induce deviations when snowfall was relative less

parameterizations for these two processes (i.e., solid fraction in sleet and fresh snow cover fraction) are important for albedo estimation

Sensitivity to the precipitation type discrimination scheme



- Different threshold temperature would lead to different simulated glacier melt
- The threshold temperature might vary on different glaciers

Precipitation type discrimination scheme with dynamic threshold temperature is important for glacier melt simulation

Sensitivity to the turbulent flux parameterization

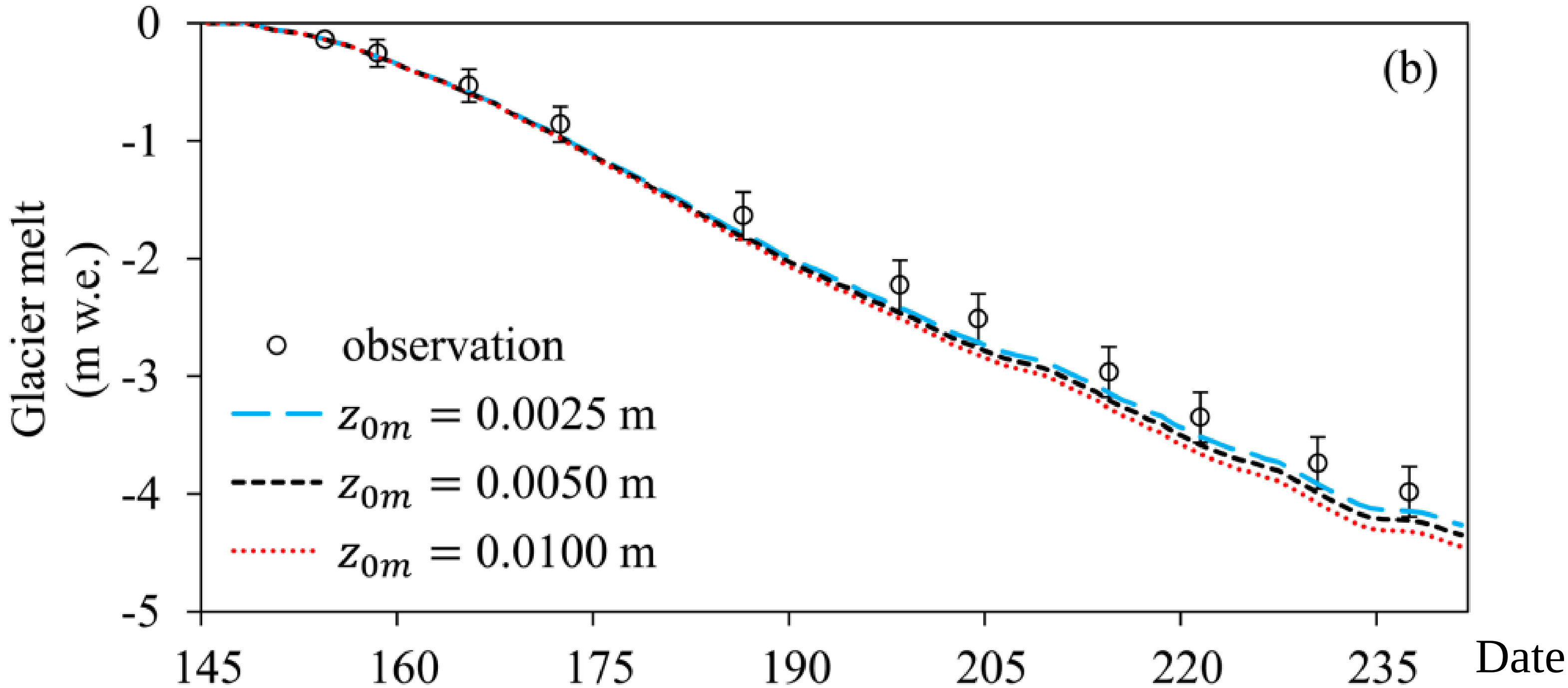
Thermal roughness length:

$$z_{h0} = \frac{70\nu}{u_*}\exp(-\beta u_*^{1/2}|\theta_*|^{1/4})$$

Aerodynamic roughness length:

$$z_{0m} = 0.0050\ \text{m}$$

(Yang et al., 2008)



Insensitive to the aerodynamic roughness lenth (z_{0m}), **which proves the feasibility of the turbulent flux parameterization.**

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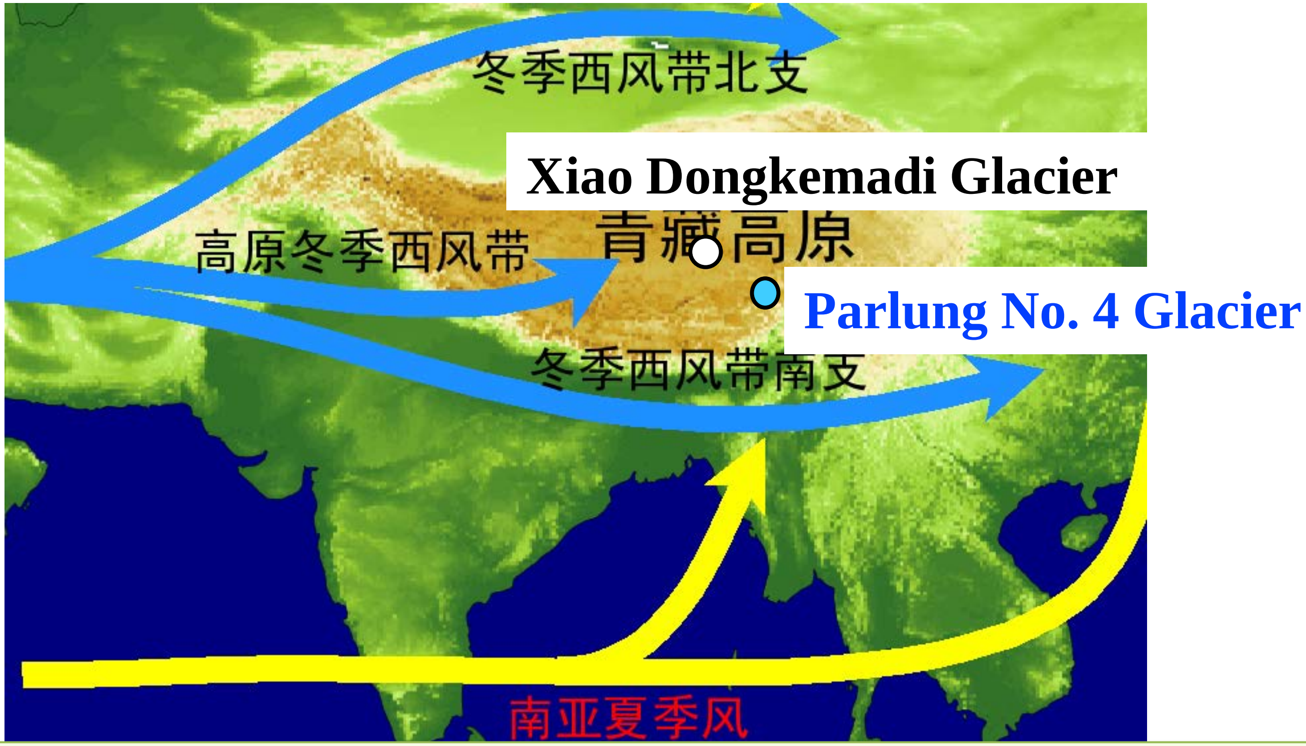
Analysis of the energy budget difference between two glaciers and quantification of sublimations in non-melting season



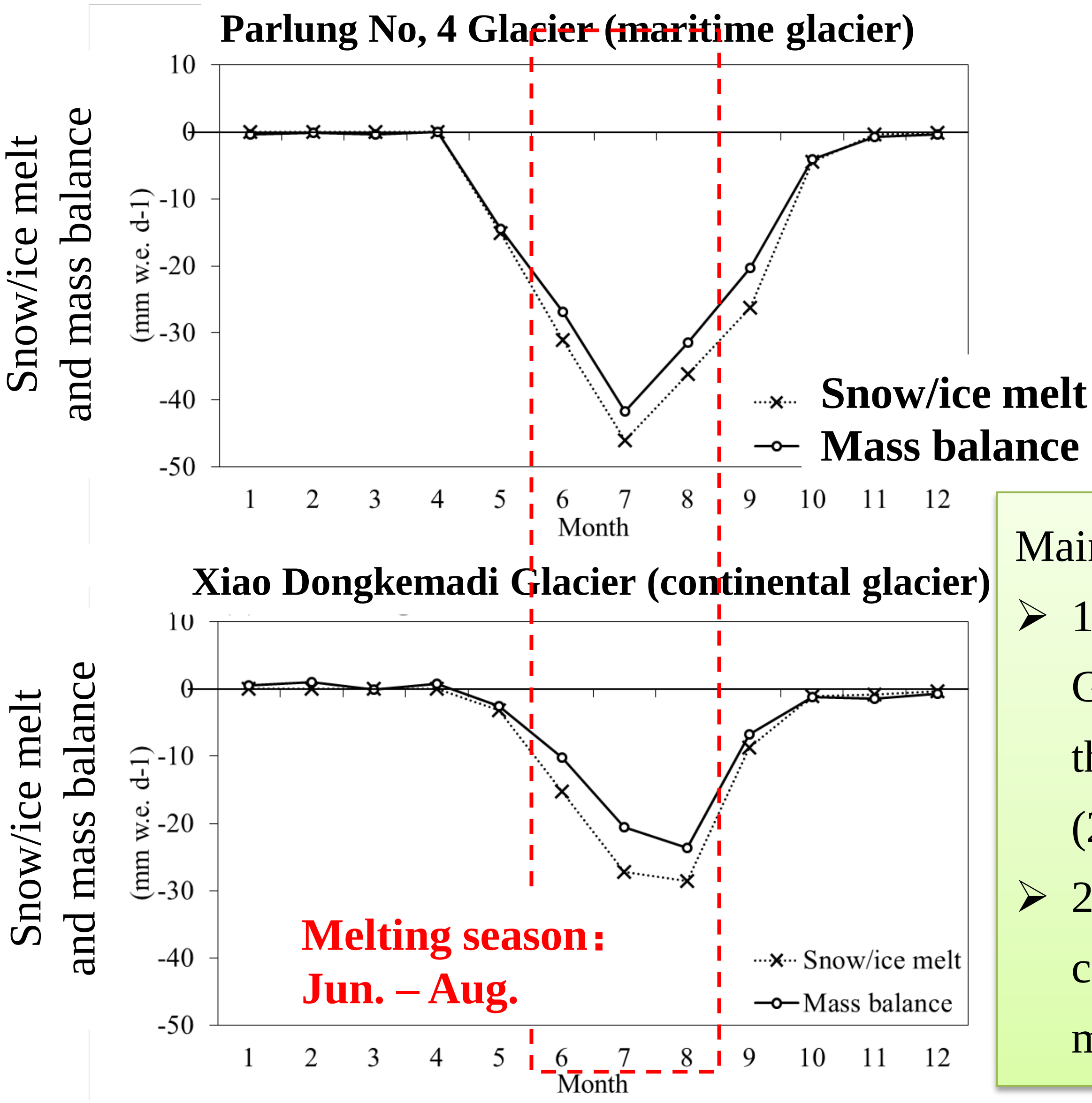
- Parlung No. 4 Glacier (maritime glacier)

Affected by Indian Ocean Monsoon, to be warm and wet, precipitation mainly in spring and summer, low windy

- Xiao Dongkemadi Glacier (continental glacier)

Affected by westerlies in winter half year, cold, dry, windy; affected by Indian Ocean Monsoon in summer half year, cool, wet, precipitation mainly in summer

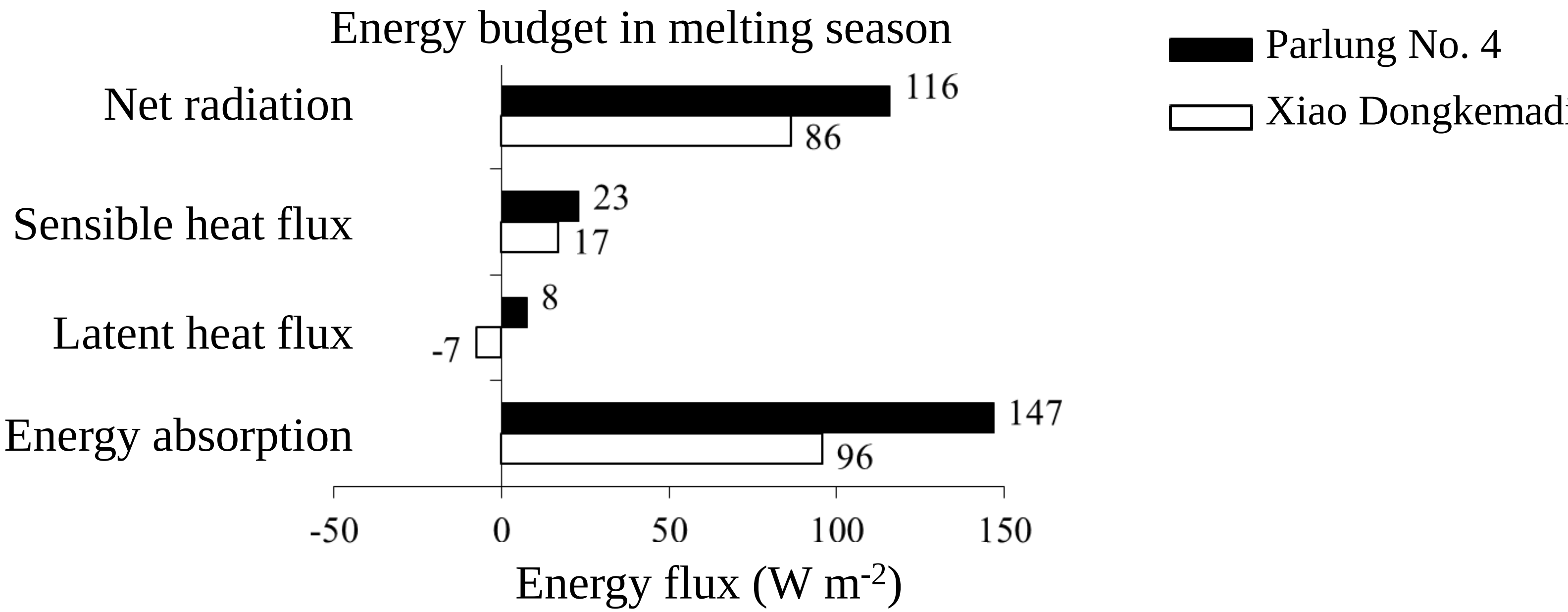
Analysis of the energy budget difference between two glaciers and quantification of sublimations in non-melting season



Main results:

- 1. Mass balance on Parlung No. 4 Glacier (4.3 m w.e.) is larger than that on Xiao Dongkemadi Glacier (2.0 m w.e.)
- 2. Snow/ice melt is the main contributer to the glacier surface mass balance

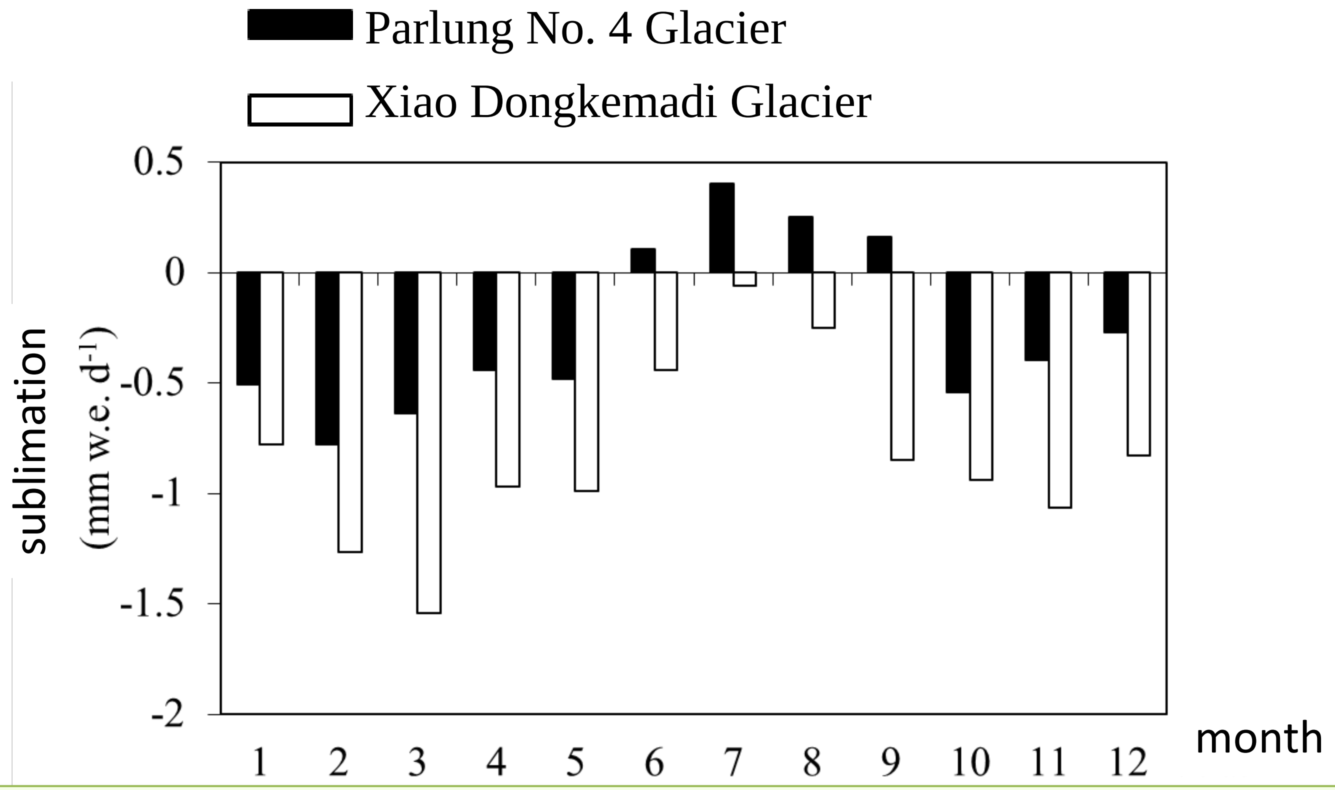
Analysis of the energy budget difference between two glaciers and quantification of sublimations in non-melting season



$$\text{Contribution} = \frac{\text{Energy flux on Parlung} - \text{corresponding energy flux on Xiao Dongkemadi}}{\text{Difference of energy absorption between the two glaciers}}$$

- In the melting season in 2012, the difference of net radiation between the two glaciers (30 W m^{-2}), the sensible heat flux difference (6 W m^{-2}), the latent heat flux difference (15 W m^{-2}) account for about 59%, 12%, and 29% of the energy absorption difference (51 W m^{-2}), respectively。
- The net radiation is the main contributor for the energy absorption difference, and the contribution of the latent heat flux could not be ignored either.

Analysis of the energy budget difference between two glaciers and quantification of sublimations in non-melting season



Sublimation is difficult to observe, however, it is easy to simulate by WEB-GM. It is found that the sublimation during non-melting season is very large for both glaciers.

- For Parlung, the sublimation in non-melt season (117 mm w.e.) is about 61% of the precipitation in non-melt season (191mm w.e.)
- For Xiao Dongkemadi, the sublimation in non-melt season (278 mm w.e.) is about 86% of precipitation (322 mm w.e.).

(to be submitted)

Summary

- This study develops an energy budget-based glacier mass balance model (WEB-GM), in which enthalpy is used as unknown to simplify the computation and improve the simulation accuracy. A new albedo scheme is developed to consider the impacts of sleet and shallow snow. A dynamic threshold scheme for precipitation type discrimination is developed based on temperature, relative humidity, and elevation. A turbulent flux scheme proper for glacier surface is implemented in the model.
- This model was evaluated using the dataset from field experiments in the ablation zone of the Parlung No. 4 Glacier and Xiao Dongkemadi Glacier. The evaluation shows that the model can reproduce the observed glacier ablation depth, surface albedo, surface temperature, sensible heat flux, and latent heat flux with high accuracy. Comparing with a traditional energy budget-based glacier mass balance model, this enthalpy-based model shows a superior capacity in simulation accuracy.
- The simulation results of a maritime glacier (Parlung No. 4 Glacier) and a continental glacier (Xiao Dongkemadi Glacier) by the new model are compared. The results show that the difference of surface energy absorptions between the two glaciers is mainly due to the net radiation and latent heat flux. The net sublimation is an important sink of the surface mass balance, even more crucial during the non-melting season.

ESA-MOST Dragon Cooperation

中国科技部-欧洲空间局“龙计划”合作

Thank you!

Institute of Tibetan Plateau Research
Chinese Academy of Sciences

26-30 June 2017 | Copenhagen, Denmark

2017年6月26-30日，丹麦 哥本哈根