Evaluation of Turbulent Flux Parameterizations over a Continental Glacier on the Tibetan Plateau

Yichan Xu[1,2], Meilin ~~Zhu[2]~~Zhu[1,*], Jing Gao[3,*], Daijiao Lin[1,2], Lei Hui[4], Fei Zhu[5], Huabiao Zhao[3], Fengying Zhang[1,2]

[1]~~College of Earth and Environmental Sciences~~[1]Center for the Pan-Third Pole Environment, Lanzhou University, Lanzhou, 730000, China

[2]~~Center for the Pan Third Pole Environment~~[2]College of Earth and Environmental Sciences, Lanzhou University, Lanzhou, 730000, China

[3]State Key Laboratory of Tibetan Plateau Earth System, Environment, and Resources (TPESER), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

[4]Danghe River Basin Water Resources Administration Bureau, Dunhuang, Gansu, 736200, China

[5]College of Surveying and Geo-Informatics, Tongji University, Shanghai, 200092, China

Correspondence to: Meilin Zhu (zhuml@lzu.edu.cn) and Jing Gao (gaojing@itpcas.ac.cn)

Abstract. A lack of observations of turbulent fluxes over continental glaciers limits our understanding of the mechanisms that control glacier variations and associated water resource changes across the Tibetan Plateau (TP). Here, we present the first comprehensive analysis of turbulent flux characteristics and a systematic evaluation of turbulent flux methods for a continental glacier on the TP, using eddy covariance observations from the Dunde Glacier (May–October, 2023). The Dunde Glacier persistently lost energy through latent heat flux (mean LE: −10.34 W m^{-2}) and gained energy via sensible heat flux (mean H: 6.93 W m^{-2}), with pronounced seasonal and ~~diurnal~~daily variability. On the basis of these measured data, we tested five turbulent flux methods for the Dunde Glacier, including those derived from katabatic flow models, simplified Monin–Obukhov similarity theory without stability corrections, Monin–Obukhov similarity theory with stability corrections using two different bulk Richardson numbers, and the Monin–Obukhov similarity theory with universal stability functions~~.~~ ~~Among all~~, with different roughness length parameterizations applied. All schemes showed generally good performance. Among them, the ~~Monin–Obukhov similarity theory with universal stability functions achieved the highest accuracy for~~method employing Richardson-number (Ri_b) stability correction exhibited comparatively better performance in simulating both H and LE ~~at different~~ across multiple timescales. We further ~~evaluated~~assessed the performance of these parameterizations ~~in~~within energy and mass balance modeling. ~~Our~~The results ~~show~~indicate that ~~the~~ recalibrated turbulent flux parameterizations ~~are an effective approach for improving~~effectively improve the accuracy of

~~modelled~~modeled glacier energy and mass balance, and that the ~~Monin-Obukhov similarity theory~~approach employing Richardson-number stability correction together with universal stability functions ~~yielded the best simulation performance for modelled~~achieved relatively high accuracy in glacier mass balance~~.~~ simulations. Our analysis also reveals a clear glacier type dependence in aerodynamic roughness length, with continental glaciers exhibiting a broader and generally lower roughness length distribution compared with maritime glaciers. We also found that during the humid heatwave event, the Dunde Glacier experienced a sharp increase in H ~~and reversal in~~ , while the magnitude of LE ~~during a humid heatwave event, shifting~~decreased and occasionally even reversed direction, leading to a transition from ~~a~~the commonly observed negative total turbulent heat flux under ~~the~~ mean ~~climate condition~~climatic conditions to positive values during the extreme event. However, none of the ~~turbulent flux methods~~existing schemes fully captured the ~~high~~LE values ~~that occurred~~observed during the extreme ~~weather and climate~~ event, indicating that there is currently an underestimation of the contribution of turbulent fluxes to glacier melt energy. These findings advance our knowledge of turbulent fluxes for continental glaciers on the TP and provide important guidance for the improvement of glacier models.

1 Introduction

Turbulent fluxes, including latent heat flux (LE) and sensible heat flux (H), are critical components of the surface energy balance (SEB) of glaciers and markedly influence glacier mass-loss processes. Research on the Tibetan Plateau (TP) shows that turbulent fluxes contribute approximately 14%–35% of the glacial energy budget ~~(Li et al., 2011; Mandal et al., 2022; Zhang et al., 2013; Zhu et al., 2017), serving as the primary energy source sustaining sublimation-driven mass loss, particularly during the cold season (October–May) (Azam et al., 2014a; Potocki et al., 2022). In addition, turbulent fluxes are one of the primary energy sources driving extreme glacier loss events (Thibert et al., 2018). Such events enhance the provision of water resources to downstream regions (Gao et al., 2019; Yao et al., 2022), altering hydrological processes therein (Radić and Hock, 2011; Zhu et al., 2024a); they may also be linked to glacier-related disasters, such as glacier avalanches (Zhao et al., 2022). Under ongoing global warming, the frequencies and intensities of extreme weather and climate events are projected to increase, likely contributing to severe future glacier mass loss owing to enhanced turbulent fluxes (Brun et al., 2018; Duan et al., 2012; Hugonnet et al., 2021; Yao et al., 2012). Therefore, a comprehensive understanding of the magnitude and variability of turbulent fluxes is essential to accurately quantify glacier SEB and project future glacier mass~~ (Li et al., 2011; Mandal et al., 2022; Zhang et al., 2013; Zhu et al., 2017), serving as the primary energy source sustaining sublimation-driven mass loss, particularly during the cold season (October–May) (Azam et al., 2014a; Potocki et al., 2022). In addition, turbulent fluxes are one of the primary energy sources driving extreme glacier loss events (Thibert et al., 2018). Such events enhance the provision of water resources to downstream regions (Gao et al., 2019; Yao et al., 2022), altering hydrological processes therein (Radić and Hock, 2011; Zhu et al., 2024); they may also be linked to glacier-related disasters, such as glacier avalanches (Zhao et al., 2022). Under ongoing global warming, the frequency and intensity of extreme weather events are projected to increase, which may lead to severe future glacier mass loss due to multiple contributing factors, such as enhanced turbulent fluxes and increased incoming longwave radiation (Duan et al., 2012; Yao et al., 2012; Brun et al., 2018; Hugonnet et al., 2021). Therefore, a comprehensive understanding of the magnitude and variability of turbulent fluxes is essential to accurately quantify glacier SEB and project future glacier mass balance changes.

Currently, glacier turbulent flux data are obtained through two main approaches: direct measurement using the eddy covariance (EC) method and estimation using numerical models. Turbulent flux observations over glaciers on the TP remain scarce, primarily owing to the difficulty of obtaining sustained measurements on glacier surfaces (Box and Steffen, 2001; Cullen et al., 2007; Kuipers Munneke et al., 2009). Notably, Yang et al. (2011) carried out observations over a 3-month period on the Parlung No. 4 Glacier, a maritime glacier on the southeastern TP characterized by high air temperatures and precipitation. They reported that during summer, the observed average H reached 28 W m^{-2}, whereas LE remained relatively low at −1 W m^{-2}. However, to date, there have been no reported observations of turbulent fluxes over continental glaciers on the TP characterized by low temperatures and precipitation, one of the most widely distributed glacier types on the TP. This data gap has resulted in an inadequate understanding of the energy balance processes of TP glaciers, which, in turn, is important to understand the climatic mechanisms controlling glacier variations across the TP.

Owing to the scarcity of observational data, numerical modeling has become the primary method by which glacier turbulent fluxes are estimated on the TP (Mölg et al., 2012; Yang et al., 2011; Zhu et al., 2018). Current turbulent flux modeling approaches predominantly rely on Monin–Obukhov similarity theory (MOST) (Monin and Obukhov, 1954), which provides accurate simulations of turbulent fluxes but is computationally intensive. In addition to sophisticated turbulent flux models that strictly implement MOST (Hock and Holmgren, 2005; Yang et al., 2002), various simplified turbulent flux parameterizations have been developed to derive LE and H. To improve computational efficiency, Oerlemans (2000) developed a highly simplified derivative model based on MOST, eliminating typically required iterative calculations. Essery and Etchevers (2004) and Suter et al. (2004) introduced stability functions to simulate turbulent fluxes. Oerlemans and Grisogono (2002) developed a turbulent flux model adapted to local glacier climatic conditions, which considers the influence of glacier wind on turbulent fluxes. However, the modeled turbulent fluxes for a given glacier tend to differ substantially across different turbulent flux parameterizations (Radić et al., 2017). Taking the Zhadang Glacier as an example, Zhang et al. (2016) found that the turbulent heat fluxes were 13.4 and 5.7 W m^{-2} for the winter and summer seasons, respectively, during the period 2011–2014; meanwhile, Li et al. (2014) reported that the turbulent heat fluxes were −1 and −11 W m^{-2} for the winter and summer seasons, respectively, during the period 2006–2011. The important reasons of such difference are the lack of observational data which can be used to calibrate the turbulent flux parameterizations. evaluations of the accuracy of those

~~different turbulent flux parameterizations remain limited on the TP. Guo et al. (2011) evaluated three turbulent flux parameterizations for the Parlung No.4 Glacier (maritime glacier) and found that the scheme proposed by Yang et al. (2002) produced lower errors in turbulent flux estimates during both individual melt phases and the entire ablation season. Compared with the other two schemes evaluated (Andreas, 1987; Smeets and van den Broeke, 2008), the mean absolute deviation (MAD) was reduced by approximately 12–29%. Yet, no comprehensive analysis exists for continental glaciers and no evaluation of the impact of the various parameterizations on glacier mass balance simulation on the TP. And we still do not know if these parameterizations can accurately capture the influence of extreme weather and climate events on turbulent fluxes. These uncertainties hinder accurate simulations of glacier energy and mass balances and impede a comprehensive understanding of accumulation and ablation processes and the physical relationship between glaciers and climate (Zhu et al., 2023).~~

Currently, glacier turbulent fluxes are derived through two main approaches: direct measurements using the eddy covariance (EC) method and model-based estimates using numerical models. Turbulent flux observations over glaciers on the TP remain scarce, primarily owing to the difficulty of obtaining sustained measurements on glacier surfaces (Box and Steffen, 2001; Cullen et al., 2007; Kuipers Munneke et al., 2009). Notably, Yang et al. (2011) carried out observations over a 3-month period on the Parlung No. 4 Glacier, a maritime glacier on the southeastern TP characterized by high air temperatures and precipitation. They reported that during summer, the observed average H reached 28 W m^{-2}, whereas LE remained relatively low at −1 W m^{-2}. However, to date, there have been no reported observations of turbulent fluxes over continental glaciers on the TP characterized by low temperatures and precipitation, one of the most widely distributed glacier types on the TP. This data gap has resulted in an inadequate understanding of the relative contributions of individual energy balance components to the overall surface energy budget of TP glaciers, which, in turn, is crucial for understanding the weather patterns controlling glacier variations across the TP.

Owing to the scarcity of observational data, numerical modeling is the primary method by which glacier turbulent fluxes have been estimated on the TP (Yang et al., 2011; Mölg et al., 2012; Zhu et al., 2018). Current turbulent flux modeling approaches predominantly rely on Monin–Obukhov similarity theory (MOST) (Monin and Obukhov, 1954), which has been widely applied for parameterizing near-surface turbulent fluxes. However, its performance over glaciers remains uncertain (Lord-May and Radić, 2024), particularly under strongly stable stratification and katabatic flow conditions, where the

fundamental assumption of vertically constant turbulent fluxes is frequently violated (Grisogono et al., 2007). In addition to sophisticated turbulent flux models that strictly implement MOST (Yang et al., 2002; Hock and Holmgren, 2005), various simplified turbulent flux parameterizations have been developed to derive LE and H. To improve computational efficiency, Oerlemans (2000) applied a highly simplified bulk formulation to estimate near-surface turbulent fluxes, assuming logarithmic vertical profiles of wind speed, temperature, and humidity to be valid under prevailing stable conditions, without explicitly accounting for stability-dependent flux modifications. Essery and Etchevers (2004) and Suter et al. (2004) implemented stability correction functions based on the bulk Richardson number (Ri_b) to modify turbulent flux estimates within bulk aerodynamic methods. Oerlemans and Grisogono (2002) developed a turbulent flux model adapted to local glacier climatic conditions, which considers the influence of glacier wind on turbulent fluxes. As a result, turbulent flux estimates for the same glacier can differ substantially depending on the choice of turbulent flux parameterization (Radić et al., 2017). Previous studies on the Zhadang Glacier clearly demonstrate this model-dependent variability, showing that the estimated multi-year mean turbulent heat fluxes for both winter and summer differ substantially when different modeling approaches are applied. Zhang et al. (2016) employed a highly simplified Monin–Obukhov–based bulk approach with constant exchange coefficients driven by near-surface wind speed and derived multi-year mean turbulent heat fluxes of 13.4 W m^{-2} in winter and 5.7 W m^{-2} in summer for the period 2011–2014. In contrast, Huintjes et al. (2015) adopted a bulk method in which atmospheric stability is represented by the bulk Richardson number, yielding multi-year mean turbulent heat fluxes of 8.0 W m^{-2} in winter and −28 W m^{-2} in summer during 2001–2011. Such differences may partly arise from variations in the study periods; However, a more important factor is the limited availability of observational data for calibrating turbulent flux parameterizations, as well as differences among the turbulent flux models themselves. Consequently, evaluations of the accuracy of different turbulent flux parameterizations over the TP remain limited, are largely confined to short time scales, and are constrained by the scarcity of EC observations. Moreover, comprehensive assessments of turbulent-flux schemes specifically for continental glaciers are still lacking. Guo et al. (2011) evaluated three turbulent flux parameterizations for the Parlung No.4 Glacier (maritime glacier) and found that the scheme proposed by Yang et al. (2002) produced lower errors in turbulent flux estimates during both individual melt phases and the entire ablation season. Compared with the other two schemes evaluated (Andreas, 1987; Smeets and van den Broeke, 2008), the mean absolute deviation (MAD) was reduced by

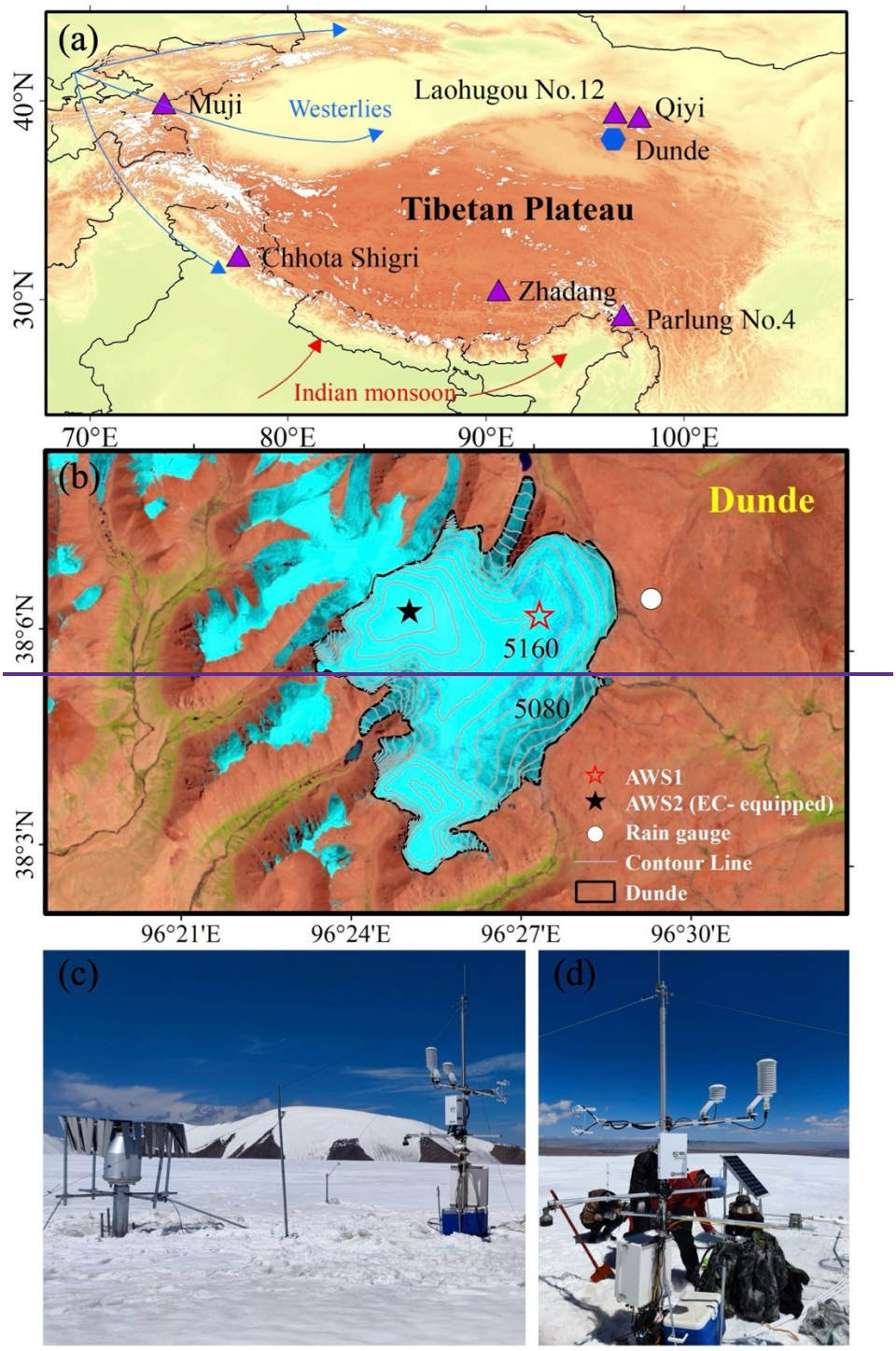
approximately 12–29%. Liu et al. (2024) employed eddy-covariance measurements to validate a one-camera time-lapse structure-from-motion (O-T-SfM) photogrammetry approach for monitoring snow sublimation on the August-one ice cap. The results indicate that, under snow-free conditions, glacier surface sublimation rates estimated using the O-T-SfM method were in good agreement with EC measurements. Both methods successfully captured daily snow sublimation during the winter season. However, to date, no comprehensive analysis has been conducted specifically for continental glaciers. Previous assessments focusing on maritime glaciers on the TP cannot be directly applied to the widely distributed continental glaciers due to fundamental differences in glacier characteristics. Continental glaciers therefore require observation-based evidence that is more directly applicable to their climatic and surface conditions (Zhu et al., 2023).

Here we provide the first ~~systematically analyze~~systematic analysis of meteorological and glacier mass balance observations and direct eddy-covariance-based turbulent flux measurements at the Dunde Glacier in the Qilian Mountains, the northeastern TP, to evaluate the applicability of multiple widely used turbulent flux methods over continental glaciers on the TP. We systematically analyze observed and modeled turbulent fluxes across multiple temporal scales, including ~~seasonal,~~ daily mean, ~~diurnal~~daily, and notably under extreme weather conditions, to test the ~~model robustness~~performance of the turbulent flux models. Finally, we assess the influence of the various turbulent flux parameterizations on the simulated glacier mass balance by implementing the parameterizations in the energy and mass balance model. The findings allow us to improve the accuracy of glacier surface energy and mass balance modeling and to advance our understanding of ablation processes on continental glaciers on the TP.

2 Study Area and Data

~~The Dunde Glacier is located in the western part of the Qilian Mountains, on the northeastern TP. It is a typical continental glacier, with an elevation ranging from 4400 to 5500 m (Guo et al., 2015). The ice cap covers an area of approximately 60 km^2, with an average annual elevation change rate of +0.04 ± 0.15 m yr^{-1} (Hugonnet et al., 2021; Shean et al., 2020). The region experiences pronounced annual and diurnal temperature variations, with a mean annual temperature of approximately −5 °C and annual precipitation ranging from 300 to 400 mm. Meltwater from the glacier primarily feeds into the Tataleng and Haerteng rivers, which provide an important water source to their respective drainage basins.~~

~~Turbulent fluxes were measured using the eddy covariance (EC) instrument (Campbell IRGASON), operating from 14 May until 12 October, 2023; this is a widely adopted technique in micrometeorological research that enables real-time, high-precision, and continuous monitoring of atmospheric turbulence. All turbulence raw data were collected at 10 Hz, including the three components of wind velocity, virtual temperature, and water vapor concentration. The observation site was situated on the surface of the Dunde Glacier (38°06′23″ N, 96°24′54″ E) at an elevation of 5317 m a.s.l., as shown in Fig. 1. In addition, air temperature (T_a), air pressure, relative humidity, wind speed and direction, incoming and outgoing shortwave radiation, incoming and outgoing longwave radiation, and glacier surface height were also measured at this site, using Campbell ClimaVUE50 automatic weather station (AWS). Precipitation was measured using a Geonor T-200B rain gauge at 4970 m a.s.l., and missing values in the precipitation record were supplemented using ERA5 reanalysis data. Details of the sensors used to measure each variable are provided in Table 1.~~



2.1. Measurement site

The Dunde Glacier is located in the western part of the Qilian Mountains, on the Northeastern TP. It is a typical continental glacier, with an elevation ranging from 4400 to 5500 m (Guo et al., 2015). The ice cap covers an area of approximately 60 km², with an average annual elevation change rate of −0.501 ± 0.08 m yr^{-1} (Hugonnet et al., 2021). The region experiences pronounced annual and daily temperature variations, with a mean annual temperature of approximately −5 °C and annual precipitation ranging

from 300 to 400 mm. Meltwater from the glacier primarily feeds into the Tataleng and Haerteng rivers, which provide an important water source to their respective drainage basins. The observation site was situated on the surface of the Dunde Glacier (38°06′23″ N, 96°24′54″ E) at an elevation of 5,317 m a.s.l., as shown in Fig. 1, and served as the primary observation site for this study.

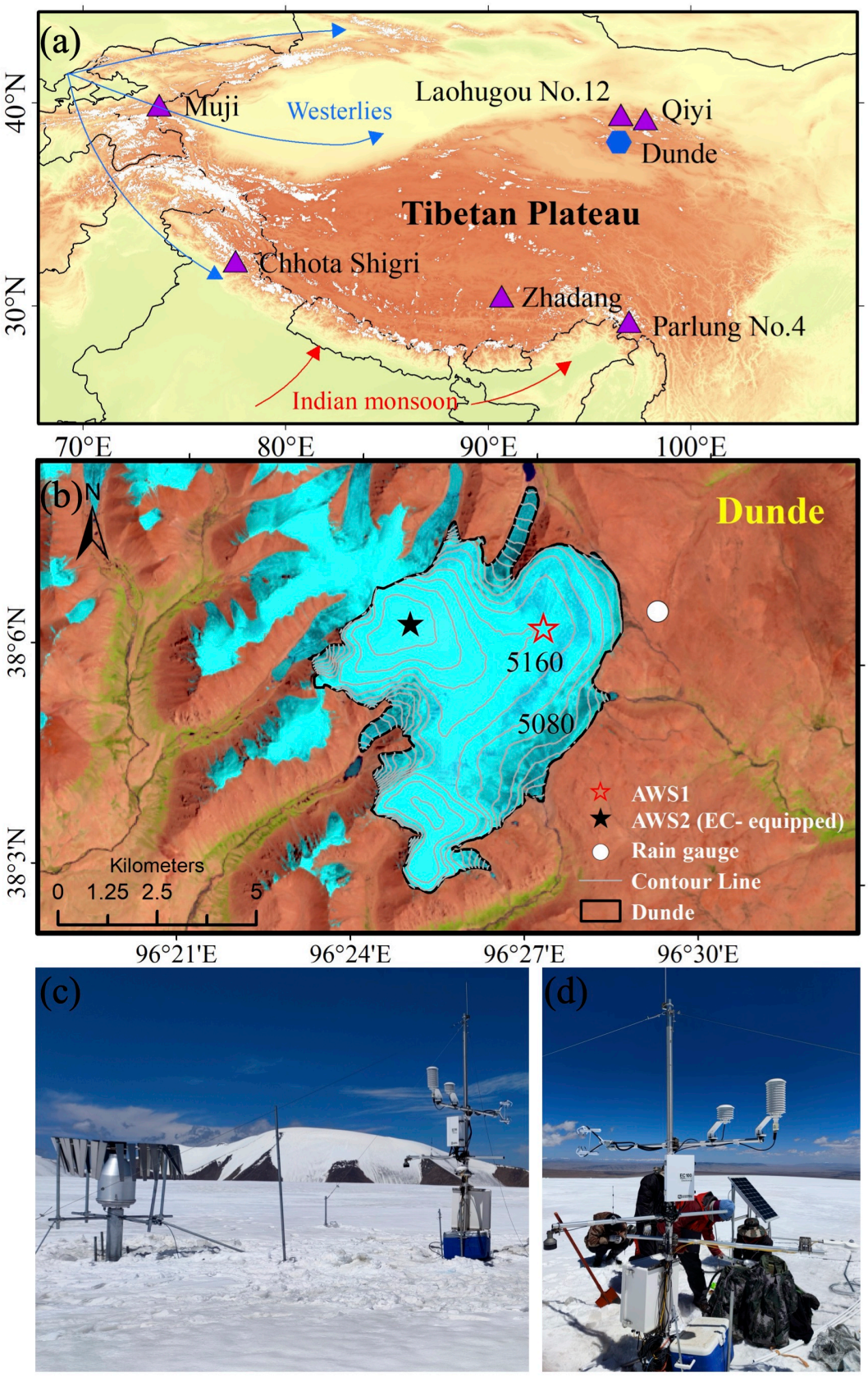


Figure 1: (a) Locations of the Dunde Glacier (blue hexagon) and selected reference glaciers (purple triangles) on the Tibetan Plateau. (b) Topographic map of the Dunde Glacier (40 m contour intervals) and locations of AWS1 and AWS2 (red and black stars, respectively). (c–d) Photographs of AWS2, equipped with an eddy

covariance (EC) system; the three-dimensional sonic anemometer was oriented toward the downwind direction of the prevailing westerlies (i.e., facing east), such that the sonic measurement volume was exposed to undisturbed incoming flow and flow distortion from the instrument and mounting structure was minimized (Photo credit: Meilin Zhu).

~~Table 2:~~**2.2. Meteorological data**

Meteorological variables, including air temperature, air pressure, relative humidity, wind speed and direction, incoming and outgoing shortwave radiation, incoming and outgoing longwave radiation, and glacier surface height, were primarily measured at the study site using a Campbell-ClimaVUE50 automatic weather station (AWS1) located at 5,317 m a.s.l. To ensure temporal continuity, occasional data gaps in these variables were filled using linear interpolation based on observations from a nearby auxiliary station (AWS2). The glacier surface temperature used in this study was derived from the observed outgoing longwave radiation, assuming a constant surface emissivity of 0.98. Details of the sensors used to measure each variable are provided in Table 1.

Precipitation was treated separately from other meteorological variables due to the lack of continuous in situ measurements at AWS1. Precipitation at 4,970 m a.s.l. was reconstructed using ERA5 reanalysis data following a two-step procedure. First, precipitation amounts were corrected for gauge under-catch as a function of air temperature and wind speed during precipitation events, following Ma et al. (2019). Second, a constant scaling factor of 1.16 was applied to the daily precipitation totals. To suppress unrealistically small precipitation signals, daily precipitation was set to 0 when ERA5 precipitation in the corresponding grid cell was lower than 0.45 mm, consistent with the criteria adopted in previous studies (Yang et al., 2013). After reconstructing the precipitation at 4970 m a.s.l., precipitation at 5317 m a.s.l. was estimated by extrapolating the reconstructed precipitation using three constant precipitation gradients (ΔP1, ΔP2, and ΔP3), following Zhu et al. (2022).

Table 1: Characteristics of the sensors installed in the eddy covariance system to measure turbulent fluxes and meteorological variables in this study.

Variable	Symbol (unit)	Sensor	Accuracy	Range	Height
Air temperature	T_a (℃)	Vaisala HMP155A	20 to 60 °C: ± (0.055 + 0.0057*×T_a) ℃ −80 to 20 °C: ± (0.226	−80 to 60 ℃	2.17 m

			− 0.0028×T_a) °C		
Relative humidity	RH (%)	Vaisala HMP155A	± ~~1~~2%	0%–100%	2.17 m
Wind speed	u (m s^{-1})	~~LICOR LI-7500DS~~Young05103	± 1.5%	0–100 m s^{-1}	2.05 m
Wind direction	WD (°)	~~LICOR LI-7500DS~~Young05103	± 2º	360 º	2.05 m
Air pressure	P (~~pa~~Pa)	Vaisala PTB210	± 0.5 hPa	50–1100 hPa	2.05 m
Incoming and outgoing longwave radiation	LWI, LWO (W m^{-2})	Campbell CNR4	± 1%	−250 to 250 W m^{-2}	1.~~6~~60 m
Incoming and outgoing shortwave radiation	SWI, SWO (W m^{-2})	Campbell CNR4	± 1%	0–2000 W m^{-2}	1.~~6~~60 m
Three-dimensional wind components	u′, v′, w′ (m s^{-1})	Sonic anemometer integrated in the Campbell IRGASON EC system	±1 mm s^{-1} (u′, v′) ±0.5 mm s^{-1} (w′)	-	2.05 m
Precipitation	(mm)	Geonor T-200B	± 0.1% ~~FS~~Full Scale	0–600 mm	1.~~7~~70 m

2.3. Eddy-Covariance systems

Turbulent fluxes were measured using a Campbell IRGASON eddy covariance (EC) system during the period from 14 May to 12 October 2023. The EC method is a widely adopted micrometeorological technique that enables real-time, accurate, and continuous monitoring of atmospheric turbulence. All raw turbulence data were recorded at a frequency of 10 Hz, including the three-dimensional wind components, virtual temperature, and water vapor concentration.

Turbulence data were processed using EddyPro software. A flux averaging interval of 30 min was applied during data processing. Prior to flux calculation, the raw high-frequency data were screened using the instrument-provided quality flags to identify and remove invalid or unreliable measurements. This

quality-flag-based filtering was applied at the high-frequency level before covariance calculation, and no interpolation was performed for the removed samples. Turbulent fluctuations were subsequently defined using the detrending options implemented in EddyPro. Time lags between wind components and scalar quantities were compensated using covariance maximization based on circular correlation techniques, which is recommended for open-path EC configurations (Moncrieff et al., 1997, 2005). Coordinate rotation was applied using the double-rotation method to correct for sensor tilt and streamline distortion (Kaimal and Kristensen, 1991). Flux correction was then applied to the calculated fluxes. Spectral corrections were first implemented to ensure that density corrections were based on environmentally representative fluxes. Density fluctuation effects were corrected using the Webb–Pearman–Leuning (WPL) formulation (Webb et al., 1980). The effects of humidity on sonic temperature and temperature-related covariances were corrected following the approach of Schotanus et al., (1983). Spectral attenuation resulting from both low-frequency and high-frequency losses was addressed using spectral correction schemes based on analytical transfer functions and reference cospectral formulations derived from the Kaimal spectrum (Kaimal et al., 1972) and its subsequent developments (Moore, 1986; Moncrieff et al., 1997, 2005; Massman, 2000, 2001). After the above processing steps, residual outliers in the 30 min flux data were further removed by excluding the following time intervals: periods with mean horizontal wind speed lower than 1 m s^{-1} or higher than 8 m s^{-1}; periods when the absolute value of vertical wind velocity exceeded 0.15 m s^{-1}; and periods when the wind direction corresponded to directions obstructed by the mounting structure. After this additional screening, 72% of the EC turbulent flux data were retained.

3 Methods

3.1 The algorithm and quality control for roughness lengths

This study uses the roughness lengths of momentum derived from EC measurements to calculate turbulent fluxes. The EC data, with a 30-minute temporal resolution, provide three-dimensional wind speed components, which are then used to indirectly calculate friction velocity (u∗) and Obukhov length (L) as follows:

$$u_* = \left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{1/4}, \quad (1)$$

$$L = -\frac{T_v u_*^3}{g\kappa \overline{w'T_v'}}, \quad (2)$$

where u' and v' represent the fluctuations in the horizontal wind components around their 30-minute mean values, w' denotes the fluctuation in the vertical wind component, T_v is the 30-min averaged virtual temperature (K), g is the acceleration due to gravity (9.8 m s^{-2}), and κ is the von Kármán constant (0.4). The roughness length for momentum (z_{0m}) is then retrieved using friction velocity and L, according to the following equation:

$$z_{0m} = \exp\left[-\kappa \frac{u}{u_*} - \Psi_v\left(\frac{z}{L}\right)\right] z, \quad (3)$$

Here, z_{0m} is the momentum roughness length, and u represents the 30-min averaged wind speed. The term Ψ_v is the stability correction function for momentum. Under stable conditions ($\frac{z}{L} > 0$), it follows the formulation of Holtslag and De Bruin (1988), while under unstable conditions ($\frac{z}{L} < 0$), it follows the Businger-Dyer expression described by Paulson (1970).

Stable conditions:

$$-\Psi_v\left(\frac{z}{L}\right) = \frac{z}{L} + b\left(\frac{z}{L} - \frac{c}{d}\right)\exp\left(-\frac{dz}{L}\right) + \frac{bc}{d}, \quad (4)$$

Unstable conditions:

$$x = \left(1 - 16\frac{z}{L}\right)^{0.25}, \quad (5)$$

$$\Psi_v\left(\frac{z}{L}\right) = \log\left(\frac{1+x}{2}\cdot\left(\frac{1+x}{2}\right)^2\right) - 2\cdot\arctan(x) + \frac{\pi}{2}, \quad (6)$$

where the constants are a = 1, b = 2/3, c = 5, and d = 0.35; z is the measurement height. To provide a reference for future studies without reliance on EC data, we parameterized the scalar roughness lengths (z_{0t} and z_{0q}) as functions of the momentum roughness length z_{0m}, which was derived from EC data. This parameterization follows the methods proposed by Andreas (1987) and Smeets and van den Broeke (2008), which have been shown to provide accurate estimates of scalar roughness lengths over glaciers. Hereafter, these two parameterization schemes are referred to as A87 and SvdB, respectively. In this study, we performed quality control on the 30-minute z_{0m} values following the procedures outlined by Conway and Cullen (2013) and Li et al. (2016). Detailed processing steps can be found in Radić et al. (2017). After filtering, 183 valid z_{0m} data points remained, with inferred z_{0m} values ranging from 1.14

$\times 10^{-5}$ m to 2.08×10^{-2} m. We finally selected the median of the quality-controlled z_{0m} values (1.2×10^{-4} m) as the representative roughness length for evaluating the performance of the different turbulent flux parameterization schemes. For the measured sensible and latent heat fluxes, the same general quality control procedures as those applied to z_{0m} were adopted. However, with respect to the neutrality and wind speed criteria, flux calculations were allowed to include data satisfying $|z/L| < 2$ and $u > 1$ m s^{-1}. After screening, 592 turbulent flux data points were retained for subsequent model calculations and evaluation.

3.2 Bulk methods

Variations in the performance of different turbulent flux parameterizations primarily arise from their respective approaches to computing turbulent exchange coefficients and applying atmospheric stability corrections. These methodological differences directly affect method accuracy under varying temperature gradients, humidity gradients, and wind speed conditions, leading to discrepancies in the simulated LE and H. In this study, we evaluate two categories of bulk aerodynamic methods for calculating turbulent fluxes over glacier surfaces. The first category comprises methods in which the bulk exchange coefficient (C) is formulated as a function of surface roughness lengths and atmospheric stability. The second category includes bulk methods that explicitly incorporate a simplified katabatic (glacier wind) parameterization.

Within this framework, we analyze five bulk methods that are commonly applied to glacier surfaces. These include: (i) a simplified bulk formulation without explicit stability corrections (C_{log}); (ii) and (iii) bulk methods that account for atmospheric stability through the bulk Richardson number (C_{Rib1} and C_{Rib2}); (iv) a method based on the full Monin–Obukhov similarity theory, employing universal stability functions with iterative closure (C_{M-O}); and (v) a bulk method derived from a simplified katabatic flow model that explicitly considers glacier wind effects (C_{kat}). The detailed formulations of methods (i) through (v) are described in the following subsections.

Model performance is evaluated by comparing 30-min turbulent fluxes (H and LE) simulated by each method with eddy covariance (EC) measurements, using standard statistical metrics including the root mean square error (RMSE), mean bias error (MBE), and mean absolute deviation (MAD). For consistency between modeled and observed fluxes, turbulent fluxes are defined as positive when directed

from the atmosphere toward the glacier surface, and negative in the opposite direction. The naming of the turbulent flux methods follows the convention of Radić et al. (2017).

3.2.1. C_{kat} method

The C_{kat} method explicitly considers katabatic flows, introducing the katabatic bulk exchange coefficient (C_{kat}) to partially overcome the limitations of MOST during strong katabatic wind conditions ~~The naming of the turbulent flux calculation methods in this study follows the convention of Radić et al. (2017). However, differences exist in the implementation of the C_{M_O} method (3.5). Specifically, although both our C_{M_O} method and that of Radić et al. (2017) are based on the bulk aerodynamic method combined with Monin–Obukhov similarity theory and iterative closure of the H, the source of roughness lengths is treated differently. Radić et al. (2017) prescribed fixed roughness lengths obtained as the logarithmic means of 30-min OPEC inversions under near-neutral conditions, whereas in this study, the roughness lengths are computed dynamically following Andreas (1987), as functions of the friction velocity and the Reynolds number. This modification allows the scalar roughness lengths (z_{0t} and z_{0e}) to respond to changes in atmospheric stability and flow regime, thereby providing a more physically responsive formulation.~~

~~3.1. C_{kat} method~~

~~The C_{kat} method incorporates the influence of glacier winds (katabatic flows) on surface energy fluxes using the bulk aerodynamic method, which relates turbulent fluxes to the structure of the ambient atmosphere (Oerlemans and Grisogono, 2002). In a stably stratified atmosphere, it identifies H and vertical advection as the primary contributors to the surface energy budget; LE and H are expressed as:~~

(Oerlemans and Grisogono, 2002). This approach emphasizes intensified katabatic turbulence during nocturnal cooling or cold-air intrusions, enhancing turbulent exchange (Horst and Doran, 1988). However, the C_{kat} method lacks explicit stability corrections and dynamic roughness length adjustment, leading to a slow response under rapidly changing surface conditions (Denby, 2000). Hence, its application is more suited to small and medium-sized glaciers rather than large-scale domains. LE and H are expressed as:

$$LE = \rho \frac{0.622}{P} \rho L_{s/f} C_{kat}(e_a - e_s) \mathrm{C_{kat}}(e_a - e_s) \quad (7)$$

$H = \rho C_p C_{kat}(T_a - T_s)$ $H = 0.622\rho C_p C_{kat}(T_a - T_s)$ $\rho C_p C_{kat}(T_a - T_s)$,

(2 (8)

where, ρ and C_P are the density (kg·m⁻³) and heat capacity of air, respectively; P is atmospheric pressure (Pa), $L_{s/f}$ is the latent heat of sublimation/fusion, selected based on surface temperature; e_a and e_s are the atmospheric vapor pressure and saturated vapor pressure at the glacier surface (Pa), respectively; T_a and T_s denote the air temperature and glacier surface temperature, respectively; and C_{kat} is the katabatic bulk exchange coefficient, calculated using the following equation:

$C_{kat} C_{kat} = -C_{tub} C_{tub2}^2 C \left(\frac{g}{T_0 \gamma P_r}\right)^{1/2}$,

(3 9)

Here, C_{tub} and C_{tub2} are dimensionless empirical constants; used to optimize the parameterization of turbulent fluxes; C is replaced by the air–surface temperature difference (T_a–T_s); T_0= 273.15 K; γ is the potential temperature gradient, which is prescribed as a constant value of 0.005 K m⁻¹ (Oerlemans and Grisogono, 2002); and P_r is the Prandtl number (~ 0.71); and g is gravitational acceleration (~ 9.8 m·s⁻²).).

3.2.2. C_{log} method

The C_{log} method represents a highly simplified derivative of MOST. This method employs a constant exchange coefficient (C_h) driven by near-surface wind speed and the difference in air temperature (or humidity) and surface temperature (or humidity), providing a simplified, computationally efficient structure suitable for large-scale climate models (Oerlemans, 2000). It does not dynamically adjust atmospheric stability, and instead retains only a linear relationship for surface fluxes. Being a wind-speed-driven scheme, it performs well under less stable stratification conditions. However, the method also exhibits certain limitations. Owing to the absence of atmospheric stability parameters in its structure, it cannot identify or respond to surface inversions forming at night or in the early morning. This method represents a highly simplified derivative of MOST (Oerlemans, 2000). It does not dynamically adjust atmospheric stability, and instead retains only a linear relationship for surface fluxes; LE and H are expressed as:

$LE = 0.622\rho L_{s/f} C_h u(e_a - e_s)/P$, (4)

LE and H are expressed as:

$$LE = 0.622\rho L_{s/f} C_h u(e_a - e_s)/P, \quad (10)$$

$$H = \rho C_P C_h u(T_a - T_s) \quad (11)$$

~~(5~~

~~where, u is wind speed (m·s⁻¹), P is atmospheric pressure (Pa), and $C_{\emptyset}$ is the turbulent exchange coefficient.~~

~~3~~where, u is wind speed (m·s⁻¹), and C_h is the turbulent exchange coefficient. Following (Oerlemans, 2000), turbulent fluxes are regulated through the exchange coefficient C_h. Here, C_h is treated as a calibration parameter and optimized by minimizing the mismatch between modeled and observed turbulent fluxes.

3.2.3. C_{Rib1} method

~~The C_{Rib1} method replaces the Monin–Obukhov length (L) with the bulk Richardson number (Ri_b) to diagnose atmospheric stability (Suter et al., 2004). It replaces the stability functions (ψ) in MOST with a composite function ($f_{\emptyset}(Ri_b)$), derived from stability functions for momentum ($\emptyset_m$), heat ($\emptyset_{\emptyset}$), and water vapor ($\emptyset_q$) (Dyer, 1974; Holtslag and Bruin, 1988). This approach avoids complex iterative calculations while preserving the core MOST principle of stability modulated turbulent exchange.~~

The C_{Rib1} method retains the C_{log} formulation for turbulent flux calculation but introduces the bulk Richardson number (Rib) to allow for flux reduction under stable stratification (Suter et al., 2004). The bulk Richardson number can be related to the stability functions for momentum (ϕ_m), heat (ϕ_h), and water vapour (ϕ_q) in the following way ((Oke, 1987); see Eq. 14). In this formulation, the composite function ($f_h(Ri_b)$) is constructed from the stability functions for momentum (ϕ_m), heat (ϕ_h), and water vapor (ϕ_q) (Dyer, 1974; Holtslag and Bruin, 1988).

$$LE = \rho L_{s/f} \frac{k^2}{k^2} \kappa^2 z_u z_q \left(\frac{\Delta\bar{u}\Delta\bar{q}}{z^2}\right) \frac{(\emptyset_m \emptyset_{\emptyset})^{-1}}{(\phi_m \phi_h)^{-1}} \quad (12)$$

~~(6~~

$$H = \rho C_P \frac{k^2}{k^2} \kappa^2 z_u z_t \left(\frac{\Delta\bar{u}\Delta\bar{T}}{z^2}\right) \frac{(\emptyset_m \emptyset_q)^{-1}}{(\phi_m \phi_q)^{-1}}, \quad (13)$$

~~(7~~

~~$\begin{cases}(\phi_m\phi_{h,q})^{-1} = (1-5Ri_b)^2 & (\mathrm{Rib} > 0) \\ (\phi_m\phi_{h,q})^{-1} = (1-16Ri_b)^{0.75} & (\mathrm{Rib} \le 0)\end{cases}$~~ $\begin{cases}(\phi_m\phi_{h,q})^{-1} = (1-5Ri_b)^2 & (Ri_b > 0) \\ (\phi_m\phi_{h,q})^{-1} = (1-16Ri_b)^{0.75} & (Ri_b \le 0)\end{cases}$,

~~(8~~(14)

$$Ri_b = \frac{g\frac{\Delta\bar{T}}{\Delta Z}}{\bar{T}\left(\frac{\Delta\bar{u}}{\Delta Z}\right)^2} \quad ,$$

~~(9~~(15)

~~where, k (~ 0.4) is the von Kármán constant;~~where $\bar{u}$, $\bar{q}$, and $\bar{T}$ represent the mean wind speed, specific humidity, and air temperature, respectively; ~~z is the measurement height,~~ where $z_{u,t,q}$ are the log mean heights defined as:

$$z_{u,t,q} = \frac{z - z_{0u,t,q}}{ln\left(\frac{z}{z_{0u,t,q}}\right)} \quad ,$$

(~~10~~16)

and $z_{0u,q,t}$ denotes the surface roughness lengths for momentum, humidity, and temperature~~, which are typically assumed equal~~.

~~3.4. C_{Rib2} method~~

~~Similar to C_{Rib1}, the C_{Rib2} method is a non-iterative method for calculating turbulent fluxes (Essery and Etchevers, 2004). It replaces L and ψ with Ri_b and $f_h(Ri_b)$, respectively, thereby reducing computational complexity while preserving the physical consistency of MOST. Turbulent fluxes in the C_{Rib2} method are calculated as:~~

~~$LE = \rho L_{s/f} C_H u[q_{sat}(T_s, P_s) - q]$, (11)~~

3.2.4. C_{Rib2} method

Similar to C_{Rib1}, the C_{Rib2} method is a non-iterative method for calculating turbulent fluxes (Essery and Etchevers, 2004). It employs Ri_b and $f_h(Ri_b)$, thereby reducing computational complexity while preserving the physical consistency of MOST. Turbulent fluxes in the C_{Rib2} method are calculated as:

$$LE = \rho L_{s/f} C_H u[q_{sat}(T_s, P) - q], \quad (17)$$

$$H = \rho C_P C_H u[T_s - T_a] \quad ,$$

(~~12~~18)

~~where, $q_{sat}(T_s, P_s)$ denotes the saturation specific humidity at surface temperature T_s and pressure P_s, and C_H is a surface exchange coefficient. Following Louis (1979), the exchange coefficient for surface sensible and latent heat flux is calculated as $C_H = C_{Hn} f_h$, where~~

~~$$C_{Hn} = 0.16 \left[\ln\left(\frac{z_t}{z_0}\right)\right]^{-2}, \quad (13)$$~~

where, $q_{sat}(T_s, P)$ denotes the saturation specific humidity at surface temperature T_s and pressure P, and C_H is a surface exchange coefficient. Following Essery and Etchevers (2004) and Louis (1979), the exchange coefficient for surface sensible and latent heat flux is calculated as $C_H = C_{Hn} f_h$, where

$$C_{Hn} = \kappa^2 \left[\ln\left(\frac{z}{z_{0m}}\right)\right]^{-2}, \quad (19)$$

is the neutral exchange coefficient for roughness length ~~z_0~~z_{0m} and

$$f_h = \begin{cases} (1 + 10Ri_b)^{-1} & Ri_b \geq 0 \\ 1 - 10Ri_b\left(1 + 10Ri_b C_{Hn}\sqrt{-Ri_b}/f_z\right)^{-1} & Ri_b < 0 \end{cases},$$

(~~14~~20)

with

$$f_z = \frac{1}{4}\left(\frac{z_0}{z_t}\right)^{~~1/2~~}\left(\frac{z_{0m}}{z}\right)^{1/2},$$

(~~15~~21)

Although atmospheric stability is also characterized by Ri_b, the calculation approach in C_{Rib2} method differs from that in C_{Rib1} method as follows:

~~$$Ri_b = \frac{g z_1}{u^2}\left\{\frac{T_a - T_s}{T_a} + \frac{q - q_{sat}(T_s, P_s)}{q + \epsilon/(1-\epsilon)}\right\},$$~~

~~(16)~~$$Ri_b = \frac{g z_1}{u^2}\left\{\frac{T_a - T_s}{T_a} + \frac{q - q_{sat}(T_s, P)}{q + \epsilon/(1-\epsilon)}\right\}, \quad (22)$$

where, ~~z_t~~ ~~ϵ~~ is ~~the observation height and ϵ is~~defined as the ratio of the molecular weights of water ~~and~~to dry air, with a value of 0.622.

3.2.5. C_{M-O} method

~~This method, which adds stability corrections using universal stability functions, employs a complete MOST framework that explicitly calculates the friction velocity (u*), ψ, and L (Hock and Holmgren, 2005). It separately applies roughness lengths for temperature (z_{0t}), humidity (z_{0e}), and~~

~~momentum (z_{0w}). Iterative calculations ensure closure of the turbulent fluxes, utilizing nonlinear stability functions from Beljaars and Holtslag (1991) under stable conditions, and Businger–Dyer expressions for unstable conditions, iteratively solving for u* and L (Beljaars and Holtslag, 1991; Paulson, 1970).~~

This method replaces the composite stability function $f_h(Ri_b)$ used in the C_{Rib} with the universal stability functions (ψ) to introduce stability corrections. It adopts a complete MOST framework and explicitly calculates the friction velocity ($u*$), ψ, and L (Hock and Holmgren, 2005). Separate roughness lengths are applied for momentum (z_{0m}), temperature (z_{0t}) and humidity (z_{0e}). Turbulent fluxes are obtained through an iterative solution procedure that ensures closure of the nonlinear stability equations.Under stable conditions, the nonlinear stability functions of Beljaars and Holtslag (1991) are used, whereas under unstable conditions, the Businger–Dyer relationships are applied (Beljaars and Holtslag, 1991; Paulson, 1970). The variables $u*$ and L solved iteratively to achieve convergence.

$$LE = L_{s/f}\frac{0.622\rho}{P_0}\frac{k^2}{\left[\ln\left(\frac{z}{z_{0w}}\right)-\psi_M\left(\frac{z}{L}\right)\right]\left[\ln\left(\frac{z}{z_{0e}}\right)-\psi_E\left(\frac{z}{L}\right)\right]}\frac{k^2}{\left[\ln\left(\frac{z}{z_{0m}}\right)-\psi_M\left(\frac{z}{L}\right)\right]\left[\ln\left(\frac{z}{z_{0e}}\right)-\psi_E\left(\frac{z}{L}\right)\right]}u(e_a-e_s) \quad , \tag{~~17~~23}$$

~~$$H = \rho C_p\frac{k^2}{\left[\ln\left(\frac{z}{z_{0w}}\right)-\psi_M\left(\frac{z}{L}\right)\right]\left[\ln\left(\frac{z}{z_{0t}}\right)-\psi_H\left(\frac{z}{L}\right)\right]}u(T_a-T_s), \tag{18}$$~~

~~**3.6. Evaluation of model performance**~~

~~We used three statistical measures to quantify model accuracy: root mean square error (RMSE), MAD, and mean bias error (MBE). The RMSE quantifies the differences between observed (Q_o) and modeled (Q_m) fluxes:~~

~~$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Q_{mi}-Q_{oi})^2}, \tag{19}$$~~

~~The MAD reflects the average magnitude of deviations:~~

~~$$MAD = \frac{1}{n}\sum_{i=1}^{n}|Q_{oi}-Q_{mi}|, \tag{20}$$~~

$$H = \rho C_P\frac{k^2}{\left[\ln\left(\frac{z}{z_{0m}}\right)-\psi_M\left(\frac{z}{L}\right)\right]\left[\ln\left(\frac{z}{z_{0t}}\right)-\psi_H\left(\frac{z}{L}\right)\right]}u(T_a-T_s)\,, \tag{24}$$

For clarity and reproducibility, all model-specific parameters and physical constants used in this study are summarized in Table 2, together with their numerical values, units, and data sources where applicable.

Table 2: Summary of model-specific parameters and physical constants adopted in this study.

Parameter	Description	Value	Unit	Source
C_{turb}	dimensionless empirical constants	0.0001	–	this study
C_{turb2}	dimensionless empirical constants	0.007	–	this study
γ	potential temperature gradient	0.005	K m^{-1}	Oerlemans and Grisogono, 2002
P_r	Prandtl number	0.71	–	Standard value
$L_{s/f}$	latent heat of sublimation/evaporation	L_f = 2514000 L_s = 2849000	J kg^{-1}	Standard value
Cp	heat capacity of air	1005	J kg^{-1} K^{-1}	Standard constant
C_h	turbulent exchange coefficient (recalibrated in this study)	0.0005	–	this study
C_h	turbulent exchange coefficient (reference value)	0.00127	–	Oerlemans, 2000
κ	von Karman constant	0.4	–	Standard constant
P_0	mean atmospheric pressure at sea level	101325	Pa	Standard value
z_0	Aerodynamic roughness length (literature value)	0.003	m	Essery and Etchevers, 2004
z_{0m}	Aerodynamic roughness length (literature value)	0.01	m	Hock and Holmgren, 2005

3.3 Energy Balance Model

The ~~MBE~~approximate SEB (in W m^{-2}) can be written as:

$$Q_m = S_{\text{in}} + S_{\text{out}} + L_{\text{in}} + L_{\text{out}} + H + LE + Q_{\text{rain}} + Q_{\text{sub}} \quad (25)$$

where Q_m is the energy available for melt, S_{in} represents ~~systematic biases in model predictions~~the incoming shortwave radiance, S_{out} is the reflected shortwave radiation, and L_{in} and L_{out} refer to the incoming and outgoing longwave radiation, respectively. Q_{rain} is the heat transfer due to rainfall, while Q_{sub} denotes the heat flux into the ice. In the model, the energy fluxes are expressed in a way that the surface temperature is the only unknown variable, which is determined by iteratively solving Eq. (25)

with the left-hand-side set to zero. If the computed surface temperature exceeds the melting point, it is constrained to the melting point, and the energy fluxes are recalculated. In this scenario, the sum of fluxes becomes positive, and melting will occur (EBFM; Van Pelt et al., 2012, 2019). The mass balance (MB, mm w.e.), is calculated as follows:

~~$MBE = \frac{1}{n}\sum_{i=1}^{n}(Q_{oi} - Q_{mi})$,~~ (21)

$$MB = \int \left(\frac{Q_m}{L_m} + P_{snow} + \frac{Q_L}{L_s}\right) dt \,, \quad (26)$$

P_{snow} is the snow accumulation, Q_L is the mass exchange due to sublimation. L_m is the latent heat of melting (~ 3.34 × 10^5 J kg^{-1}). Since this study is based on point data and does not involve spatial data, topographical parameters were not set in EBFM during the analysis.

4 Results

4.1 Meteorological conditions on the Dunde Glacier

~~Meteorological data observed at 5317 m a.s.l., including air temperature (T_a), glacier~~ Figure 2 shows the temporal evolution of near-surface ~~temperature (T_s), relative humidity (RH), wind speed (u) and direction (WD), and atmospheric pressure (Pres), were collected~~meteorological conditions during the observation period from 14 May to 12 October~~,~~ 2023~~ (Fig. 2). During the study period,~~ . The daily mean T_a at the Dunde Glacier ranged from −14.1 to 3.3 °C, ~~averaging −~~with an average of −4.0 °C (Fig. 2a). ~~Instances of a daily mean T_a above 0 °C occurred primarily in~~ The warmest months were July and August, ~~which are the warmest months, with a mean value of −~~averaging −1 °C. October was the coldest month, with ~~an average~~a mean daily ~~mean~~ T_a of −9.5 °C. ~~Air temperature exhibited pronounced seasonal variability, with higher summer averages (−2.1 °C) compared with spring (−7.8 °C) and autumn (−6.5 °C). The mean daily T_s was −5.4 °C, ranging~~The mean daily T_s ranged from −17.2 °C ~~(7 October)~~ to 0 °C ~~(10 and 11 July, and 14 and 16 August; Fig. 2c). Seasonal variations in T_s closely mirrored those~~ , with a mean of ~~T_a, peaking in summer (average of −3~~ −5.4 °C (Fig. 2d) and exhibited seasonal variability. Over the study period, the mean surface temperature deficit ($T_a - T_s$) was 1.4 °C~~) and dropping substantially in spring (average of −9.0 °C) and autumn (average of −8.3 °C). The difference between T_a and T_s also exhibited seasonal variability~~, reaching ~~a maximum in autumn (1.8 °C), with lower~~its highest values in ~~spring~~July and September (1.~~2~~9 °C) and ~~summer (1.3~~its lowest value in June (0.7 °C). ~~In addition, both T_a and T_s displayed clear~~To isolate the diurnal variability from the dominant seasonal signal, Fig. 2c and

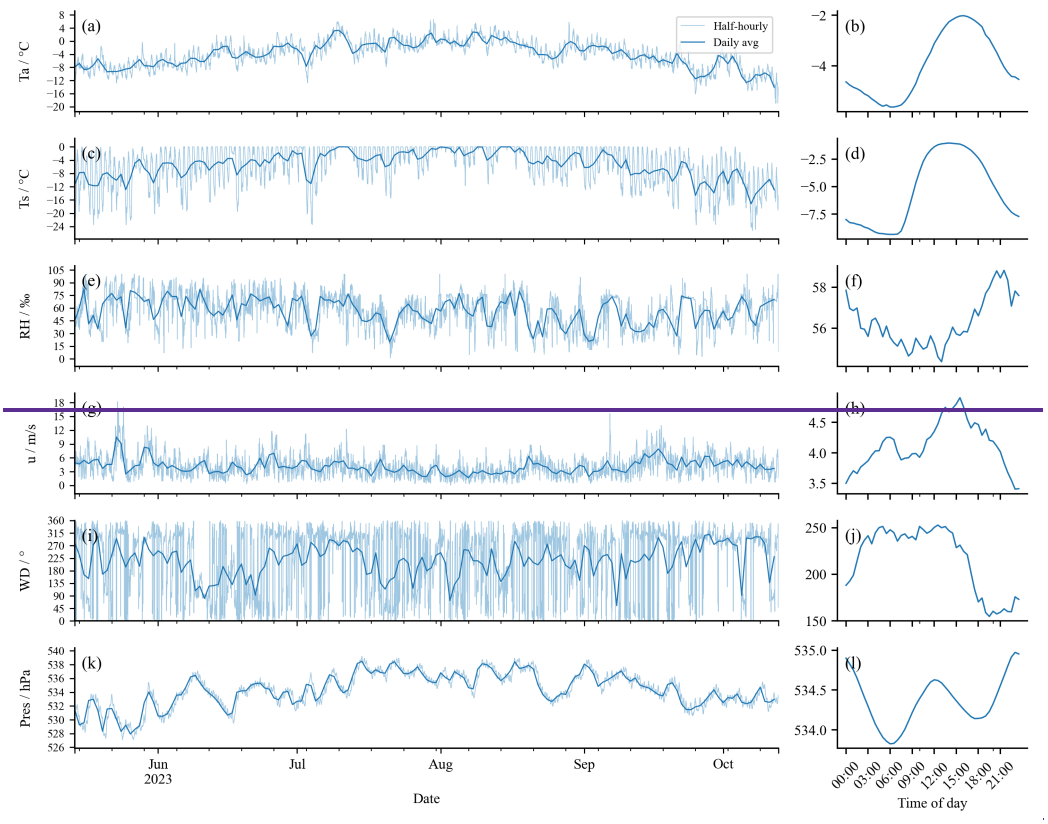
f presents detrended daily cycles~~, characterized by single trough~~ of T_a and T_s. After detrending, both variables display clear and consistent single-peak and single-~~peak~~ trough diurnal patterns;~~ T_s peaked at −1.0 °C around 14:00, while T_a reached a maximum of −2.0 °C at 16:00, about two hours later. In contrast, both T_s and T_a exhibited minimum values at 06:00, with T_s dropping to −9.4 °C and T_a to −5.6 °C.~~ The earlier T_s peak is interpreted to reflect the rapid radiative response of the glacier surface to incoming solar radiation; T_a responds more slowly owing to the thermal inertia of air and gradual development of convective mixing. At night, however, both the glacier surface and air cool synchronously under stable stratification and weak turbulence, resulting in the coincident early morning T_s and T_a minima. Generally, T_a was higher than T_s for most of a given day, indicative of a persistent near-surface temperature inversion layer over the glacier surface (Fig. ~~2b~~2t and ~~du~~).

Mean daily relative humidity at the Dunde Glacier was 56.3%, with notable seasonal variability (Fig. ~~2e~~2g). The highest seasonal average occurred in ~~spring~~May-Jun (62.6%), whereas ~~autumn~~Sep-Oct was the driest season (50.7~~%), particular September, which recorded the lowest monthly average (47.5%).~~%). On a ~~diurnal~~daily scale, relative humidity ~~exhibited an inverse pattern compared with that of T_a,~~ characterized by a distinct midday trough and nighttime peak (Fig. ~~2f). Daily minimum humidity typically occurred around noon, coinciding with peak solar radiation and higher T_a. Thereafter, relative humidity gradually increased, reaching a maximum of 58.8% at approximately 21:30; this likely resulted from the combined effects of rapid radiative cooling of the glacier surface, low T_a, and weak wind conditions.~~2i).

Daily mean wind speeds ranged from 1.7 to 10.5 m s^{-1}, averaging 4.1 m s^{-1}, with marked seasonal variability (Fig. ~~2g~~2j). The strongest winds occurred during ~~spring~~May-Jun (average of 5.51 m s^{-1}), while ~~summer~~Jun-Aug recorded the weakest winds (average of 3.6 m ~~s^{-1}), particularly August, which recorded the lowest monthly mean (3.1 m s^{-1}). Autumn wind speeds were intermediate, averaging 4.6 m s^{-1}.~~ s^{-1}). On a ~~diurnal~~daily scale, wind speed exhibited ~~substantial variations~~ a pronounced diurnal cycle, with ~~an average diurnal range~~the mean daily cycle showing a peak-to-trough difference of approximately 1.5 m ~~s^{-1}. Morning winds were generally weak, increasing notably after 10:30, peaking around 15:30, and subsequently decreasing to a daily minimum around 23:30~~ s^{-1} (Fig. 2l). ~~2h).~~Wind direction was presented using circular statistics. Nighttime wind speeds ~~remained relatively stable, associated~~exhibited limited variability, consistent with stable atmospheric stratification. Prevailing wind directions were westerly and northwesterly (Fig. ~~2i~~2m and ~~jo~~), highlighting the dominant influence of the mid-latitude westerlies

on regional meteorological conditions.

Daily mean atmospheric pressure at the Dunde Glacier during our study period ranged from 527.9 to 538.4 hPa, with an average of 534.4 hPa (Fig. ~~2k~~2p). The highest seasonal mean atmospheric pressure occurred in ~~summer~~Jun-Aug (535.2 hPa) and the lowest in ~~spring~~May-Jun (530.6 hPa). On a ~~diurnal~~daily scale, atmospheric pressure exhibited a distinct double-peak, double-trough daily pattern~~, with minimum pressure occurring at 06:00, maximum at 23:30, a secondary minimum between 17:30 and 18:00, and a secondary maximum at 12:00~~ (Fig. 2r). Overall, ~~2l). Variations in~~ atmospheric pressure ~~markedly influence glacier surface energy exchange by altering specific humidity gradients and air density, thus indirectly controlling~~variations were relatively small over the study period and therefore likely played only a minor role in modulating turbulent fluxes ~~on the glacier surface.~~ .



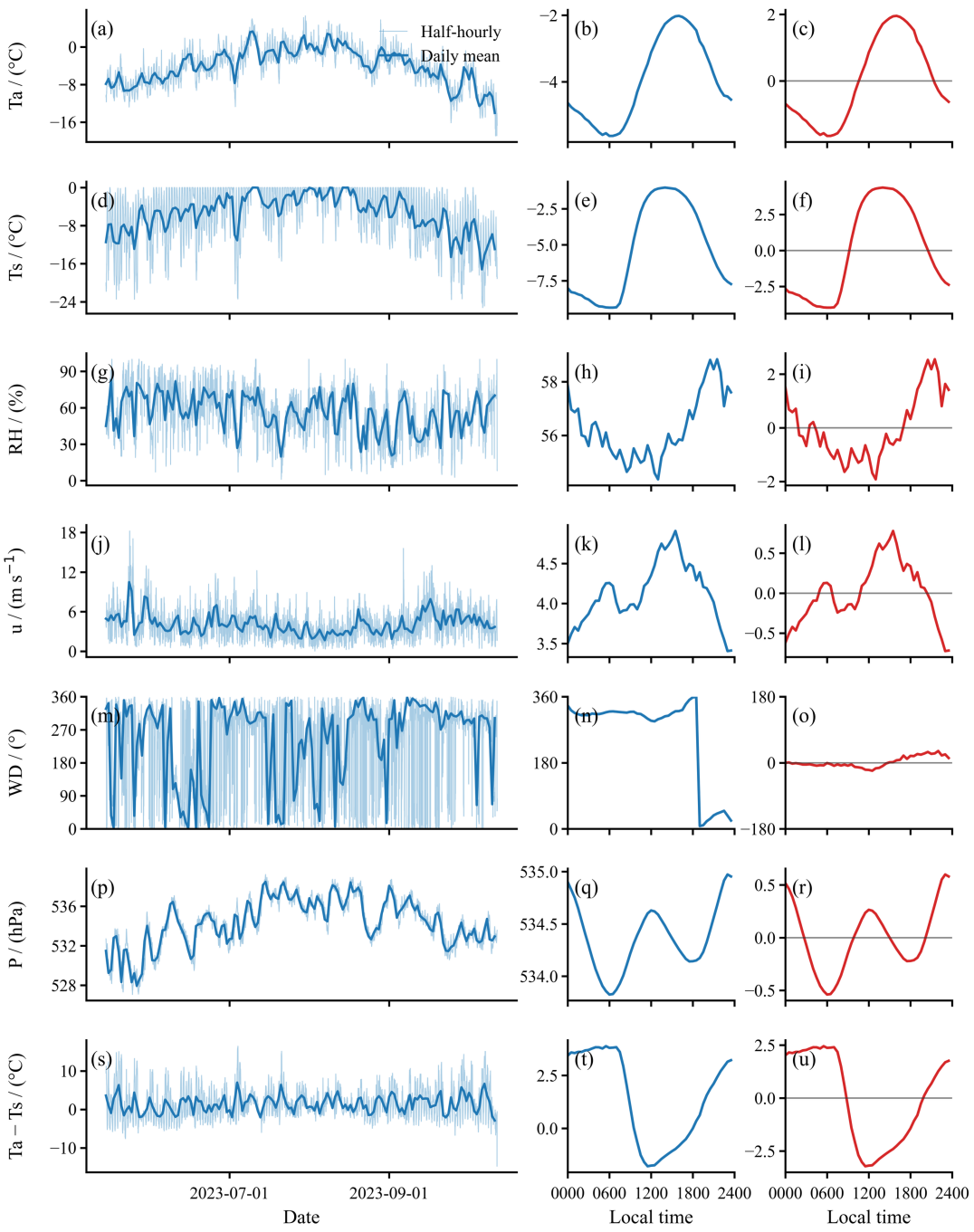


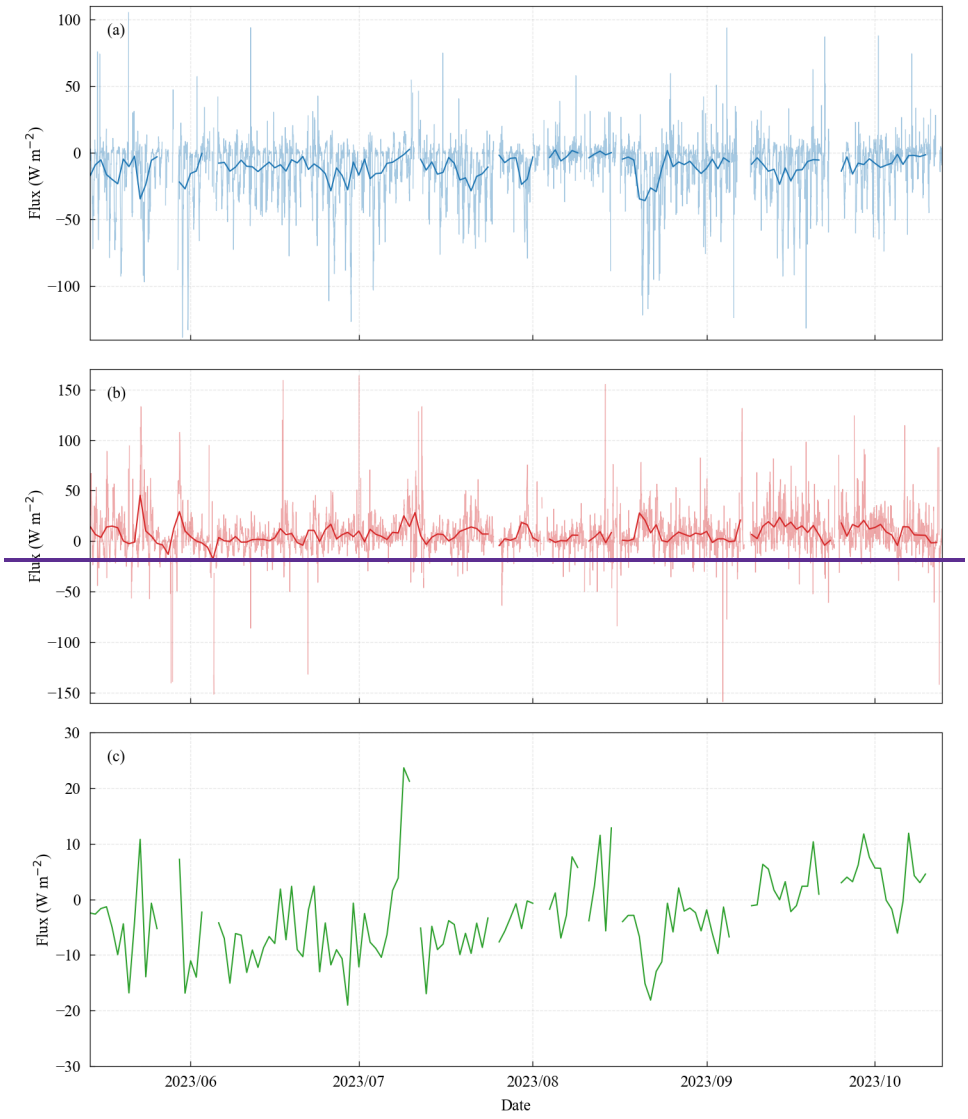
Figure 2. Half-hourly and daily average values (left panels~~) together with~~), original mean diurnal cycles (middle panels), and detrended mean diurnal cycles (right panels) of six meteorological variables at the Dunde Glacier for the period May–October, 2023: (a, b, c) air temperature (T_a); (~~c,~~ d, e, f) surface temperature (T_s); (~~e, f~~g, h, i) relative humidity (RH); (~~g, h~~j, k, l) wind speed (u); (~~i, j~~m, n, o) wind direction (WD); ~~and (k, l~~(p, q, r) atmospheric pressure (~~Pres~~P); and (s, t, u) surface temperature deficit ($T_a - T_s$).

4.2 Observed turbulent fluxes on the Dunde Glacier

~~Herein, turbulent fluxes are defined as positive when directed from the atmosphere to the glacier, and negative in the opposite direction.~~ Figure 3 shows that the observed daily mean LE ranged from −35.9 W m^{-2} (21 August, 2023) to 10.4 W m^{-2} (11 July, 2023), with an average of −9.6 W m^{-2} over the study period, indicating persistent sublimation/evaporation from the glacier surface. There was notable seasonal variability, with the absolute mean seasonal LE being highest in ~~spring~~May-Jun (−15.1 W m^{-2}), lowest in ~~autumn~~Sep-Oct (−8.1 W m^{-2}), and moderate in ~~summer~~Jun-Sep (−10.4 W m^{-2}), reflecting varying intensities of moisture exchange between the glacier and the atmosphere ~~(Fugger et al., 2022)~~(Fugger et al., 2022).

In contrast, observed H was generally positive, averaging 6.9 W m^{-2}, indicating continuous heat transfer from the atmosphere to the glacier. There were pronounced seasonal variations, with high mean H values in ~~spring~~May-Jun (9.3 W m^{-2}) and ~~autumn~~Sep-Oct (9.2 W m^{-2}), and a monthly peak in September (10.1 W m^{-2}). The lowest values were recorded in ~~summer~~Jun-Sep, which averaged 5.4 W m^{-2}, ~~with~~and June ~~having~~exhibited the lowest monthly average (3.1 W m~~$^{-2}$).~~ $^{-2}$), coinciding with the period when the surface temperature deficit reached its minimum. During June, both T_a and glacier T_s increased; however, the glacier surface warmed more rapidly than the overlying air, reducing the surface temperature deficit to its lowest level. As a result, the monthly mean H reached its minimum in June.

Overall, the absolute magnitude of LE generally exceeded that of H. This resulted in a predominantly negative total turbulent flux (LE + H), averaging −2.9 W m^{-2}, indicating net heat loss from the glacier through turbulent exchange. From May to mid-September, the total turbulent flux was negative (glacier losing energy), while from mid-September to mid-October, it became positive (glacier receiving energy). June exhibited the strongest turbulent flux (−8.0 W m^{-2}), whereas September recorded the weakest (1.5 W m^{-2}). These findings underscore the overall state of heat loss from the glacier through turbulent fluxes during the study period.


(a)
(b)
(c)
Flux (W m^{-2})
100
50
0
−50
−100
150
−150
30
20
10
−10
−20
−30
2023/06
2023/07
2023/08
2023/09
2023/10
Date

606

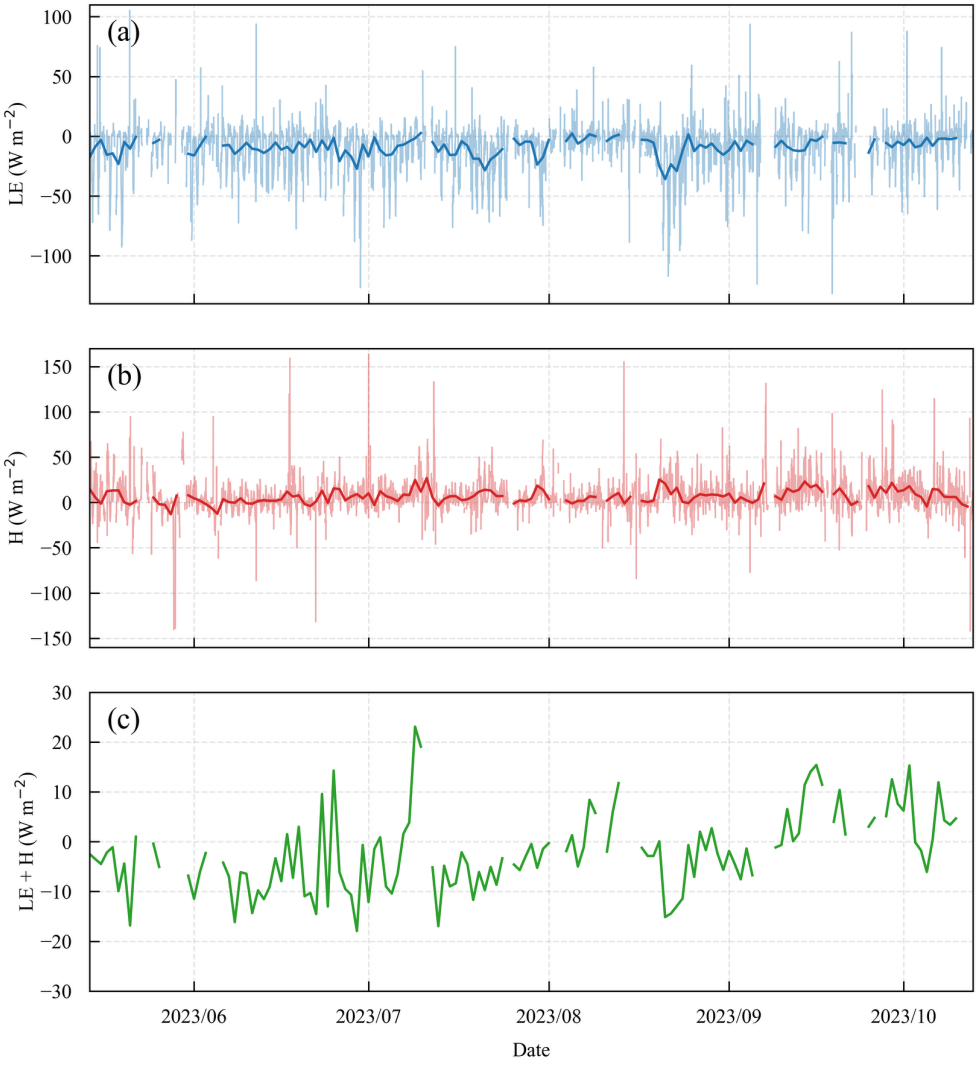


Figure 3: Half-hourly (thin lines) and daily average (thick lines) variations in (a) latent heat flux, (b) sensible heat flux, and (c) total turbulent flux over the Dunde Glacier during the study period. The green line in (c) represents the daily average of total turbulent flux.

4.3 Evaluation of different turbulent flux parameterizations

In this section, we present the results of our evaluation of the simulation ability of five turbulent flux methods (C_{kat}, C_{log}, C_{Rib1}, C_{Rib2}, and C_{M-O}) across different timescales. To ensure that the assessment is based on high-quality data, only the 30-minute measured turbulent flux observations that passed the screening procedures described in Section 3.1 were used for validation.

~~4.3.1~~4.3.1 Model–observation correspondence and statistical significance

The scatter plots reveal pronounced differences among the five evaluated schemes in estimating

turbulent heat fluxes over the Dunde Glacier (Fig. 4). Overall, all methods exhibit relatively higher accuracy for both latent and sensible heat fluxes when the absolute flux magnitudes are small, with modeled values showing good agreement with the observations. However, as the absolute magnitude of the fluxes increases, the simulation errors tend to increase, accompanied by a gradual decline in model performance. This behavior indicates that the stability of the parameterization schemes under higher flux conditions is limited, leading to reduced reliability of the modeled turbulent fluxes.

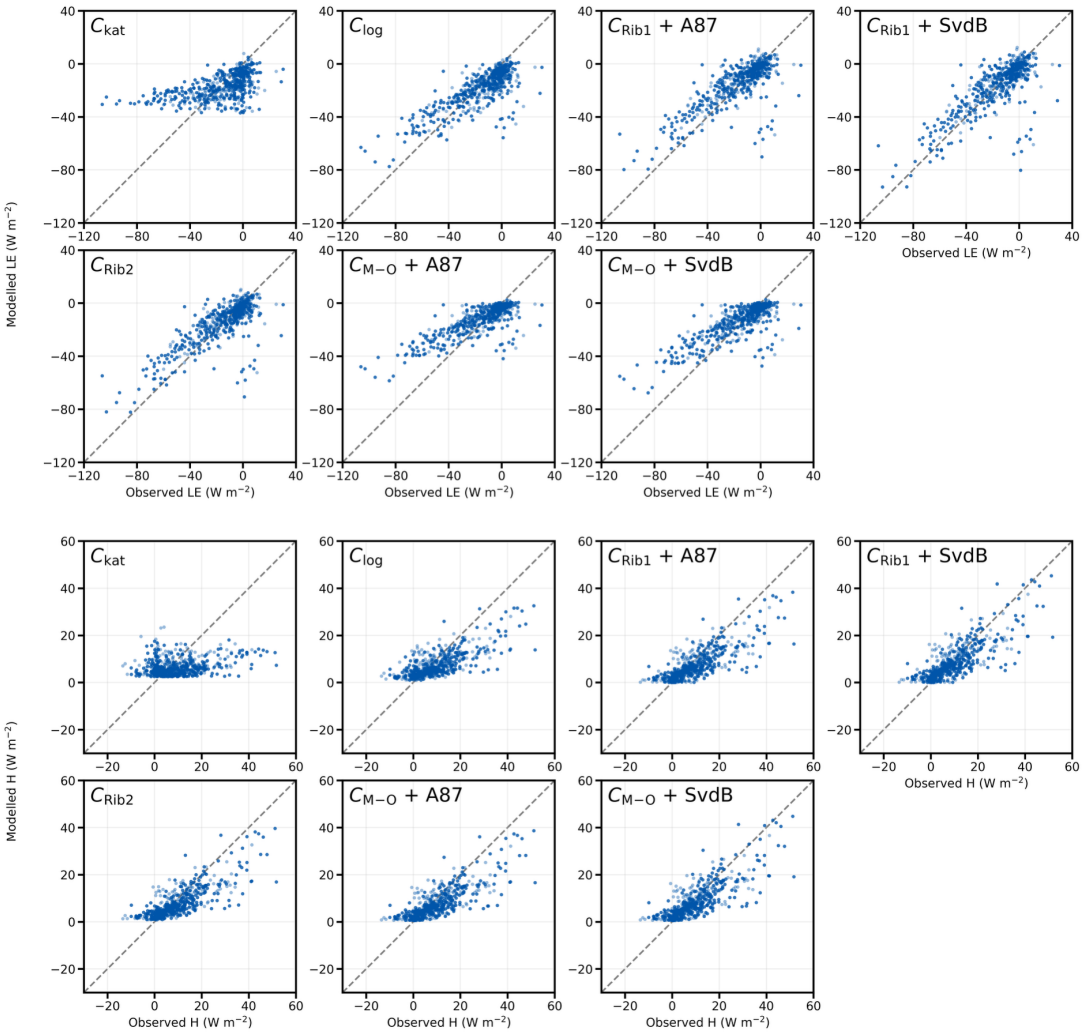


Figure 4: Comparison of 30-min observed (eddy-covariance-derived) and modeled H and LE according to the five turbulent flux methods.

Under near-neutral conditions, most parameterization schemes exhibit small mean biases in LE, with 95% confidence intervals encompassing zero. This suggests that, within the estimated uncertainty

range, the majority of schemes do not show statistically significant systematic deviations from the eddy-covariance observations in terms of mean behavior. In contrast, all schemes display a consistent negative bias in H, with confidence intervals that do not include zero. This systematic underestimation may partly arise from uncertainties in the surface–air temperature gradient, such as potential errors in glacier surface temperature estimation, rather than from random variability alone. These findings highlight potential limitations of bulk turbulent flux parameterizations over glacier surfaces and underscore the need for careful interpretation of modeled H under near-neutral atmospheric conditions.

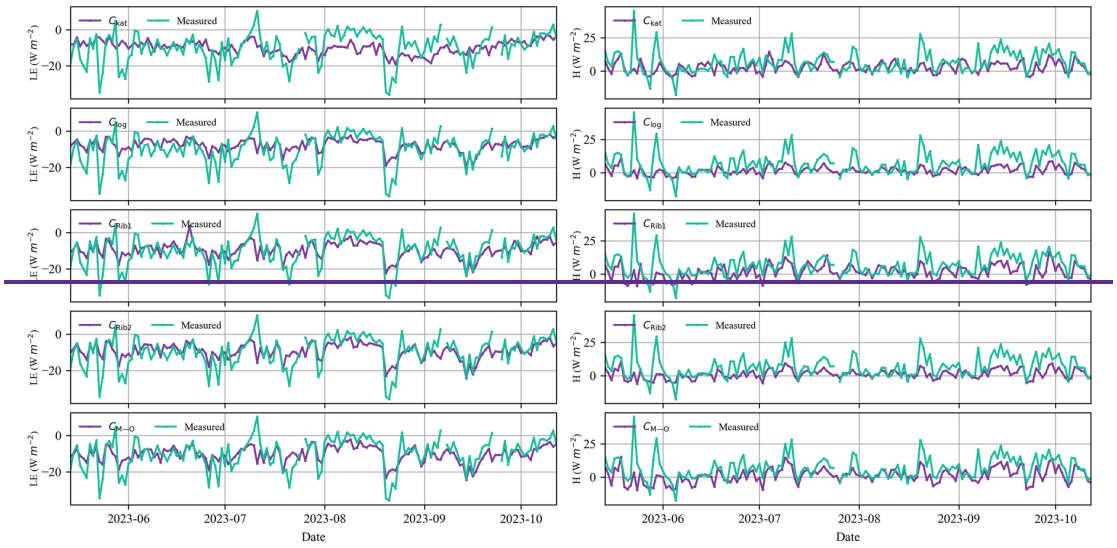
Table 3. Mean bias (Bias) and associated 95% confidence intervals of modeled latent heat flux (LE) and sensible heat flux (H) under near-neutral conditions for the five turbulent flux parameterization schemes. Positive (negative) bias values indicate overestimation (underestimation) relative to eddy-covariance (EC) observations.

	LE (W m^{-2})		H (W m^{-2})	
Method	Bias (W m^{-2})	95% CI (W m^{-2})	Bias (W m^{-2})	95% CI (W m^{-2})
C_{kat}	1.2	[−3.0, 5.3]	−4.3	[−7.4, −1.6]
C_{log}	−2.2	[−5.3, 0.5]	−3.1	[−4.7, −1.7]
C_{Rib1} + A87	1.7	[−1.8, 4.6]	−3.0	[−4.2, −1.8]
C_{Rib1} + SvdB	−0.8	[−4.4, 2.0]	−1.7	[−2.7, −0.7]
C_{Rib2}	0.8	[−2.5, 3.8]	−2.4	[−3.7, −1.2]
C_{M-O} + A87	4.4	[0.8, 8.1]	−2.7	[−4.0, −1.5]
C_{M-O} + SvdB	2.8	[−0.5, 6.0]	−1.7	[−2.7, −0.7]

4.3.2 Overall model performance during the entire study period

We compared the temporal evolution of modeled LE and H at the Dunde Glacier against in-situ observations (Fig. ~~4).~~5). The results from the C_{kat} and C_{log} methods were obtained using their respective optimal parameters, whereas the other schemes used EC-derived z_{0m} as an input parameter and applied different parameterizations of scalar roughness lengths. Over the observation period, nearly all models reasonably captured the ~~general trend~~overall temporal evolution of turbulent fluxes ~~reasonably well.~~, but most simulations exhibited varying degrees of underestimation. For LE, during the three periods of abrupt flux changes—early and mid-July, and mid-August— nearly all schemes underestimated the

magnitude of the observed transitions. Outside these transition periods, particularly during intervals of relatively low LE, the simulations generally showed better agreement with the observations. Although the C_{kat} and C_{log} methods substantially improved agreement with observations through parameter optimization, they still showed a tendency to underestimate LE. For H, schemes that use the bulk exchange coefficient as a function of roughness lengths and atmospheric stability clearly outperformed the C_{kat} method, especially during periods of elevated sensible heat flux. However, during ~~May,~~periods when ~~turbulent fluxes fluctuated to the greatest degree, all model simulations substantially underestimated the observed variability. Model-simulated H also deviated considerably from observations~~H exhibited a downward trend—most notably in ~~early to mid-September, characterized by systematic underestimation. Additionally, during abrupt changes in observed LE in late June and mid-August, the C_{kat} and C_{log} methods failed to reproduce the observed flux transitions, markedly underestimating LE during these periods~~mid-August—none of the methods successfully reproduced this behavior.



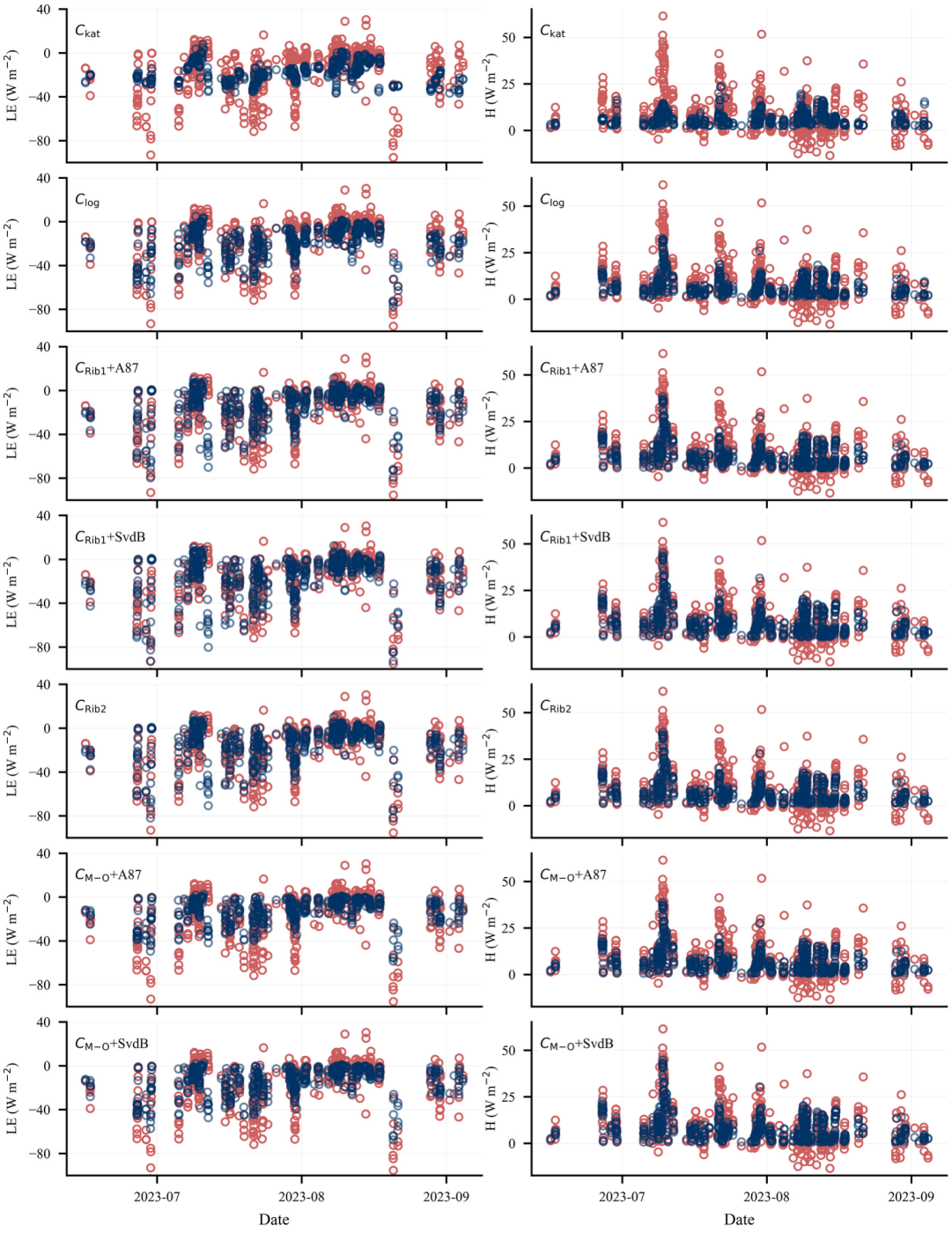


Figure 45: Time series of ~~daily mean latent heat (~~30-min LE~~)~~ and ~~sensible heat (~~H~~) fluxes modeled~~ simulated by the five different schemes (C_{kat}, C_{log}, C_{Rib1}, C_{Rib2}, and C_{M-O}~~) compared with eddy covariance-derived values (measured).~~), compared with eddy covariance–derived values. The C_{Rib1}, C_{Rib2}, and C_{M-O} schemes were calculated by the observed aerodynamic roughness length (z_{0m} = 1.2 × 10^{-4} m), whereas C_{kat} and C_{log} were calculated using optimized parameters obtained by minimizing the differences between modeled and observed turbulent fluxes. Blue dots represent model simulations, and red dots denote observations.

Statistical comparisons between modeled and observed fluxes were conducted ~~for~~over the entire

study period to quantitatively assess method performance (~~Table 2~~Table 4). For LE, the C_{kat}, C_{log}, and C_{Rib1} schemes using the SvdB scalar roughness length parameterization exhibited slight overall overestimation (with negative MBE indicating direction), whereas the remaining schemes—particularly C_{M-O} ~~method slightly underestimated the flux, while~~ —tended to underestimate LE. Excluding C_{kat}, the other ~~three methods (C_{log}, C_{Rib1} and C_{Rib2}) tended to give overestimations. The C_{kat} method exhibited the highest~~ four schemes showed comparable performance, with RMSE values ranging from 11.2 to 13 W m^{-2}, indicating generally good agreement with observations. Although C_{kat} employed parameter optimization, its performance in terms of RMSE and MAD ~~values, indicating poorer LE simulation accuracy compared with~~ was inferior to that of the other ~~methods. Meanwhile, C_{log} presented the largest systematic bias (MBE = 1.96). Hence,~~schemes. Regarding the influence of scalar roughness length parameterizations, only minor differences were observed between the A87 and SvdB formulations for both the C_{Rib1}~~, C_{Rib2},~~ and C_{M-O} methods, suggesting that the choice of scalar roughness length parameterization had a limited impact on LE simulations over Dunde Glacier. For H, all schemes exhibited slight underestimation. However, overall model performance for H was better than that for LE. The observation-based schemes (C_{Rib1}, C_{Rib2}, and C_{M-O}), together with the parameter-optimized C_{log} method, performed ~~best in terms of LE, with the C_{Rib1} and C_{Rib2} methods slightly underestimating the flux, and the C_{M-O} method slightly overestimating it. For H, all methods showed some underestimation, with the C_{kat}~~ slightly better than the katabatic-wind-based C_{kat} scheme. In contrast to the LE results, the choice of scalar roughness length parameterization exerted a noticeable influence on H simulations, with the SvdB formulation generally outperforming A87 for both C_{Rib1} and C_{M-O} ~~methods exhibiting lower RMSE values (8.60 and 8.63 W m^{-2}, respectively), indicating the best accuracy among the tested methods~~.

Table ~~2~~4: Comparative statistics of modeled ~~latent heat (~~LE~~)~~ and ~~sensible heat (~~H~~) fluxes~~ over the entire study period ~~(based on adjusted parameterizations)~~ using the observed aerodynamic roughness length, compared against eddy–covariance observations. RMSE = root mean square error; MAD = mean absolute deviation; MBE = mean bias error.

	LE (W m^{-2})			H (W m^{-2})		
Method	RMSE	MAD	MBE	RMSE	MAD	MBE
C_{kat}	~~7.96~~15.8	~~6.~~12.5	~~−0.31~~1.7	~~8.60~~6.3	~~6.02~~5.0	~~−3.83~~1.7
C_{log}	~~6.82~~11.2	~~4.82~~7.6	~~1.96~~−2.8	~~8.82~~4.6	~~6.08~~3.5	~~−5.17~~1.6

C_{Rib1} + A87	12.7	7.4	1.2	4.1	2.9	−1.6
C_{Rib1} + SvdB	6.6213.0	4.786.8	0.03−1.1	8.803.5	6.432.4	−5.160.7
C_{Rib2}	12.4	7.0	0.3	3.9	2.9	−1.1
$C_{Rib2}C_{M-O}$ + A87	6.3512.4	8.4.48	4.0.30	8.854.0	6.222.9	−5.581.4
C_{M-O} + SvdB	6.3611.5	4.647.6	=0.662.5	8.633.6	6.182.5	−5.460.7

4.3.2 Seasonal variability in method performance

To further explore method behavior under different atmospheric conditions, we conducted seasonal evaluations of the five turbulent flux methods, providing critical insights into their applicability across varying meteorological regimes (Table 3). All five methods exhibited similar patterns of seasonal error. For LE, the largest simulation errors occurred in spring, typically manifested as underestimations, while the smallest errors were found in autumn, with a tendency for slight overestimations. For H, the largest errors occurred in spring and the smallest in summer, with underestimations in both cases. These findings suggest that the simulation accuracy of all methods decreases under conditions of intense turbulent exchange, such as high temperature, humidity, and wind speed, whereas performance is more stable during other seasons.

In a seasonal context, for LE, all parameterizations consistently exhibited the lowest simulation accuracy in spring (Table 3). The C_{M-O} scheme achieved the best spring performance, with an RMSE of 8.48 W m^{-2} and MAD of 6.59 W m^{-2}, these values being markedly lower than those of the other schemes. In summer, the C_{Rib2} and C_{M-O} methods exhibited the lowest RMSE values, outperforming the other schemes. In autumn, the C_{log} method yielded the best LE simulation performance (RMSE: 3.86 W m^{-2}, MAD: 2.68 W m^{-2}), while the C_{kat} method exhibited the lowest accuracy. The remaining schemes displayed intermediate and comparable performances. In addition, the C_{kat} and C_{log} methods exhibited the greatest seasonal variability in accuracy, with RMSE differences between spring and autumn reaching 6.84 and 6.70 W m^{-2}, respectively, indicating poor seasonal consistency and limited robustness under non-extreme conditions. In contrast, the C_{M-O} method demonstrated remarkable seasonal stability, with only a 3.26 W m^{-2} difference in RMSE between spring and autumn, highlighting its adaptability and robustness across seasons.

For H, all methods exhibited reduced accuracy in spring, although the C_{kat} method performed

~~relatively well with a RMSE of 13.78 W m^{-2}, MAD of 8.65 W m^{-2}, and MBE of −6.3 W m^{-2}. Other methods showed similar spring statistics. Summer was the best performing season for H across all parameterizations, with the C_{M_O} method achieving the lowest summer errors. In autumn, both C_{kat} and C_{M_O} yielded relatively low RMSE values (8.71 and 8.73 W m^{-2}, respectively), while the C_{Rib2} method exhibited the highest RMSE at 9.19 W m^{-2}; the remaining schemes produced intermediate and comparable results. Overall, the C_{M_O} method achieved the best performance for H during both summer and autumn.~~

~~Table 3: Seasonal performance of latent heat (LE) and sensible heat (H) flux methods, evaluated against eddy covariance observations. RMSE = root mean square error; MAD = mean absolute deviation; MBE = mean bias error.~~

		~~LE (W m^{-2})~~			~~H (W m^{-2})~~		
~~Method~~	~~Season~~	~~RMSE~~	~~MAD~~	~~MBE~~	~~RMSE~~	~~MAD~~	~~MBE~~
	~~Spring~~	~~12.78~~	~~9.66~~	~~7.02~~	~~13.78~~	~~8.65~~	~~−6.30~~
~~C_{kat}~~	~~Summer~~	~~7.47~~	~~5.99~~	~~−1.13~~	~~7.07~~	~~5.17~~	~~−2.61~~
	~~Autumn~~	~~5.94~~	~~4.81~~	~~−1.76~~	~~8.71~~	~~6.73~~	~~−5.41~~
	~~Spring~~	~~10.56~~	~~8.10~~	~~6.39~~	~~14.19~~	~~9.18~~	~~−7.77~~
~~C_{log}~~	~~Summer~~	~~6.86~~	~~5.07~~	~~2.21~~	~~7.13~~	~~5.01~~	~~−3.98~~
	~~Autumn~~	~~3.86~~	~~2.68~~	~~−0.65~~	~~9.12~~	~~7.08~~	~~−6.64~~
	~~Spring~~	~~9.41~~	~~7.06~~	~~4.20~~	~~14.79~~	~~10.71~~	~~−9.67~~
~~C_{Rib1}~~	~~Summer~~	~~6.49~~	~~4.71~~	~~0.41~~	~~7.01~~	~~5.42~~	~~−3.79~~
	~~Autumn~~	~~5.19~~	~~3.87~~	~~−2.79~~	~~8.83~~	~~6.79~~	~~−6.19~~
	~~Spring~~	~~9.37~~	~~7.05~~	~~4.61~~	~~14.48~~	~~9.85~~	~~−8.88~~
~~C_{Rib2}~~	~~Summer~~	~~6.22~~	~~4.49~~	~~0.66~~	~~7.04~~	~~5.06~~	~~−4.32~~
	~~Autumn~~	~~4.70~~	~~3.29~~	~~−2.55~~	~~9.19~~	~~7.16~~	~~−6.90~~
	~~Spring~~	~~8.48~~	~~6.59~~	~~2.92~~	~~14.81~~	~~10.71~~	~~−9.88~~
~~C_{M_O}~~	~~Summer~~	~~6.32~~	~~4.55~~	~~−0.14~~	~~6.70~~	~~5.01~~	~~−4.26~~
	~~Autumn~~	~~5.22~~	~~3.94~~	~~−3.51~~	~~8.73~~	~~6.78~~	~~−6.16~~

~~4.3.3~~4 Evaluation of ~~diurnal~~daily variations

An evaluation of ~~diurnal~~daily variations in modeled turbulent fluxes ~~offers~~offered important diagnostic information on the simulation ability of a given parameterization. ~~At the~~ To ensure statistical robustness, days with less than 50% missing half-hourly observations (i.e., days with more than 50% valid data coverage) were first defined as effective observation days. Based on these effective days, individual time-of-day bins were then included in the diurnal averaging only when their occurrence frequency exceeded 50% of the number of effective observation days. This two-step screening ensured that the derived diurnal cycles were constructed from sufficiently representative and consistently sampled observations. This screening procedure ensured that the derived diurnal cycles were based on sufficiently representative observations.

At the daily scale, the simulated turbulent fluxes ~~aligned well~~showed good agreement with the in-situ observations, with both LE and H exhibiting ~~a distinct single-trough daily pattern~~diurnal variations similar to the measured values (Fig. ~~5~~6). For LE, the observed and simulated ~~values obtained from all methods exhibited higher accuracy during nighttime and early morning hours, with smaller deviations from observed values (Fig. 5a). In contrast, during periods of intense flux variability—typically~~fluxes for all methods reached their maximum around ~~noon—method performance declined, and simulation errors became larger. For H, the methods~~15:30; however, the modeled values were generally ~~performed better than for LE during noon, but all exhibited limited capability in capturing the early-morning fluctuations (Fig. 5b). Among the five schemes, the C_{M-O} method exhibited the best overall performance (Fig. 5); it accurately captured turbulent fluxes during the relatively stable 18:00–08:00 period, and despite some degree of error, it most effectively~~lower than the observations (Fig. 6a). Meanwhile, differences among the parameterizations became apparent. Specifically, the two Richardson number-based stability correction schemes (C_{Rib1} and C_{Rib2}) reproduced ~~the pronounced fluctuations in LE and H during the period of intensified flux activity (13~~LE more accurately, showing smaller deviations from the observations, particularly during periods of high LE, when they better captured the amplitude of flux variability. In contrast, the other methods—especially C_{M-O}—tended to underestimate LE during these high-flux periods. During relatively stable periods (after approximately 20:00), C_{kat} and C_{log} exhibited overestimation, with comparatively larger deviations. Regarding the scalar roughness length parameterizations, the two schemes performed similarly during low LE periods; however, at higher LE values, the SvdB parameterization outperformed A87. This pattern was evident in both the C_{Rib1} and C_{M-O} frameworks. For H, both observations and simulations showed a gradual diurnal increase, with

minimum values occurring around 12:00 and maximum values around 23:00 ~~15:00).~~ (Fig. 6b). Differences among the parameterizations were relatively small. Compared with LE, all methods demonstrated generally better agreement for H, although a systematic underestimation persisted. The underestimation was generally more evident during periods when H values were relatively high (e.g., around 18:30 and 21:30). Concerning the scalar roughness length parameterizations, the SvdB scheme consistently performed slightly better than A87 across the evaluated time bins, although the differences between the two schemes remained modest.

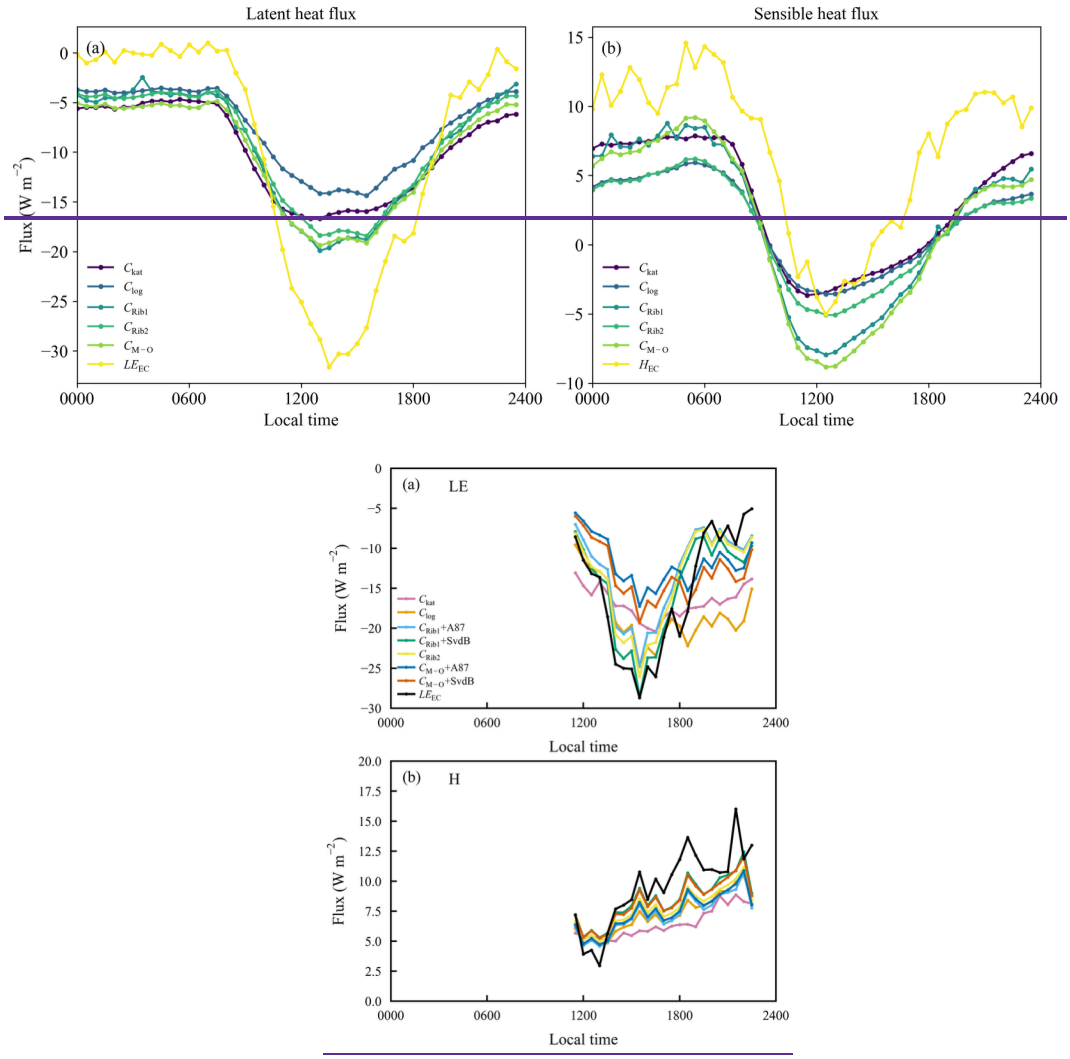


Figure ~~5~~6: Mean ~~diurnal~~daily cycles of modeled latent heat and sensible heat fluxes obtained from the five different schemes (C_{kat}, C_{log}, C_{Rib1}, C_{Rib2}, and C_{M-O}) compared with eddy covariance-derived values (LE_{EC} and H_{EC}).

~~In summary, among the five evaluated methods, the C_{M-O} method delivered the most accurate and stable performance for LE throughout the study period, and it also ranked among the top performers for H. Both the C_{kat} and C_{M-O} methods performed well for H, without any substantial seasonal deficiencies. Moreover, the C_{M-O} method also demonstrated the best agreement with observations in reproducing the diurnal variations in LE and H across different seasons. Therefore, the C_{M-O} method emerges as a particularly suitable option for simulating turbulent fluxes on the Dunde Glacier, offering both high accuracy and temporal robustness on daily and seasonal scales.~~

In summary, among the five evaluated methods, both the C_{kat} and C_{log} schemes exhibited a tendency to underestimate the observed turbulent fluxes to some extent; however, the optimized parameters adopted in these schemes provide useful references for studies of continental glaciers. For the EC-based approaches derived from observations (i.e., the C_{Rib1}, C_{Rib2}, and C_{M-O} methods), the overall performance in simulating both LE and H was broadly comparable throughout the study period, with generally higher simulation accuracy for H than for LE. Nevertheless, differences among the schemes became more evident when examining the diurnal variations. In particular, the C_{Rib1} and C_{Rib2} methods showed closer agreement with observations in reproducing the diurnal evolution of LE, whereas the differences among schemes in simulating H were relatively small. In addition, considering both the overall period and the diurnal cycle, the SvdB scalar roughness length parameterization consistently outperformed the A87 scheme. Overall, although the differences among the five schemes were not substantial, the methods employing Richardson number-based stability corrections combined with the SvdB scalar roughness parameterization demonstrated comparatively balanced performance in simulating both LE and H, and were able to more accurately reproduce the diurnal evolution of turbulent fluxes. Therefore, among the five evaluated schemes, this class of approaches can be regarded as a relatively favorable option for simulating turbulent fluxes over the Dunde Glacier. More broadly, it may also be applicable to turbulent flux simulations over continental glaciers on the TP.

5 Discussion

5.1 ~~Differences in performance among turbulent flux methods~~

~~Variations in the performance of different turbulent flux parameterizations primarily arise from their respective approaches to computing turbulent exchange coefficients and applying atmospheric stability corrections. These methodological differences directly affect method accuracy under varying~~

~~temperature gradients, humidity gradients, and wind speed conditions, leading to discrepancies in the simulated LE and H.~~

~~The C_{kat} method explicitly considers katabatic flows, introducing the katabatic bulk exchange coefficient (C_{kat}) to partially overcome the limitations of MOST during strong katabatic wind conditions (Oerlemans and Grisogono, 2002). This approach emphasizes intensified katabatic turbulence during nocturnal cooling or cold-air intrusions, enhancing turbulent exchange (Horst and Doran, 1988). However, the C_{kat} method lacks explicit stability corrections and dynamic~~**Glacier type dependence of aerodynamic roughness length** ~~adjustment, leading to a slow response under rapidly changing surface conditions (Denby, 2000). Hence, its application is more suited to small and medium-sized glaciers rather than large-scale domains such as the Greenland Ice Sheet.~~**variability**

~~The C_{log} method employs a constant exchange coefficient (C_H) driven by near-surface wind speed and the difference in air temperature (or humidity) and surface temperature (or humidity), providing a simplified, computationally efficient structure suitable for large-scale climate models (Oerlemans, 2000).~~Aerodynamic roughness length (z_{0m}) over glacier surfaces spans several orders of magnitude, and the reported ranges vary substantially among different glacier types and climatic settings. Compared with previous studies, the range inferred in this study (10^{-5} – 10^{-2} m) is consistent with values documented in the literature. For example, calculated values over August-one Glacier on the TP were approximately 10^{-5} to 10^{-2} m (Guo et al., 2018), while observations from the Greenland Ice Sheet (Haven et al., 2025) documented ranges of roughly 10^{-6} to 10^{-2} m. These comparisons indicate that the values derived here are physically reasonable and consistent with established glacier surface characteristics. Previous studies of continental glaciers on the TP have predominantly relied on SEB models to investigate glacier change and its underlying mechanisms. In most of these studies, roughness lengths, together with other meteorological parameters, were adjusted to improve the simulated cumulative mass balance produced by the surface energy mass balance framework. In such cases, parameter selection primarily aimed to optimize overall SEB model performance rather than to explicitly constrain turbulent flux representation. Moreover, the lack of independent turbulent flux observations has limited the constraint on simulated sensible and latent heat fluxes, introducing substantial uncertainty into SEB based flux estimates. This limitation, in turn, hampers our understanding of continental glacier change and its underlying mechanisms. By contrast, observations of roughness length and turbulent fluxes provide a constrained optimization range for parameter calibration in SEB models. This allows the simulated turbulent fluxes to better reflect actual surface conditions, thereby improving our understanding of glacier change. Given

this importance, it is therefore essential to characterize the observed variability and magnitude of roughness lengths themselves, particularly across different glacier types and climatic regimes.

Glacier type appears to systematically influence the characteristic magnitude and range of z_{0m}. Reported values from studies over the Greenland Ice Sheet collectively span approximately 10^{-6} – 10^{-2} m, although the specific intervals vary among studies depending on observational period and methodology (Meesters et al., 1997; Lenaerts et al., 2014; Van Tiggelen et al., 2020). For maritime glaciers on the TP, the limited available observations—primarily from Parlung No. 4 Glacier—indicate values between 10^{-4} and 10^{-2} m (Guo et al., 2011). In contrast, continental glaciers on the Tibetan Plateau often show lower characteristic magnitudes but broader reported ranges, spanning approximately 10^{-5} – 10^{-1} m, although most of these estimates are derived from SEB model calibration rather than independent turbulent flux observations (Giesen et al., 2008; Guo et al., 2018; Sun et al., 2018). Taken together, these comparisons indicate that continental glaciers tend to exhibit lower but more widely distributed roughness lengths than maritime glaciers, which are generally characterized by relatively higher and narrower ranges. The broad z_{0m} range derived from the observational data in this study further suggests that surface roughness conditions over continental glaciers can vary considerably over time. A plausible reason why such variability is more clearly captured in the derived values is the comparatively slow evolution of continental glacier surfaces, which allows changes in roughness length to be tracked more consistently in the observational record.

It should also be emphasized that most previous measurements were confined to short ablation season campaigns, whereas the present study spans a longer observation period from May to October. The wider range identified here may therefore partly result from the extended temporal coverage. Furthermore, the observation site is located in the accumulation zone, where melt intensity is relatively weak and surface conditions are comparatively stable; such conditions may allow a broader range of roughness length variations to be captured in the observations. Nevertheless, given the scarcity of long-term eddy-covariance measurements over continental glaciers, additional observations are still required to evaluate the reliability and broader applicability of these findings.

~~Being a wind-speed-driven scheme, it performs well under less stable stratification conditions. However, the method also exhibits certain limitations. Owing to the absence of atmospheric stability parameters in its structure, it cannot identify or respond to surface inversions forming at night or in the early morning. Herein, the LE RMSE in spring reached 10.56 W m^{-2}, ranking among the largest errors~~

~~of all evaluated methods (Table 3); this method also exhibited substantial diurnal simulation errors.~~

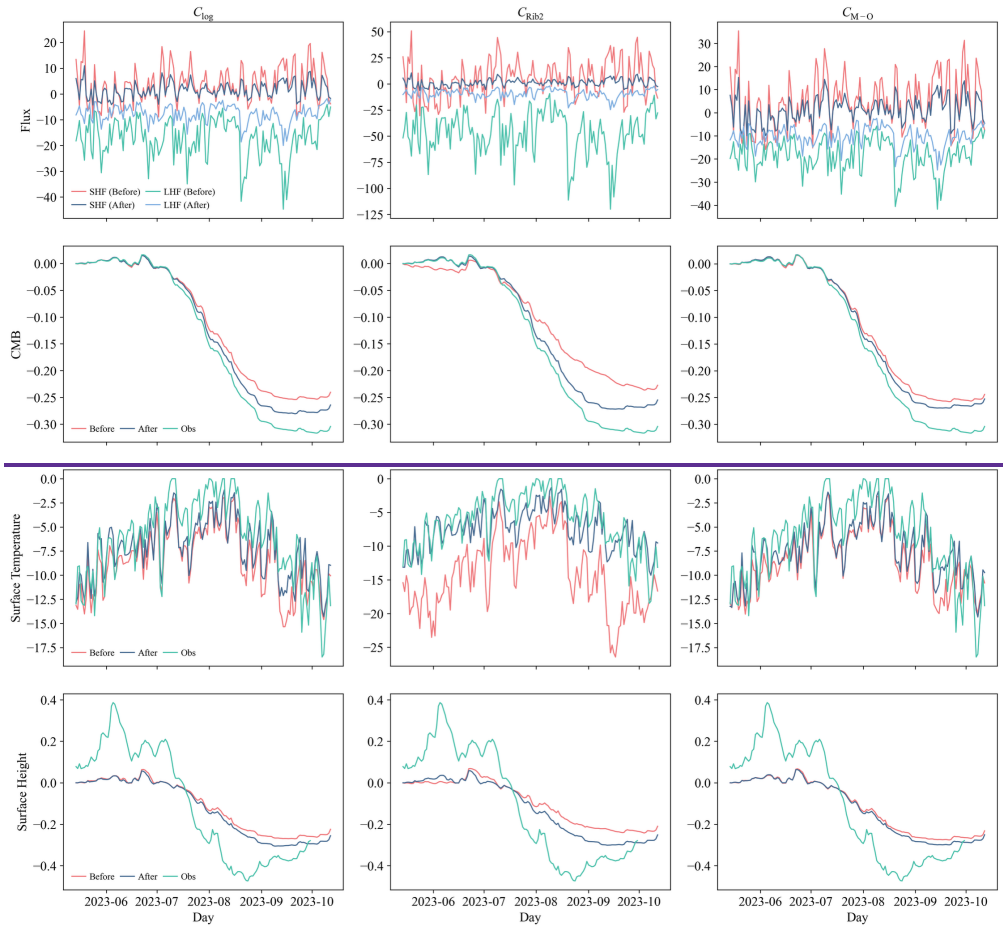
~~The C_{Rib1} and C_{Rib2} methods are based on a single-step turbulence parameterization method centered on the Richardson number for stability correction. Their structures are concise, do not rely on multi-level observational data, and avoid complex iterative procedures, making them among the most robust parameterization schemes for simulating turbulent fluxes. However, these approaches also have limitations. They do not dynamically iterate L, which limits their responsiveness to complex and rapidly changing atmospheric conditions when compared with fully dynamic MOST-based methods (Högström, 1988). In addition, the adjustment of z_0 not only affects the simulation of turbulent fluxes but also influences surface albedo, complicating independent parameter calibration and hindering reliable flux validation.~~

~~The C_{M_O} method, which exhibited the best performance among all evaluated methods in this study, adopts a complete implementation of the MOST framework, explicitly calculating u*, stability correction functions, and L. The scheme separately applies distinct roughness lengths for momentum (z_{0w}), temperature (z_{0t}), and humidity (z_{0e}), enhancing physical consistency in flux estimation. The utilization of a robust iterative algorithm ensures energy balance closure. From our overall statistical evaluation, the C_{M_O} method achieved one of the best performances among the five evaluated methods, with an RMSE of only 6.36 W m^{-2} for LE and 8.63 W m^{-2} for H (Table 2). More importantly, the C_{M_O} method exhibited minimal seasonal variability in flux estimation accuracy. The RMSE values for LE in spring, summer, and autumn were 8.48, 6.32, and 5.22 W m^{-2}, respectively, giving an inter-seasonal RMSE difference of approximately 3.3 W m^{-2}, much smaller than the differences observed in other methods (e.g., a difference exceeding 5 W m^{-2} for the C_{Rib1} method). Additionally, the C_{M_O} method demonstrated higher sensitivity and precision in simulating diurnal variations in turbulent fluxes, showing the closest alignment with observed diurnal cycles of LE and H, particularly during periods of intense midday convection. Nonetheless, the C_{M_O} method also possesses structural limitations. Specifically, the roughness lengths (z_{0t}, z_{0e}, and z_{0w}) lack direct observational support, necessitating iterative parameter calibration, thereby reducing method interpretability and generalizability.~~

5.2 Performance improvement of the SEB model by optimizing turbulent flux methods

~~To assess the importance of turbulent flux methods in simulating glacier mass balance, we included three representative turbulent flux methods (the C_{log}, C_{Rib2}, and C_{M_O} methods) in a coupled energy~~

~~balance snow and firn model (EBFM; Van Pelt et al., 2012, 2019) applied at the point scale. The turbulent fluxes, T_s, ice surface height, and cumulative mass balance (CMB) were simulated using both original and recalibrated parameters, and compared against observational data (Fig. 6). Quantitative evaluation indices, including the correlation coefficient (R), RMSE, and MAD and estimates of CMB, were used to demonstrate improvements resulting from model optimization (Table 4).~~



To assess the importance of turbulent flux methods in simulating glacier mass balance, we included three representative turbulent flux methods (the C_{log}, C_{Rib2}, and C_{M-O} + SvdB methods) in a coupled energy balance–snow and firn model applied at the point scale. For each method, turbulent fluxes were computed using both the original parameter sets reported in the literature and the recalibrated parameters developed in this study, while all other model inputs, including incoming and outgoing longwave radiation, incoming and outgoing shortwave radiation, snow depth, surface albedo, and rainfall, were prescribed from in situ observations at AWS1 to ensure a controlled experimental setup.

Under this framework, the coupled model simulated glacier surface temperature, ice surface height

(SH), and cumulative mass balance (CMB). For each variable, model results obtained using the original and recalibrated turbulent flux parameter sets were evaluated against the corresponding observational data, allowing a direct assessment of the impact of turbulent flux parameterization and calibration on model performance (Fig. 7). In parallel, turbulent fluxes calculated with the original and recalibrated parameter sets were compared to quantify the effects of parameter recalibration on turbulent heat exchange itself. Model performance was assessed using the correlation coefficient (R), RMSE, MAD, and estimates of cumulative mass balance, thereby demonstrating the improvements achieved through turbulent flux optimization (Table 5).

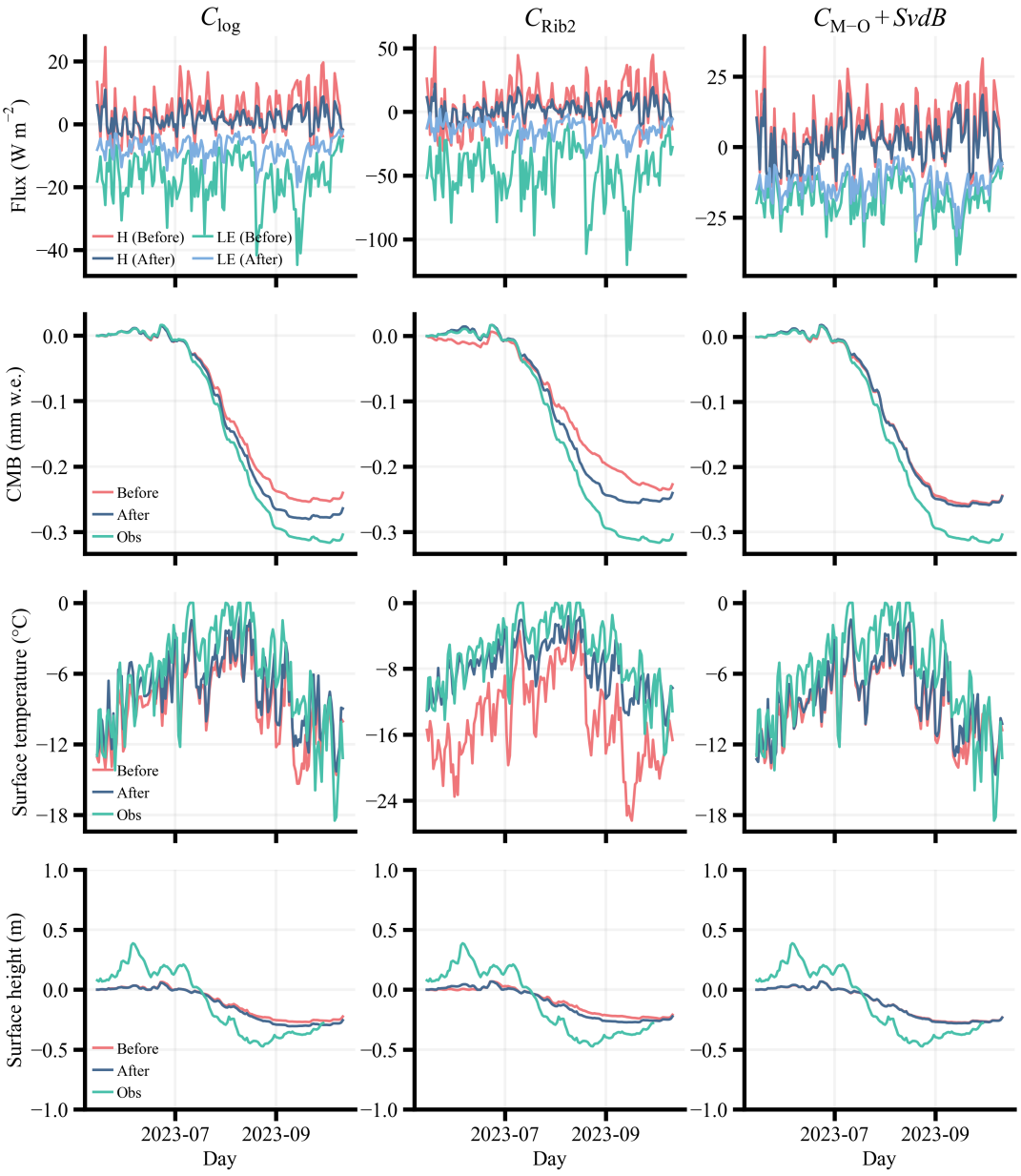


Figure 67: Time series of turbulent fluxes, cumulative mass balance (CMB), surface temperature, and surface height over the Dunde Glacier during the study period, based on original methods (before), recalibrated methods (after), and observations (obs).

Table 45: Comparative statistics between observations and surface energy balance model simulations of surface temperature (T_s), surface height, and cumulative mass balance at the Dunde Glacier, using both original (before) and recalibrated (after) parameters.

Method	Before			After		
	T_s(°C) (R/RMSE,	~~Surface height~~SH	~~Mass balance~~	T_s (R/RMSE,	~~Surface height~~SH	~~Mass balance~~

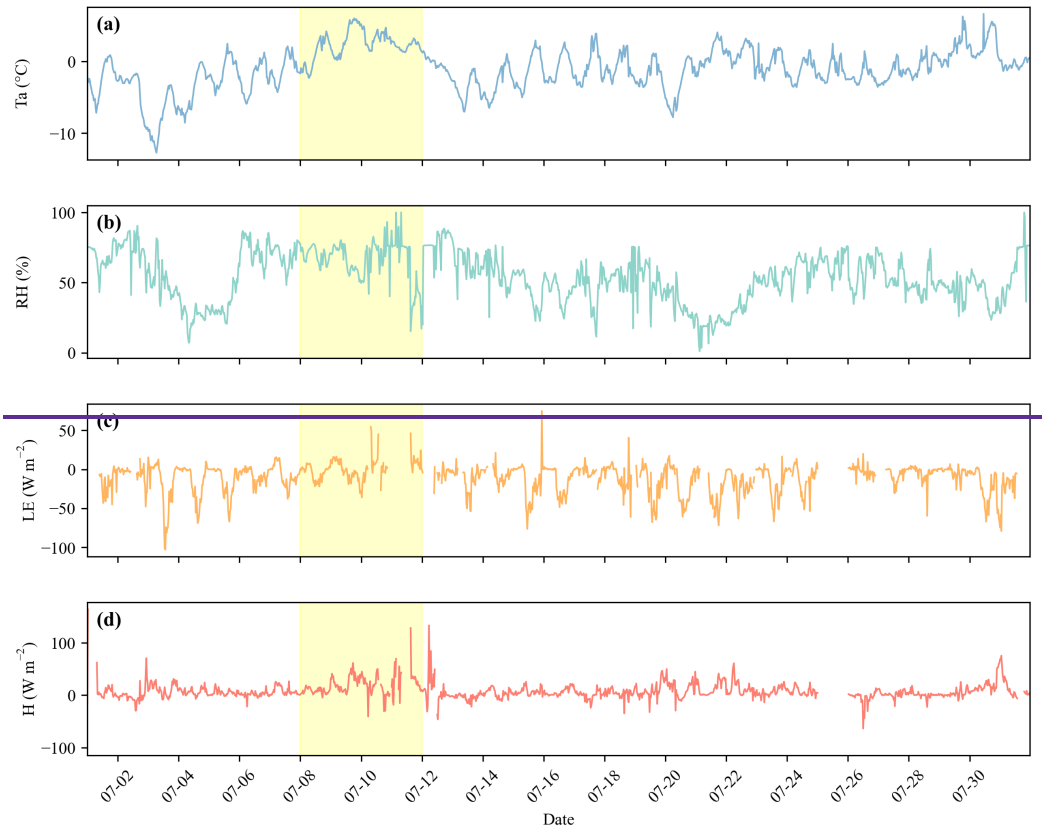
	°C)	(R/RMSE/ MAD, m)	CMB (mm)	°C)	(R/RMSE/ MAD, m)	CMB (mm)
C_{log}	R = 0.84 RMSE = 3.263	R = 0.93 RMSE = 0.16 MAD = 0.14	−238.44	R = 0.85 RMSE = 2.455	R = 0.93 RMSE = 0.15 MAD = 0.14	−262.14260.3
C_{Rib2}	R = 0.78 RMSE = 8.798	R = 0.91 RMSE = 0.18 MAD = 0.16	−225.778	R = 0.8587 RMSE = 2.538	R = 0.9394 RMSE = 0.15 MAD = 0.1314	−252.87238.6
C_{M-O}	R = 0.86 RMSE = 3.162	R = 0.94 RMSE = 0.16 MAD = 0.14	−242.44	R = 0.8688 RMSE = 2.536	R = 0.94 RMSE = 0.14 MAD = 0.1314	−256.80249.5

We first ran the SEB models under uncalibrated conditions with three turbulent flux methods (the C_{log}, C_{Rib2}, and C_{M-O} + SvdB methods). These gave RMSE values for T_s of 3.263, 8.798, and 2.53 3.2 °C, respectively. The R values between modeled and measured T_s exceeded 0.78 for all three schemes. The RMSE values for surface height change ranged from 0.16 to 0.18 m, while the CMB estimates were −238.414, −225.778, and −242.41 mm4 mm, respectively, all deviating markedly from the observed value of −304.19 mm298.6 mm. Following parameter calibration, all three schemes exhibited marked improvements in model performance. The C_{Rib2} method showed the greatest improvement, giving a CMB value of −252.87 mm238.6 mm, equating to an error reduction of 34.555.6% relative to the uncalibrated result. In parallel, the RMSE values for T_s and surface height decreased by 7168.2% and 16.63.2%, respectively. The C_{M-O} method models based model yieldedon the highestC_{M-O} and C_{Rib2} methods achieved relatively high overall accuracy after optimization, with R values of 0.8687 and 0.88 for T_s, respectively, and 0.94 for surface height in both cases. Although a residual bias remained in the CMB simulation, it was substantially mitigated compared with the original configuration. Overall, these findings highlight that turbulent flux parameter optimization is an effective approach to improve glacier SEB model accuracy.

5.3 Evaluation of turbulent flux methods under extreme weather conditions

Our analysis above demonstrates that the optimization of turbulent flux parameterizations markedly

enhances the accuracy of glacier surface energy and mass balance simulations under the mean climate state (e.g., multi-year averages of T_a and precipitation). However, the ability of SEB models to simulate turbulent fluxes under extreme ~~weather and climate~~ events remains uncertain and warrants further investigation. Between 8 and 11 July, 2023, the Dunde Glacier experienced a typical humid heatwave ~~(Fig. 7).~~(Dong et al., 2024). During this event, the daily average air temperature reached 2.4 °C, this being substantially higher than the July average outside of the heatwave event (−1.5 °C). Nighttime air temperatures from 9 to 11 July consistently exceeded 0 °C, exhibiting reduced ~~diurnal~~daily fluctuations, and then sharply dropped below freezing on 12 July immediately after the heatwave event~~.~~ (Fig. 8a). Relative humidity during the humid heatwave reached an average of 94.3%, this being markedly higher than during the July non-heatwave period (89.1%). The concurrent anomalies in air temperature and humidity during this humid heatwave would inevitably lead to anomalous turbulent fluxes.



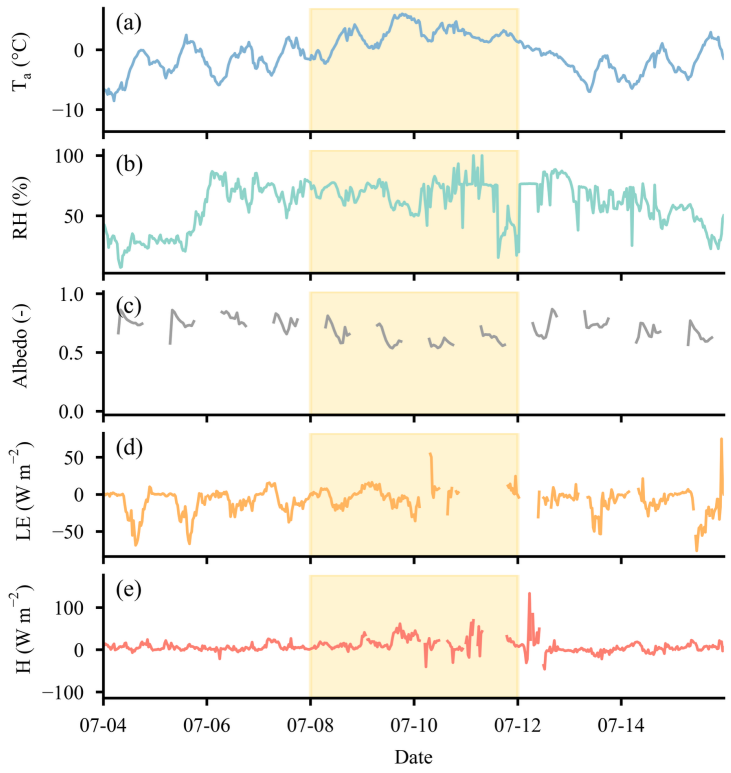


Figure ~~7~~8: Half-hourly values of (a) air temperature (T_a), (b) relative humidity (RH), (c) latent heat flux (LE), and (d) sensible heat flux (H) over the Dunde Glacier during July, 2023. The yellow-shaded area highlights the period of the humid heatwave event (8–11 July, 2023).

~~To clarify turbulent flux behaviors under such anomalous climatic conditions, we compared turbulent fluxes during the humid heatwave (8–11 July, 2023) with those during the non-heatwave period (the remainder of July, 2023) based on observational data. The H markedly increased during the humid heatwave, reaching a daily average of 18.3 W m^{-2}, this being nearly three times higher than the non-heatwave average (6.13 W m^{-2}). The peak H of 128.2 W m^{-2} occurred at 15:00 on 11 July, 2023. Moreover, the diurnal variation in H during the heatwave event ranged from 0.85 to 61.2 W m^{-2}, substantially exceeding the range observed during the non-heatwave period (−5.0 to 16.3 W m^{-2}). This extraordinary increase in H during the humid heatwave indicates that substantial heat was transferred from the atmosphere to the glacier during this event. Concurrently, LE exhibited a remarkable reversal during the humid heatwave. During the non-heatwave period, LE remained negative, with an average value of −12.5 W m^{-2}. Such negative LE values are a common characteristic of continental glaciers on the TP. However, during the humid heatwave, LE values became positive, averaging 0.11 W m^{-2}. This shift was further reflected in diurnal LE variations, with a range of −19.2 to 24.3 W m^{-2} during the humid heatwave, which~~

~~was markedly different from the range of −36.5 to 1.2 W m⁻² observed during the rest of July. This unusual reversal implies pronounced atmosphere-to-surface moisture condensation, resulting in increased heat input onto the glacier surface (Zhang et al., 2017). Such positive LE values are commonly observed over maritime glaciers (Yang et al., 2011).~~

To clarify turbulent flux behaviors under such anomalous climatic conditions, we compared turbulent fluxes during the humid heatwave (8 – 11 July 2023) with those during the non-heatwave period (the remainder of July 2023) based on quality-controlled observational data. The H markedly increased during the humid heatwave, reaching a daily average of 17.5 W m⁻², this being nearly 2.5 times higher than the non-heatwave average (7.5 W m⁻²). Moreover, the daily variation in H during the heatwave event ranged from 7.5 to 26.5 W m⁻², substantially exceeding the range observed during the non-heatwave period (−1.5 to 22.1 W m⁻²). This extraordinary increase in H during the humid heatwave indicates that substantial heat was transferred from the atmosphere to the glacier during this event. Concurrently, LE decreased during the humid heatwave period. During the non-heatwave period, LE remained negative, with an average value of −25.2 W m⁻². Such negative LE values are a common characteristic of continental glaciers on the TP. However, during the humid heatwave, the absolute magnitude of LE decreased, with a mean value of −3.1 W m⁻² (with a mean of 5.1 W m⁻² on July 11). This change was further reflected in daily LE variations, with a range of −7.6 to 5.1 W m⁻² during the humid heatwave, which was markedly different from the range of −58.8 to −2.6 W m⁻² observed during the rest of July. This shift implies a weakening of the upward latent heat flux and, at times, a reversal in flux direction, reflecting enhanced moisture condensation from the atmosphere onto the glacier surface and thus increased latent heat input (Zhang et al., 2017). Such weakly negative LE values, and occasional positive values, are more commonly observed over maritime glaciers and in high-latitude Arctic regions. In maritime settings, they are primarily associated with relatively high air temperatures and abundant precipitation, whereas in Arctic regions they are linked to weak solar radiation, which may occasionally cause glacier surface temperatures to fall below air temperature (Kuipers Munneke et al., 2009, 2018; Yang et al., 2011).

The glacier surface transitioned into a state of net turbulent energy gain, with the mean total turbulent flux (LE + H) reaching ~~18.53~~14.4 W m⁻² during the humid heatwave. In contrast, the non-heatwave period in July was characterized by net turbulent energy loss, averaging ~~−6.25 W m~~13.8 W m⁻². This contrast underscores a distinct shift from turbulent heat loss to heat gain under humid heatwave

conditions. Concurrently, ~~surface albedo decreased and melt energy increased, triggering intense ablation.~~rising T_a during the humid heatwave promoted snowmelt on the glacier surface, leading to rapid snow metamorphism characterized by grain growth and rounding. As the humid heatwave persisted, continued melting may have locally removed portions of the seasonal snow cover, potentially exposing underlying ice. This reduction in surface albedo enhanced melt energy, triggering intense ablation (Fig. 8c; nighttime albedo values were not interpreted because albedo cannot be meaningfully observed without incoming shortwave radiation). Thus, although short-lived, such anomalous turbulent flux variations during the humid heatwave markedly altered the glacier's energy-balance processes by modifying albedo and melt energy, with potential implications for longer-term melt dynamics ~~(Zhu et al., 2024b).~~.

We further evaluated the ability of the five methods to simulate turbulent fluxes under extreme weather ~~and climate~~ events. Among the five turbulent flux methods tested, all captured the pronounced increase in H during the humid heatwave ~~(Fig. 4),~~, with the C_{Rib1} and C_{M-O} ~~method showing~~schemes combined with the SvdB scalar roughness length parameterization performing best ~~performance~~. Although the ~~C_{M-O} method calculated~~ mean ~~(10.2 W m^{-2}) was~~ values simulated by C_{Rib1} + SvdB and C_{M-O} + SvdB (16.7 and 16.4 W m^{-2}, respectively) were slightly lower than the observed value (~~18.3 W m^{-2}), it outperformed~~ 17.5 W m^{-2}), their performance was still superior to that of the other schemes. The ~~C_{log}~~C_{kat} method exhibited the poorest performance, simulating a mean H of only ~~5.3 W m~~7.9 W m^{-2}. Meanwhile, the mean H values during the humid heatwave simulated by the ~~C_{kat}~~C_{log}, C_{Rib1}~~, and~~ + A87, C_{Rib2} and C_{M-O} + A87 methods were ~~5~~12.7, ~~8.9~~14.3, 14.7, and ~~5.5 W m~~14.4 W m^{-2}, respectively. ~~In contrast~~For LE, all methods ~~failed to reproduce the observed reversal of LE during~~exhibited noticeable deviations from the observations. Among the ~~humid heatwave (Fig. 4).~~five evaluated methods, the C_{kat} scheme performed relatively better, with a mean value of −9.2 W m^{-2}, which may be related to its generally lower simulated fluxes throughout the study period. The next best performance was obtained by the C_{M-O} + A87 scheme, with a mean value of −11.6 W m^{-2}. The remaining methods showed broadly similar results: the mean LE values simulated by ~~the C_{kat},~~ C_{log}, C_{Rib1} + A87, C_{Rib1} + SvdB, C_{Rib2}, and C_{M-O} ~~methods~~+ SvdB were ~~−5.8, −6~~16.0, −14.1, −16.2, ~~−6.7, −6.9~~14.1, and ~~−7.7 W m~~13.0 W m^{-2}, respectively, all substantially deviating from the observed value of ~~0.11 W m^{-2}. The reasons behind this discrepancy warrant further investigation.~~−3.1 W m^{-2}. Overall, the methods, particularly the C_{M-O} ~~method, demonstrated a strong response to~~+ SvdB scheme, reproduced the anomalous increase in H

during the humid heatwave~~. However, none of the methods captured the observed reversal of LE. All calculated values were markedly lower than the measured values, suggesting~~ with relatively high consistency and accuracy, and captured the decreasing tendency of LE during this period. However, the estimation errors for LE were non-negligible, and the models failed to reproduce the occasional reversal in LE direction (on July 11). Part of the discrepancy between modeled and observed results may be attributed to observational limitations. The meteorological variables used to drive the models are based on half-hourly observations. Such temporal averaging may obscure short-lived near-surface temperature and humidity gradients, thereby limiting the models' ability to reproduce transient fluctuations. Nevertheless, the discrepancies in turbulent fluxes identified in this study suggest that current ~~turbulent flux parameterizations~~parameterization schemes may underestimate the ~~magnitudes of H and~~mass loss driven by LE under extreme meteorological conditions, ~~and hence underestimate their contributions to~~thereby underestimating its role in glacier ~~melting~~melt processes.

~~Under ongoing global warming, the climate system is recording notable warming and moistening trends on the TP (Wang et al., 2010). This means that the TP will likely experience an increased frequency and intensity of humid heatwave events (Zhang et al., 2025). Such conditions will cause continental glaciers, such as the Dunde Glacier, to increasingly exhibit turbulent flux characteristics that resemble those of maritime glaciers, including reversed LE directions and markedly increased H. Thus, continued warming may drive future glacier-type transitions.~~

Under ongoing global warming, the climate system is recording notable warming and moistening trends on the TP (Wang et al., 2010). This means that the TP will likely experience an increased frequency and intensity of humid heatwave events (Zhang et al., 2025). Such conditions will cause continental glaciers, such as the Dunde Glacier, to increasingly exhibit turbulent flux characteristics that resemble those of maritime glaciers, including reduced LE magnitudes and even reversals in LE direction, as well as a pronounced enhancement of H. This phenomenon warrants further investigation and is likely related to the constraint that T_s cannot exceed 0 °C. Under humid heatwave conditions, T_a continues to rise while T_s is capped, leading to an increased surface temperature deficit and consequently a substantial enhancement of H. Meanwhile, because the humidity gradient is closely coupled to the temperature gradient, LE may also undergo anomalous changes. Consequently, continued warming may drive future transitions in glacier types (Zhu et al., 2026).

6. Conclusions

In this study, we conducted a comprehensive analysis of turbulent fluxes on the continental Dunde Glacier (Qilian Mountains, TP), using continuous meteorological observations and EC flux measurements collected from May to October, 2023. Throughout the observation period, the Dunde Glacier exhibited energy loss through LE (mean = −10.~~34~~3 W m^{-2}) while simultaneously gaining energy via H from the atmosphere (mean = 6.~~93~~9 W m^{-2}). Clear seasonal variations in turbulent fluxes were observed: the absolute magnitude of LE was largest in ~~spring~~May-Jun (mean −15.1 W m^{-2}) and smallest in ~~autumn~~Sep-Oct (mean −8.1 W m^{-2}), whereas H was higher during ~~spring~~May-Jun and ~~autumn~~Sep-Oct (means 9.3 and 9.2 W m^{-2}, respectively) and lower in ~~summer~~Jun-Sep (mean 5.4 W m^{-2}). The magnitude of LE exceeded that of H, resulting in continuous net heat loss from the glacier surface via turbulent exchange.

In addition, we systematically ~~assessed~~evaluated the performance of commonly used turbulent flux ~~methods.~~parameterizations. Among the five schemes ~~evaluated,~~ assessed, considering both the ~~method~~overall period and the diurnal cycle, when the models were applied using the aerodynamic roughness length derived from observations, the combined approach based on ~~Monin–Obukhov similarity theory with~~ Richardson-number stability correction and the SvdB scalar roughness length parameterization exhibited comparatively higher accuracy in simulating both LE and H, and more accurately reproduced the diurnal variability of turbulent fluxes. The RMSE for LE ranged between 12.4 and 13.0 W m^{-2}, while the RMSE for H ranged between 3.5 and 4.1 W m^{-2}. Moreover, statistical comparisons indicate that within both the C_{Rib1} and C_{M-O} frameworks, the SvdB scalar roughness length parameterization consistently outperformed the A87 scheme.

Our analysis further reveals that glacier type exerts a pronounced influence on the range of aerodynamic roughness length. Compared with maritime glaciers, continental glaciers exhibit a broader and generally lower roughness length distribution. This pattern further suggests substantial temporal variability in surface roughness conditions over continental glaciers. However, given the still limited availability of long-term eddy covariance observations in such environments, additional multi-season measurements are required to more precisely constrain the magnitude and range of z_{0m} across different glacier types.

Following the parameter optimization conducted in this study, the overall performance of all SEB

models improved substantially, generally showing good agreement with observations. Among them, the SEB models employing the C_{M-O} and C_{Rib2} methods—based on universal stability functions ~~demonstrated the best overall performance in simulating turbulent fluxes, both in terms of simulation accuracy (RMSE of 6.36 W m^{-2} for LE and 8.63 W m^{-2} for H) and in capturing diurnal variability. Furthermore, after parameter optimization, the SEB model incorporating this method~~ and Richardson number stability correction, respectively—achieved ~~the highest~~comparatively high accuracy~~, with~~. The corresponding R values ~~of 0.86 and~~for T_s were 0.87 and 0.88, while both approaches yielded R values of 0.94 for ~~T_s and ice~~ surface height~~, respectively.~~. These results ~~suggest that the method based on Monin–Obukhov similarity theory with universal stability functions may be the most suitable~~provide an important reference for estimating turbulent heat fluxes over continental glaciers on the TP.

Lastly, we investigated the impacts of extreme weather ~~and climate~~ events (e.g., humid heatwaves) on turbulent flux characteristics. The analyzed humid heatwave event ~~markedly~~substantially altered the typical turbulent flux patterns, ~~resulting in~~leading to a ~~dramatic~~sharp increase in H and ~~reversal~~a reduction in the absolute magnitude of ~~the~~ LE, with occasional reversals in its direction~~; this caused~~. As a result, the average turbulent flux ~~to reach 18.53 W m^{-2}~~ during the humid heatwave ~~period,~~reached 14.4 W m^{-2}, temporarily ~~transitioning~~shifting the glacier surface from a heat-loss state to a pronounced heat-gain state. However, all methods exhibited increased simulation errors under high-temperature, high-humidity, and ~~intensely~~strongly turbulent conditions (e.g., during ~~spring or~~ heatwave periods~~), demonstrating substantial limitations in method robustness under extreme or rapidly changing climate conditions. During~~). Specifically, during the analyzed humid heatwave, all methods~~, and particularly the C_{M-O} method, a complete implementation of the Monin–Obukhov similarity theory framework, successfully~~ reproduced the anomalous increase in H with relatively high accuracy and captured the ~~sharp increase~~decreasing trend in ~~H, although~~LE. Nevertheless, the ~~simulated values~~estimation errors for LE were ~~consistently lower than~~non-negligible, and the ~~observed values. Meanwhile, none of~~models failed to reproduce the ~~methods reproduced the~~occasional reversal ~~of~~in LE direction, indicating that the contribution of turbulent fluxes to glacier melt energy under extreme meteorological conditions ~~is likely~~may be underestimated.

In summary, our findings emphasize the critical importance of turbulent flux parameterizations for accurate glacier SEB modeling, and ~~specifically highlight~~indicate that the ~~superior~~approach based on Richardson-number stability correction exhibits relatively good performance and applicability ~~of the~~

~~method based on Monin–Obukhov similarity theory with universal stability functions~~ in mid-latitude continental glacier environments. Future research should intensify efforts to elucidate the physical mechanisms behind anomalous turbulent flux behavior during extreme ~~weather and climate~~ events (e.g., humid heatwaves), and thus enhance modeling accuracy under exceptional meteorological conditions.

Acknowledgments We gratefully acknowledge the Forestry and Grassland Bureau of Delingha City, Qinghai Province, for their support during our field observations. We also thank the Science Observation Station Management Center of Lanzhou University for providing part of the observation instruments.

Code/Data Availability ERA5 is available for download at https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset. The EBFM model is available via https://github.com/wardvp/EBFM-glacier. Data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author contribution XYC: data curation, formal analysis, visualization, writing (original draft preparation). ZML: conceptualization, methodology, supervision, writing (review and editing), field observations, funding acquisition. GJ: conceptualization, supervision, writing (review and editing), field observations, project administration. LDJ: data curation, field observations, writing (review and editing). HL: data curation, resources. ZF: data curation. ZHB: field observations, data curation. ZFY: project administration.

Competing interests The authors declare that they have no conflict of interest.

Financial support This study was jointly supported by the National Key R & D Program of China (Grant No. 2024YFF0808601), the Second Tibetan Plateau Scientific Expedition and Research Program (Grant No. 2024QZKK0400), the National Natural Science Foundation of China (Grant No. 42471142), and Science and Technology Program of Gansu Province (Grant No. 24YFFF002).

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