



Boundary Layer Characteristics of a Land-Terminating Ice Cliff - Turbulence Measurements from the Summit of Kilimanjaro, Tanzania

Marie Schroeder¹, Ivana Stiperski¹, Michael Winkler^{2,3}, Georg Kaser¹, Jakob Steiner⁴,
Jakob Abermann⁴, Georg Wohlfahrt⁵, and Rainer Prinz¹

¹Department of Atmospheric and Cryospheric Sciences, University of Innsbruck, Innsbruck, Austria

²GeoSphere Austria, Regional Office for Tyrol and Vorarlberg, Innsbruck, Austria

³Avalanche Warning Service Tyrol, Innsbruck, Austria

⁴Department of Geography and Regional Sciences, University of Graz, Austria

⁵Department of Ecology, University of Innsbruck, Austria

Correspondence: Marie Schroeder (marie.schroeder@uibk.ac.at)

Abstract.

Land-terminating ice cliffs (LTICs) are common features of glacier margins that can contribute disproportionately to glacier ablation, yet direct observations of their boundary-layer structure and turbulent exchange are almost entirely lacking. Here, we analyse a unique 42.5-hour eddy-covariance dataset collected at a 25 m tall near-vertical ice cliff on the summit glaciers of Kilimanjaro, Tanzania, to investigate the microclimate, turbulence structure, and surface–atmosphere exchange associated with an LTIC. The measurements reveal a geometry-induced secondary circulation superimposed on the prevailing along-cliff flow, with air moving towards and ascending the cliff during daytime and reversing at night. Strong thermal contrasts between the warm volcanic ash forefield and the cold ice surface produced pronounced spatial heterogeneity in turbulence. While the upper cliff exhibited a coherent, wall-bounded turbulence regime consistent with locally generated exchange, the cliff foot was characterized by disrupted turbulence, counter-gradient transport, and evidence of flow separation associated with the cliff geometry. Using these observations, we evaluate the applicability of a classical bulk aerodynamic parameterization to a near-vertical glacier surface. Despite the unconventional geometry, the bulk method reproduced the observed sensible and latent heat fluxes well at the upper cliff with an RMSE of 5.2 and 3.3 W m⁻², respectively. At the cliff foot, the bulk method failed to capture the nighttime flux reversal, indicating that local turbulence structure, rather than surface slope alone, determines the validity of bulk parameterizations. Compared with previous measurements over Kilimanjaro’s adjacent flat glacier surface, the LTIC exhibited substantially weaker latent heat fluxes, suggesting a shift from the sublimation-dominated regime characteristic of the plateau glaciers toward a comparatively more melt-dominated energy balance at the cliff. These observations provide the first field-based characterization of turbulence at a LTIC and point towards the idea that steep glacier margins can sustain coherent boundary-layer exchange despite their near-vertical geometry, with implications for understanding and modelling turbulent heat exchange over complex glacier terrain. Given the short duration and single-site nature of the observations, these findings should be regarded as a first case-study insight into LTIC boundary-layer processes rather than a general characterization of turbulent exchange at steep glacier margins.



1 Introduction

Steep ice faces are a recurrent but heterogeneous feature of glacierized landscapes. Commonly referred to as ice cliffs, they describe sections of glacier or ice-sheet surfaces with slopes typically exceeding 30° that persist over time while remaining dynamically connected to the glacier body (Steiner et al., 2022). Ice cliffs occur in a variety of glaciological settings, with the most widely studied examples found on debris-covered glaciers. A distinct and more extreme form of ice cliff occurs at the margins of land-terminating glaciers and ice sheets. These land-terminating ice cliffs (LTICs) develop primarily in cold, dry environments and commonly exceed slopes of 60° , often approaching vertical, with heights of up to 30 m. They have been documented in north-west Greenland (Abermann et al., 2020) and the Canadian Arctic, the Antarctic Dry Valleys (Lewis et al., 1999), and on the summit glaciers of Mount Kilimanjaro (Winkler et al., 2010). Although their spatial extent is typically limited, steep ice margins have been identified along approximately one third of the perimeter of Greenland's land-terminating glaciers (Steiner et al., 2026), suggesting that these features are more widespread than previously recognized.

1.1 Surface Energy Balance over Steep Ice

Despite their limited spatial extent, LTICs can exert a disproportionate influence on glacier mass balance. In the Antarctic Dry Valleys, for example, measurements showed that the cliffs contribute up to 20% to meltwater runoff while occupying only about 2% of the glaciers ablation zone (Lewis et al., 1998, 1999). This disproportionate contribution suggests that steep ice faces exchange energy with the atmosphere fundamentally differently than the adjacent flatter glacier surface.

The surface energy balance of glaciers has traditionally been investigated over gently sloping or nearly horizontal surfaces, where radiation and turbulent heat exchange are reasonably well described using classical boundary-layer theory and Monin–Obukhov similarity relationships. However, these assumptions become increasingly uncertain for complex and steep terrain (Stiperski and Rotach, 2016; Waterman et al., 2026).

Studies on debris-covered glaciers have shown that ice cliffs represent localized melt “hotspots”, with ablation rates often two to three times higher than those of the surrounding glacier surface (Miles et al., 2022). Their enhanced melt results from a combination of increased solar radiation, reduced albedo, cliff geometry, and modified turbulent heat exchange (Steiner et al., 2015; Miles et al., 2022; Evatt et al., 2024). These studies demonstrate that steep surface topography fundamentally alters the relative importance of individual surface energy balance components.

Despite these advances, almost all existing energy-balance studies of ice cliffs have focused on debris-covered alpine glaciers (Han et al., 2010; Reid and Brock, 2014; Steiner et al., 2015). Whether the same processes govern the LTICs of Greenland, Antarctica, and Kilimanjaro remains unknown. In particular, the contribution of turbulent sensible and latent heat fluxes to the energy balance of LTICs has not been measured directly.

1.2 Turbulence Along Vertical Ice Walls

The physical understanding of turbulent exchange along vertical walls has largely been developed through laboratory experiments and idealized numerical simulations. Field observations, especially over cold glacier surfaces, remain virtually absent.



55 Nearly all theoretical approaches consider a heated wall driving warm air upward into a cooler ambient, the thermal opposite
 of the cold ice wall encountered at an LTIC. Early experimental studies of this heated-wall configuration demonstrated that
 turbulent natural convection along heated vertical surfaces undergoes a transition from laminar to turbulent flow governed by
 the Grashof number, which describes the relative importance of buoyancy and viscous forces (Cheesewright, 1968; George Jr
 and Capp, 1979). Building on these measurements, subsequent theoretical work identified the characteristic structure of the
 60 near-wall region for this same heated-wall case, consisting of a viscous sublayer, a buffer layer, and an outer turbulent region
 exhibiting logarithmic temperature scaling (Hölling and Herwig, 2005).

More recently, direct numerical simulations have revealed additional complexity within this heated-wall framework. Ke
 et al. (2023) show that vertical natural convection exhibits multiple flow regimes as buoyancy forcing increases, transitioning
 towards fully turbulent conditions characterized by coherent flow structures. Giometto et al. (2017), in contrast, simulate both
 65 the anabatic (warm air rising along a heated slope) and katabatic (cold air draining along a cooled slope) regimes, and show
 that for a vertical wall the two are mathematically identical up to the sign of the along-wall velocity. This provides direct
 numerical support for the idea that, under the Boussinesq approximation, reversing the wall-air thermal contrast primarily
 changes the direction of the buoyancy-driven flow rather than the governing dimensionless parameters. Even so, the bulk of
 the existing literature addresses only the heated-wall case, and it remains an open question whether turbulence generated and
 70 structured under these idealized heated-wall conditions transfers directly to the cold, ice-covered walls of an LTIC, which is
 instead embedded within a comparatively warmer environment.

Additionally, the above investigations have all been conducted under highly idealized conditions, typically involving smooth
 vertical walls, homogeneous surface temperatures, and the absence of ambient wind or complex topography. Real LTICs present
 a fundamentally different environment. Ice cliffs are rough at multiple spatial scales, often embedded within complex terrain,
 75 and frequently bordered by surfaces exhibiting strong thermal contrasts. On Kilimanjaro, for example, adjacent volcanic ash
 can become $\sim 37^\circ\text{C}$ warm (measured during campaign), producing intense horizontal temperature gradients that are absent
 from classical laboratory configurations.

1.3 Kilimanjaro

The LTICs on Kilimanjaro are among the most extensively studied examples due to the long history of glaciological research
 80 on its volcanic summit. Three glacier regimes exist on Kibo, the highest summit of Kilimanjaro, each characterized by different
 glacier–climate interactions (Kaser et al., 2004): glaciers on the mountain slopes, flat tabular glaciers on the crater plateau at
 elevations close to 6000 m a.s.l., and their near-vertical LTIC margins. Over recent decades, glaciers on Kilimanjaro have
 undergone substantial retreat (Hinzmann et al., 2024; Cullen et al., 2013). Notably, the flat tabular glaciers experience much
 more lateral shrinking at the LTICs than thinning (Kaser et al., 2010). The interannual variability of the tabular glaciers’
 85 mass and energy balance is primarily controlled by atmospheric moisture (Mölg et al., 2009), while meteorological elevation
 gradients are largely governed by mesoscale atmospheric circulation over the mountain (Mölg et al., 2020).

The surface energy balance of the flat, tabular glaciers on Kilimanjaro is dominated by net radiation, while the turbulent
 latent heat flux represents the second most important energy flux. The latent heat flux is almost always directed away from



the surface, indicating persistent energy loss through sublimation (Cullen et al., 2007). Its large magnitude is primarily caused by the very dry atmosphere rather than strong winds, as wind speeds on Kilimanjaro are generally low. Although the energy available for melting is only about half the magnitude of the latent heat flux, observations show that 92% of total ablation occurs through sublimation (Cullen et al., 2007). This apparent discrepancy arises because much of the meltwater produced does not leave the glacier but refreezes within the ice. As a result, sublimation dominates the net mass loss despite the presence of melt energy.

During periods of particularly low wind speeds, turbulent exchange is reduced, suppressing the latent heat flux and allowing the glacier surface to reach the melting point (Mölg and Hardy, 2004). While the energy balance of Kilimanjaro's flat glacier surfaces is relatively well understood, far less is known about how these processes operate on the steep ice cliffs and to what extent the findings are transferable to other climatological settings where LTICs occur.

Observations of an ice cliff on Kilimanjaro over 20 months revealed a continuous retreat of the cliff front (Winkler et al., 2012). This retreat is strongly controlled by solar geometry (Winkler et al., 2010; Kaser et al., 2010), which also determines cliff orientation. Cliffs are typically either north- or south-facing, leading to periods of self-shading depending on the sign of solar declination changing twice a year in this equatorial setting. During shaded phases, retreat is mainly driven by sublimation and surface temperatures remain below the melting point. In contrast, during sunlit periods, increased energy input allows for melting and higher sublimation rates, resulting in substantially higher retreat rates (Winkler et al., 2010; Kaser et al., 2010).

The ice cliffs on Kilimanjaro are bordered by dark volcanic ash surfaces that experience strong diurnal heating, with measured surface temperatures reaching up to 37°C. This creates large horizontal and vertical temperature gradients near the cliff, which are expected to substantially influence the local energy balance and turbulence structure, as also observed on debris-covered glacier cliffs (Steiner et al., 2015). However, the microclimate and turbulent exchange associated with LTICs remain poorly quantified despite their potential importance for glacier ablation.

A unique opportunity to address this gap is provided by the eddy-covariance measurements collected at an LTIC by Winkler (2011, Chap. 4) performed in October 2010. Although these observations demonstrated that turbulent flux measurements are technically feasible in this environment, they have not previously been subjected to a detailed boundary-layer or turbulence analysis.

Building upon this unique dataset of eddy-covariance observations in a LTIC, the present study provides the first comprehensive assessment of turbulence structure and surface-atmosphere exchange at a near-vertical land-terminating ice cliff. Particular emphasis is placed on coordinate transformations, averaging strategies, quality-control procedures, and turbulent flux calculations under conditions of steep topography and complex flow.

The analysis addresses three principal research questions:

(i) What is the microclimatic setting of an LTIC situated on a dark surface? (Sect. 3.1)

(ii) What controls the turbulence structure and transport within the ice-cliff environment? (Sect. 3.2)

(iii) Can classical bulk parameterizations describe turbulent heat exchange at near-vertical ice cliffs, and what do these fluxes reveal about the ablation regime of LTICs? (Sect. 3.3)



Finally, we conclude by integrating the microclimatic observations, turbulence structure, and turbulent flux estimates to assess exchange processes at the LTIC and their implications for glacier ablation (Sect. 4)

125 2 Data and Methods

2.1 Study site and measurements

The measurements were conducted at the southern margin of the Northern Ice Field (NIF) on the crater plateau of Kibo. The investigated cliff forms part of the southern margin of the NIF, where the glacier terminates in a steep ice face bordered by dark volcanic ash surfaces (Fig. 1).

130 Long-term meteorological observations were available from two automatic weather stations (AWS). AWS2 was located near the cliff base and measured four-component radiation (with the radiometer rotated by 90° to face the cliff surface), air temperature, relative humidity, and wind speed as 30 min averages derived from 1 min measurements. Surface temperatures were measured using Campbell Scientific IR100 and IR120 infrared temperature sensors, targeting the ash-covered ground and the ice surface, respectively. The IR120 measurement is used as the Ground station ice surface temperature in the following
135 analysis and represents a localized point measurement of the ice surface.

At the Cliff station, no direct infrared measurement of the ice surface temperature was available. Instead, the outgoing longwave radiation measured by AWS2 and directed towards the cliff was used to estimate the cliff surface temperature. Owing to the approximately 150° field of view of the longwave sensor, this measurement represents a spatially integrated estimate of the ice-cliff surface temperature rather than a localized point measurement. The ice-cliff surface temperature, T_s ,
140 was calculated from outgoing longwave radiation, LW_{out} , using the Stefan–Boltzmann law:

$$T_s = \left(\frac{LW_{out}}{\varepsilon \sigma} \right)^{1/4} \quad (1)$$

where $\sigma = 5.670374419 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ is the Stefan–Boltzmann constant and a surface emissivity of $\varepsilon = 0.97$ was assumed.

A second station (AWS1), located on the flat glacier surface of the NIF above the ice cliff, provided complementary me-
145 teorological observations representative of the adjacent horizontal glacier surface. Both AWS stations were operated over a substantially longer period than the eddy-covariance campaign; however, in the present study only the observations coinciding with the EC campaign are analysed.

The eddy-covariance (EC) campaign was carried out over 42.5 h, from 8 October 2010 14:30 LT until 10 October 2010 09:00 LT, at a south-facing ice cliff located at 3.060° S, 37.349° E and 5763 m a.s.l. Turbulence measurements were performed
150 at two locations 0.46 m from the vertical ice surface: (i) at the cliff base, 1.7 m above the ash-covered ground (Ground station), and (ii) approximately 20 m above the ground directly adjacent to the cliff face (Cliff station; Fig. 1).



Both EC stations were equipped with Campbell Scientific CSAT3 three-dimensional sonic anemometers sampling at 20 Hz and fast-response E-type thermocouples (FW05). The Cliff station was additionally equipped with an open-path krypton hygrometer (KH20) and a low-frequency air temperature and relative humidity sensor.

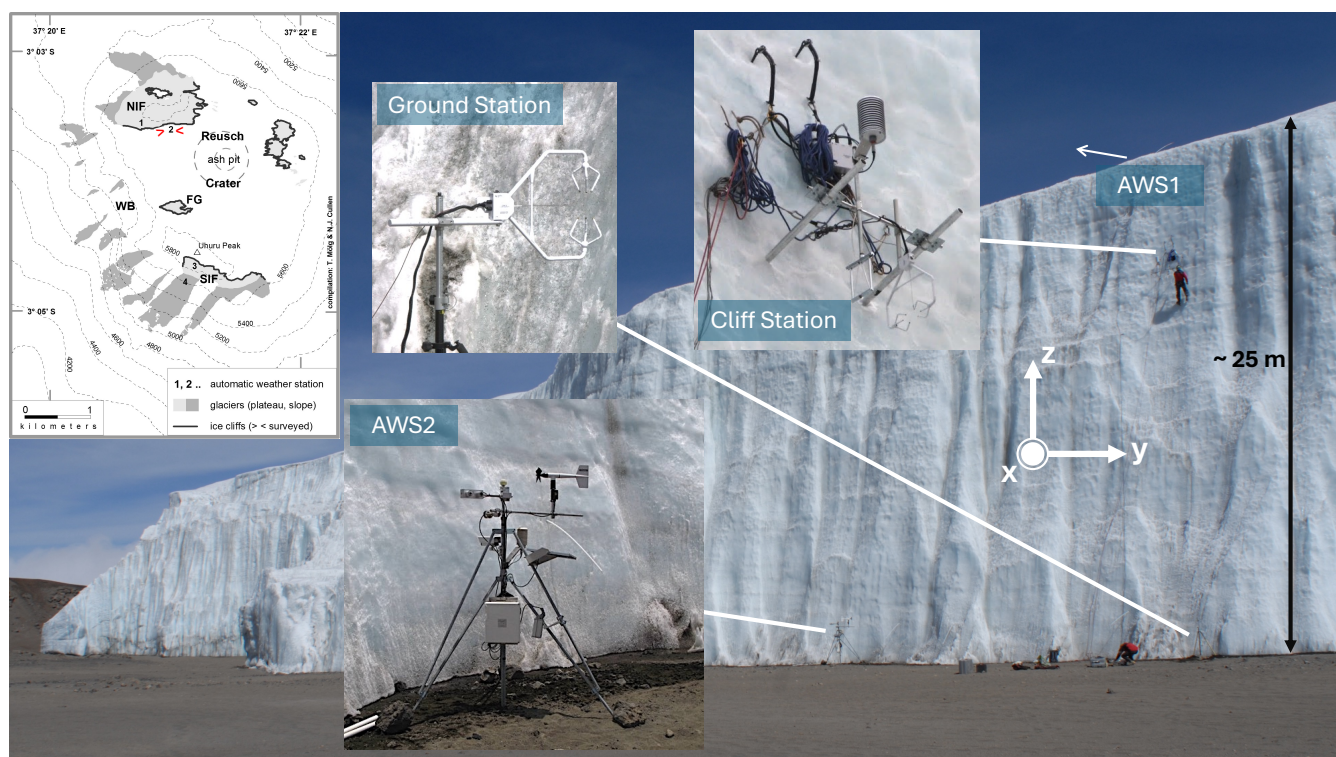


Figure 1. Measurement setup at the study ice cliff on the southern margin of the NIF, Kilimanjaro. The inset map (adapted from Winkler et al. (2010)) shows the location of the investigated cliff (red ><) together with the long-term automatic weather stations AWS1 and AWS2. The main photograph shows the measurement setup during the 42.5-hour eddy-covariance campaign, including the Ground station at the cliff base, the Cliff station approximately 20 m above the ground, and AWS2. Insets illustrate the instrumentation installed at the Ground and Cliff stations and at AWS2. The white arrows indicate the coordinate system used for the eddy-covariance measurements. (Photo Credits: Georg Kaser and Michael Winkler, 8 October 2010.)

155 2.2 Eddy-covariance processing

2.2.1 Quality Control

Quality control was applied to the high-frequency measurements before flux and multiresolution analyses. The internal CSAT3 diagnostic flags were used to exclude affected wind samples and their paired scalar measurements, comprising 30 samples (0.001%) at the cliff station and 403 (0.01%) at the ground station during the study period. Wind components, thermocouple
 160 temperature and water-vapour density were despiked using a procedure based on Vickers and Mahrt (1997). Isolated spikes



were replaced by linear interpolation where valid neighbouring samples were available. Recording gaps accounted for 3437 missing samples (171.85 s; 0.11% of the expected record). These gaps and diagnostic exclusions were retained as missing values on the regular 20 Hz grid without interpolation. Covariances were calculated from coincident valid wind and scalar samples, requiring at least 95% valid pairs within each interval used to define turbulent fluctuations. NO-MRD windows
165 overlapping missing runs longer than 10 s were excluded. Cross-correlation confirmed temporal alignment of the thermocouple and KH20 measurements with the sonic measurements.

2.2.2 Coordinate system

The two EC systems were installed with different physical orientations owing to the different geometrical constraints at the Ground and Cliff stations (Fig. 1). At the Ground station, the sonic anemometer was mounted in the conventional upright
170 orientation typically used for measurements over horizontal terrain. At the Cliff station, the instrument was mounted such that its internal coordinate system was aligned with the ice cliff, with the z axis approximately normal to the cliff face, the x axis pointing approximately vertically upwards, and the y axis oriented parallel to the cliff.

For consistency throughout this study, all variables are discussed using a common reference coordinate system corresponding to the Ground station convention (shown in Fig. 1). In this coordinate system, u denotes the horizontal cross-cliff direction (positive away from the ice surface) (x direction), v the horizontal along-cliff direction (y direction), and w the geometrical
175 vertical (z direction). Accordingly, turbulent heat fluxes are defined as negative towards the surface and positive away from the surface.

2.2.3 Multiresolution flux decomposition

To investigate the scale dependence of turbulent transport and distinguish turbulent from mesoscale motions, non-orthogonal
180 multiresolution flux decomposition (NO-MRD; Howell and Mahrt, 1997) with overlapping averaging (Haugeneder et al., 2024) was applied. NO-MRD decomposes turbulent variances and covariances into contributions from different temporal scales while preserving the total covariance.

Compared with classical spectral analysis, NO-MRD is particularly suited for analysing non-stationary atmospheric boundary-layer flows because it provides information in both the temporal and spatial scale domains. Throughout this study, NO-MRD
185 was used (i) to determine an appropriate Reynolds averaging time for the EC processing and (ii) to investigate the temporal scales contributing to turbulent transport at the Ground and Cliff stations.

2.2.4 Selection of the Reynolds averaging interval

The Reynolds averaging time determines the separation between turbulent and mesoscale motions included in the calculated turbulent fluxes. Following Vickers and Mahrt (2003), the averaging interval was selected from the NO-MRD cospectra based
190 on the spectral gap separating turbulent and mesoscale motions.



The cospectra did not reveal a common, clearly identifiable spectral gap (Fig. 2). At the Ground, the median cospectrum for positive Ground $w'T'$ (red) changed from negative to positive at approximately 200 s, suggesting a possible separation near 3 min. For negative Ground $w'T'$ (blue), the cospectrum peaked near 60 s and remained positive at longer timescales, without a comparably distinct transition. At the Cliff, the positive Ground- $w'T'$ curve crossed zero at approximately 17 s, demonstrating that the sign transition also differed between measurement locations. These contrasting scale dependencies did not support selecting a single common averaging interval directly from a diagnosed spectral gap.

We adopted a common Reynolds averaging interval of 1 min to emphasize short-timescale exchange while limiting the influence of slower variations. Appreciable covariance remained at longer timescales in some classes, so this choice does not imply that all relevant covariance was captured within 1 min.

The sensitivity of the horizontal sensible heat fluxes to this choice was assessed using independently calculated 1-, 5-, and 30-min Reynolds averaging intervals, with all estimates subsequently aggregated into 30-min reporting intervals (Fig. A1). Broad temporal patterns were often retained, but longer averaging intervals produced larger excursions and could alter both flux magnitude and sign. This comparison documents the influence of averaging interval on the short-timescale flux estimates used in the subsequent analyses.

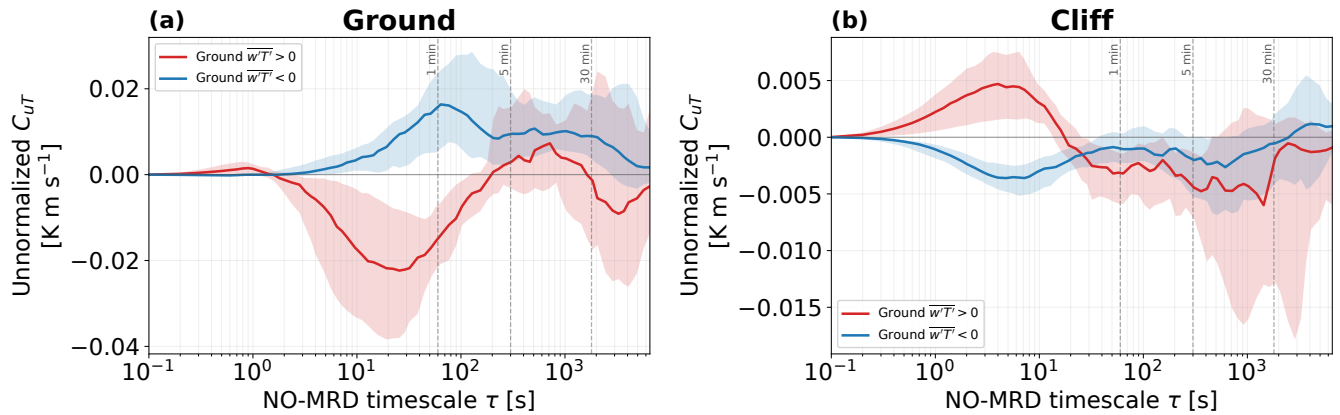


Figure 2. Unnormalized NO-MRD cospectra of horizontal velocity and temperature at the Ground (a) and Cliff (b) stations. Solid curves show the median and shading the interquartile range. Both stations use the same record classification: positive (red) or negative (blue) Ground vertical heat-flux reference, calculated from 1-min fluctuations and averaged over each decomposition record. Vertical dashed lines mark the 1-, 5-, and 30-min timescales.

2.2.5 Coordinate rotation

Three commonly used coordinate rotation methods were evaluated for the EC processing: single rotation (SR), double rotation (DR) and planar fit (PF).

Double rotation aligns the coordinate system with the mean wind direction and forces the mean vertical velocity to zero for each averaging interval. While this assumption is appropriate over horizontally homogeneous terrain, it is not expected to hold



210 near a steep ice cliff where persistent vertical motions can arise from katabatic drainage, thermally driven circulations and flow deflection by the cliff geometry. Applying DR would therefore remove physically meaningful flow components.

Single rotation was additionally evaluated by enforcing a vanishing mean cross-cliff velocity. However, unlike the vertical velocity over homogeneous terrain, no physical constraint requires the mean cross-cliff velocity to be zero, as persistent horizontal motions may arise from pressure gradients, thermal forcing or terrain-induced channelling.

215 The planar-fit method estimates a long-term streamline coordinate system from the observed wind field. Owing to the limited observation period of 42.5 h and the highly three-dimensional flow environment, the resulting tilt angles reached up to 45° at the Ground station and 74° at the Cliff station, indicating that physically meaningful flow structures were being removed rather than instrumental tilt corrected.

Because all tested rotation methods either removed physically relevant flow components or produced unrealistic tilt angles, 220 no flow-dependent coordinate rotation was applied. Fluxes were therefore calculated in the original instrument coordinate systems while being interpreted using the common reference coordinate system introduced above (see Section 2.2.2).

While the applied rotation methods result in some differences in flux magnitude, the overall temporal evolution and sign of the sensible heat flux remain similar (Fig. A2). This suggests that moderate uncertainties in the alignment of the sonic anemometers relative to the ground and cliff surfaces do not substantially alter the observed flux characteristics. Together with 225 the considerations described above, this supports the use of the unrotated coordinate system for the subsequent analysis.

2.2.6 Flux calculations

Sensible heat fluxes were calculated directly from the covariance between the cliff-normal wind component and thermocouple temperature. The EC data were processed using 1 min averaging intervals and subsequently resampled to 30 min averages to reduce random uncertainty and to match the temporal resolution of the low-frequency meteorological observations.

230 Latent heat fluxes were calculated from the covariance between the cliff-normal wind component and water vapour fluctuations measured by the KH20 hygrometer. The latent heat fluxes were corrected for oxygen absorption by the KH20 hygrometer and for density fluctuations using the Webb–Pearman–Leuning correction (Webb et al., 1980). No observations of high-frequency water vapour fluctuations are available from the Ground station.

2.3 Turbulence analyses

235 2.3.1 Quadrant analysis

Quadrant analysis was applied to investigate the contribution of coherent turbulent structures to the sensible heat flux at both measurement locations. The method partitions the instantaneous turbulent fluctuations according to the sign of the velocity fluctuation and the associated scalar fluctuation, thereby identifying the dominant turbulent events contributing to the covariance (Willmarth and Lu, 1972; Lu and Willmarth, 1973).

240 For the vertical sensible heat flux ($w'T'$), turbulent events were classified into four quadrants: warm updrafts ($w' > 0, T' > 0$), cold updrafts ($w' > 0, T' < 0$), cold downdrafts ($w' < 0, T' < 0$), and warm downdrafts ($w' < 0, T' > 0$). An analogous



decomposition was performed for the horizontal sensible heat flux ($u'T'$) to investigate turbulent heat exchange between the ice cliff and the atmosphere.

The relative contribution of each quadrant was calculated by summing the covariance contributions within each quadrant and normalizing them by the total turbulent flux. Quadrant analyses were performed separately for stable and unstable conditions to investigate how the dominant turbulent transport mechanisms varied with atmospheric stability.

2.3.2 Correlation analysis

Pearson correlation coefficients were calculated to quantify the coherence between the Ground and Cliff stations for the different turbulence statistics, mean meteorological variables and turbulent fluxes. Correlations were evaluated separately for stable and unstable conditions in order to investigate how the coupling between the two measurement locations varied with atmospheric stability.

2.4 Bulk aerodynamic method

Measured sensible and latent heat fluxes at the Cliff station were compared with fluxes estimated using the bulk aerodynamic method, which parameterizes turbulent surface–atmosphere exchange from mean meteorological variables and near-surface gradients (Hock and Holmgren, 2005). The comparison aims to assess whether a bulk parameterization commonly applied over horizontal glacier surfaces can reproduce the observed turbulent exchange adjacent to a near-vertical ice cliff.

The sensible heat flux was calculated as

$$Q_H = \rho c_p C_H U (T_s - T_a), \quad (2)$$

where ρ is the air density (kg m^{-3}), c_p is the specific heat capacity of air at constant pressure ($\text{J kg}^{-1} \text{K}^{-1}$), C_H is the bulk transfer coefficient for heat, U is the mean wind speed measured at a distance of 0.46 m from the ice surface, T_s is the ice surface temperature, and T_a is the air temperature measured at the same distance.

The latent heat flux was calculated analogously as

$$Q_L = \rho L_s C_E U (q_s - q_a), \quad (3)$$

where L_s is the latent heat of sublimation, C_E is the bulk transfer coefficient for moisture, and q_s and q_a are the specific humidity at the ice surface and in the atmosphere, respectively.

The bulk transfer coefficients for heat and moisture were calculated following Hock and Holmgren (2005),

$$C_{H,E} = \frac{\kappa^2}{\left[\ln\left(\frac{x}{z_0}\right) - \Psi_m\left(\frac{x}{L}\right) \right] \left[\ln\left(\frac{x}{z_{0h}}\right) - \Psi_h\left(\frac{x}{L}\right) \right]}, \quad (4)$$



where $\kappa = 0.4$ is the von Kármán constant, z_0 is the aerodynamic roughness length for momentum, z_{0h} is the roughness length for heat and moisture, L is the Obukhov length, and Ψ_m and Ψ_h are the integrated stability correction functions.

270 The ice surface temperature was derived from outgoing long-wave radiation measured by the infrared radiometer assuming an ice emissivity of 0.97. Roughness lengths of $z_0 = 1.7 \times 10^{-3}$ m and $z_{0h} = 1 \times 10^{-4}$ m were adopted from Cullen et al. (2007), who determined these values for the flat section of the Northern Ice Field.

A sensitivity analysis showed that atmospheric stability corrections had only a negligible influence on the calculated sensible heat flux (mean absolute error $< 1 \text{ W m}^{-2}$). Consequently, all bulk calculations presented here assume neutral atmospheric
 275 conditions by setting $\Psi_m = \Psi_h = 0$.

3 Results & Discussion

3.1 Microclimatic Setting

The observation period was characterized by pronounced diurnal meteorological variability driven by the strong radiative contrast between the dark volcanic ash surrounding the glacier and the ice surfaces (Fig. 3a). During daytime, the ash surface
 280 warmed rapidly, reaching maximum surface temperatures close to 30°C , whereas both the horizontal glacier surface and Cliff station reached the melting point during afternoon hours and the Ground station remained clearly below. Air temperatures at the Ground and Cliff stations followed a diurnal evolution, with the Ground station generally warmer than the Cliff station during daytime and colder during nighttime. This generated strong horizontal temperature gradients between the surrounding terrain, the ice cliff and the air temperature (Fig. 4a). After sunset, the ash surface cooled rapidly through long-wave radiative
 285 losses and became colder than the adjacent air, while the ice surfaces exhibited a substantially smaller diurnal temperature range.

Throughout the campaign, wind speeds at the Ground and Cliff stations remained generally below 2 m s^{-1} , whereas stronger winds were observed at AWS1 on the horizontal glacier surface (Fig. 3c). This suggests that the cliff environment was well shaded from the wind and primarily influenced by locally generated, thermally driven circulations and the larger-scale flow
 290 was slowed down by the interaction with the vertical wall. The observed meteorological conditions were accompanied by a clear diurnal cycle in the turbulent heat exchange, with sensible heat fluxes generally directed towards the ice during daytime and substantially weaker or reversed during nighttime (Fig. 3e), while latent heat fluxes remained positive throughout most of the observation period (Fig. 3f).

This strong thermal contrast between the ash forefield and the ice cliff was accompanied by a distinct structure in the mean
 295 flow (Fig. 4b and c). At both measurement locations, the along-cliff wind velocity ($\bar{v}$) was the dominant wind component, with typical magnitudes of approximately $\pm 1\text{--}1.5 \text{ m s}^{-1}$. In contrast, the cross-cliff ($\bar{u}$) and vertical ($\bar{w}$) components showed a clear diurnal reversal: during daytime, air was transported towards the ice cliff and deflected upwards along the cliff face, whereas during nighttime the circulation reversed, with descending flow and transport away from the cliff.

This flow pattern was remarkably consistent between the two measurement locations. The along-cliff component was highly
 300 correlated ($r = 0.89$), indicating that both stations were embedded within the same larger-scale along-cliff circulation, probably

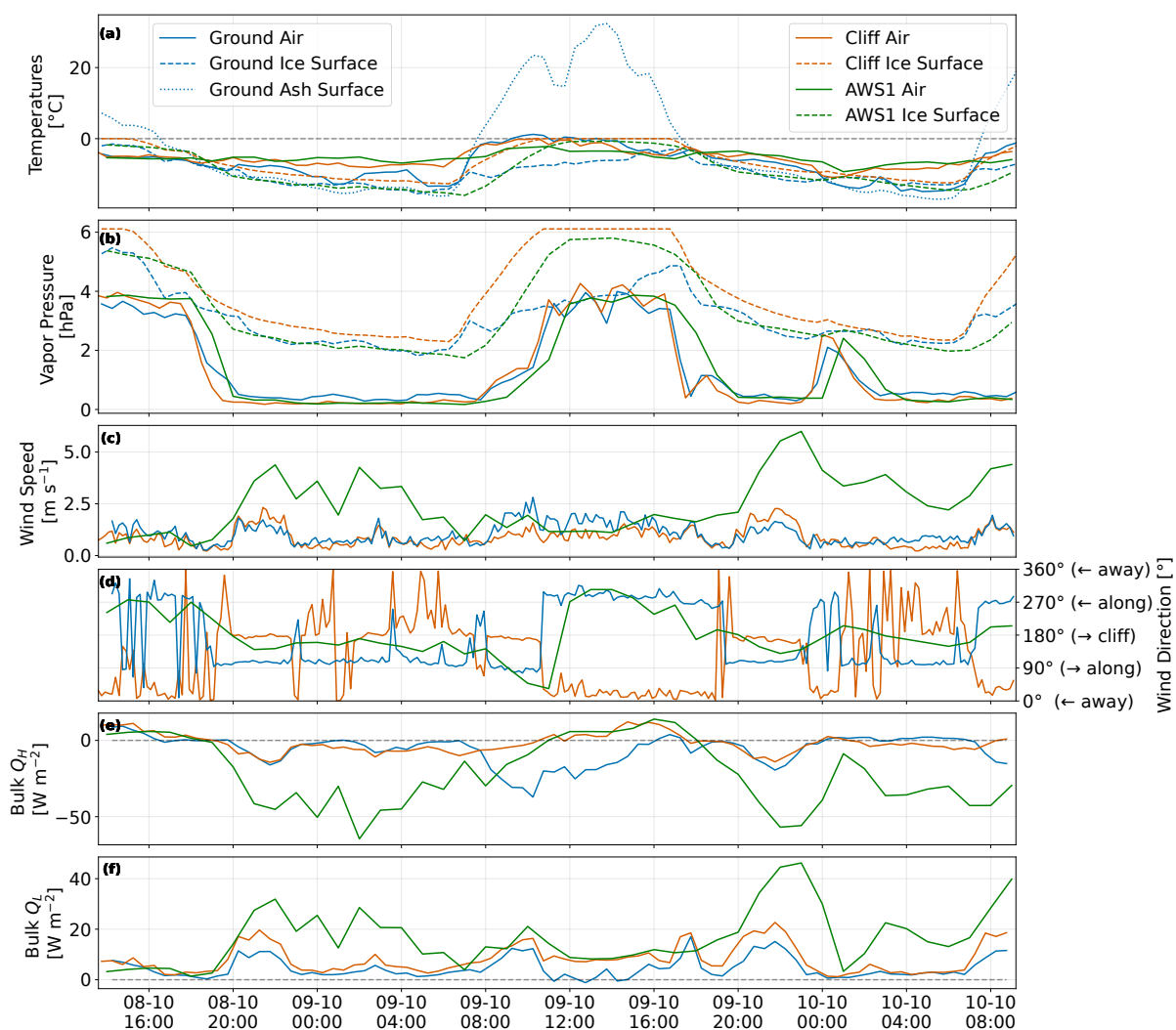


Figure 3. Overview of the meteorological conditions during the 42-hour observation period at Ground (blue) and the Cliff (orange) station and the adjacent flat glacier (AWS1, green). Shown are (a) air temperature and surface temperatures, (b) vapor pressure, (c) wind speed, (d) wind direction relative to the cliff (0° and 360° indicate flow away from the cliff, 180° flow towards the cliff, and 90°/270° flow parallel to the cliff), (e) bulk sensible heat flux, and (f) bulk latent heat flux. Dashed horizontal lines in (a), (e), and (f) indicate 0 °C and zero heat flux, respectively.

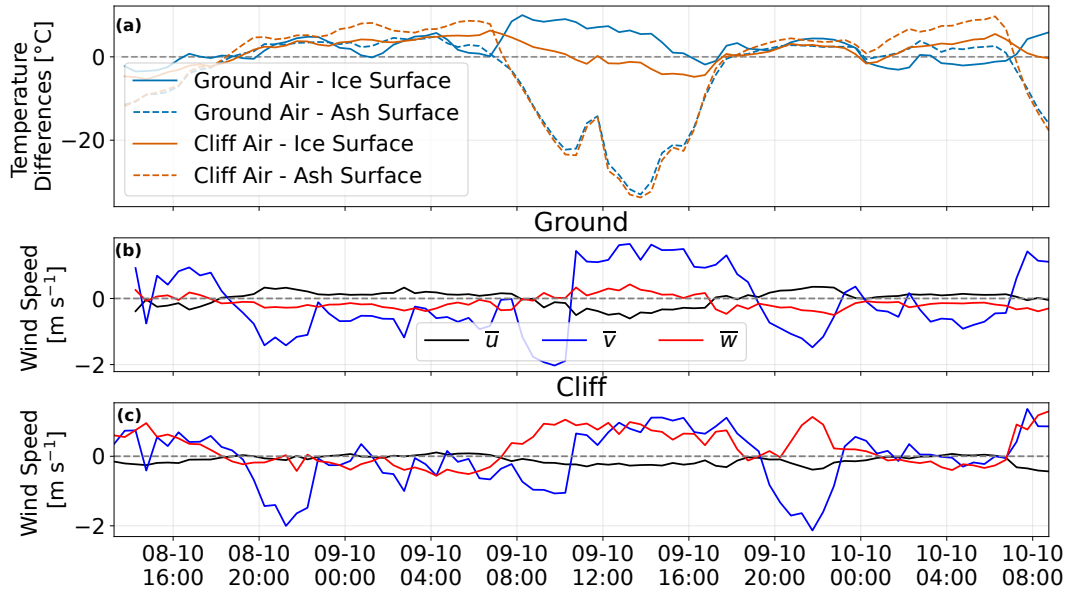


Figure 4. Temperature differences between air and surface temperatures (a) and wind speed components for the Ground Station (b) and the Cliff Station (c) in the coordinate system shown in Fig. 1

caused by the larger scale circulation being redirected by the vertical wall. In contrast, the cliff-normal and vertical velocity components ($\bar{u}$, $\bar{w}$) showed only weak correlations between the Cliff and the Ground stations ($r = 0.43$ for $\bar{u}$ and $r = 0.36$ for $\bar{w}$). Within each station, however, $\bar{u}$ and $\bar{w}$ were strongly anti-correlated ($r = -0.96$ at the Cliff and $r = -0.90$ at the Ground station). This is consistent with a cliff-induced secondary circulation, in which flow toward the ice face appears to be redirected upward during daytime and downward during nighttime. Thus, while along-cliff flow was regionally coherent during this measurement period, cross-cliff and vertical motions appear to be governed by more localized dynamics.

This coherent mean-flow structure raises the question of whether the turbulent field itself was similarly shared between the two stations, or governed by independent local processes. Correlating the turbulence statistics at the Ground and Cliff stations indicates that the two locations remained embedded in the same turbulent flow, but that this shared turbulence translated into shared heat transport only during the day (Fig. 5).

The turbulent velocity field was tightly coupled between stations irrespective of atmospheric stability: cliff-normal and vertical velocity variability (σ_u , σ_w) were both highly correlated under unstable and stable conditions alike ($r = 0.93$ – 0.96 ; Fig. 5a,b). The Cliff station generally exhibited smaller cross-cliff fluctuations during unstable periods but larger vertical fluctuations than the Ground station, indicating that the turbulent motions themselves remained coherent across the measurement domain even as their directional partitioning differed between the two locations.

This coupling did not, however, extend equally to the scalar field. Temperature variability was closely correlated between stations during the day ($r = 0.90$; Fig. 5c), but this coherence weakened substantially at night ($r = 0.49$), indicating that the

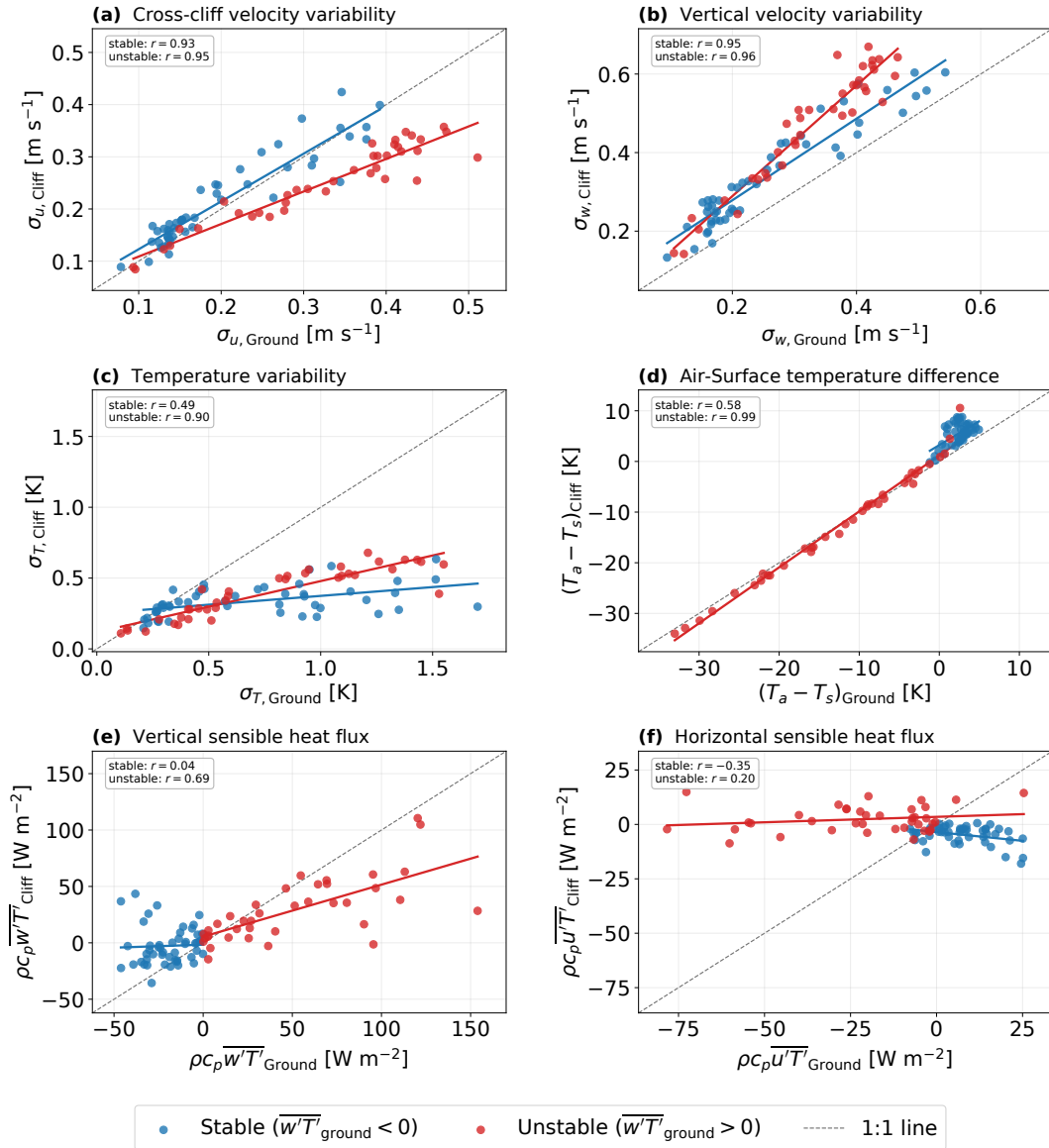


Figure 5. Comparison of turbulent quantities measured at the Ground and Cliff station. Scatterplots show Cliff values against corresponding Ground values for (A) cross-cliff velocity variability, σ_u ; (B) vertical velocity variability, σ_w ; (C) temperature variability, σ_T ; (D) air-surface temperature difference, $T_a - T_s$; (E) vertical sensible heat flux, $\rho c_p \overline{w'T'}$; and (F) horizontal sensible heat flux, $\rho c_p \overline{u'T'}$. Blue and red points denote periods classified as stable ($\overline{w'T'}_{\text{Ground}} < 0$) and unstable ($\overline{w'T'}_{\text{Ground}} > 0$), respectively. Solid lines show separate linear regressions for each stability class, with Pearson correlation coefficients (r) reported in each panel. The dashed line indicates a 1:1 relationship.



shared turbulent motions were no longer producing comparable temperature fluctuations at the two locations after sunset. The air-surface temperature difference showed the same asymmetry: nearly linear agreement between stations during the day ($r = 0.99$; Fig. 5d) but a much weaker relationship at night ($r = 0.58$), consistent with the two stations experiencing systematically different surface thermal conditions once the ash forefield had cooled.

This day-night asymmetry culminates in the turbulent heat flux itself. Vertical heat transport at the two stations was positively correlated during the day ($r = 0.71$; Fig. 5e), consistent with the same convective structures driving heat exchange at both locations, but this relationship collapsed at night ($r = 0.04$), when vertical exchange became weak and intermittent. The horizontal heat flux, by contrast, was essentially uncorrelated between stations under both conditions ($r = 0.15$ and $r = -0.35$; Fig. 5f).

Taken together, these results indicate that, over the period sampled here, the turbulent velocity field was coherent across the cliff environment at all times, while the resulting heat transport was shared between stations mainly during the day, and even then primarily in the vertical direction. Horizontal exchange instead appears to have been governed by local temperature gradients and flow orientation at each station rather than by the shared turbulent motions.

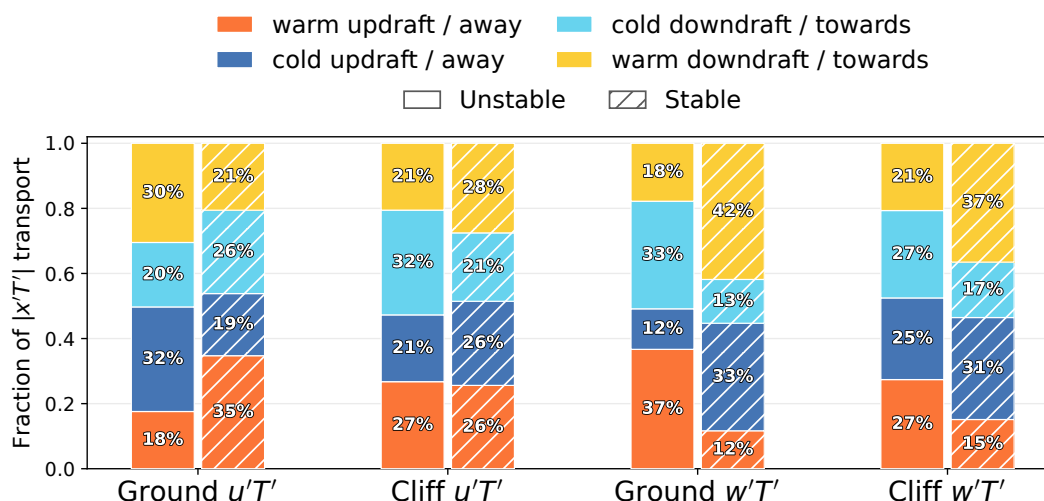


Figure 6. Relative contribution of quadrant events to the total turbulent heat transport at the Ground and Cliff station (see Sect. 2.3.1). Stacked bar charts show the fractional contribution of the four classical quadrant events to the total horizontal ($u'T'$) and vertical ($w'T'$) turbulent heat transport measured at both stations. Colors indicate the four quadrant types: warm updraft/away (Q1, orange), cold updraft/away (Q2, dark blue), cold downdraft/towards (Q3, light blue), and warm downdraft/towards (Q4, yellow). Solid bars represent unstable conditions, while hatched bars denote stable conditions. Percentages within each bar indicate the contribution of each quadrant to the total transport for the corresponding stability regime.



While the correlation analysis identifies where turbulent exchange is shared between the two measurement locations, it does not reveal which turbulent motions are responsible for the observed heat transport, or why the horizontal flux fails to couple even when the velocity field does. Quadrant analysis (Fig. 6) of the turbulent sensible heat flux addresses this directly.

During the day, vertical heat transport ($w'T'$) at the Ground station was dominated by warm updrafts (37 %) and cold
 335 downdrafts (33 %), characteristic of buoyancy-driven convection. At the Cliff station the same transport mechanisms remained dominant but were more evenly distributed among the four quadrants, suggesting that the convective structures generated over the heated ash surface were still present but had become less organized with increasing distance from their source, consistent with the moderate, though still positive, daytime correlation of the vertical sensible heat flux between stations (Fig. 5e).

The horizontal flux tells a different story, and explains the absence of any inter-station coupling noted earlier. During the
 340 day, the Ground station was dominated by warm air moving towards the ice cliff (31 %) and cold air moving away (32 %), consistent with lateral transport of heat from the warm ash surface towards the colder ice. At the Cliff station, the dominant events were reversed, with warm air preferentially moving away from the cliff (27 %) and cold air towards it (32 %). Because the two stations sat on opposite sides of their local air-surface temperature gradient, the same coherent turbulent motions appear to have produced oppositely-signed horizontal transport at each location – consistent with the absence of correlation in $u'T'$
 345 between stations despite the strongly coupled velocity field.

At night, this picture changes primarily in the vertical: the dominant quadrants reverse, with warm downdrafts (42 % and 36 % at the Ground and Cliff stations, respectively) and cold updrafts (33 % and 31 %) now accounting for most of the vertical heat flux. The horizontal flux, by contrast, shows comparatively little change in its quadrant distribution between day and night. This asymmetry mirrors the correlation results above and is consistent with vertical exchange being tied to the day-night
 350 reversal of the convective circulation, while horizontal exchange remained governed throughout by the local, station-specific thermal gradient.

These patterns, observed over a single 42.5-hour campaign at one south-facing LTIC, should be regarded as a case study rather than a general characterization of LTIC microclimates: the short duration precludes assessment of how representative this diurnal cycle is across different seasons, cliff orientations, or synoptic conditions. Nonetheless, the internal consistency of the
 355 mean flow, turbulence coherence, and quadrant-level flux structure – each independently pointing to the same geometry-induced circulation – suggests that the mechanisms identified here are physically plausible candidates for LTIC microclimates more broadly, warranting further investigation with longer and more spatially distributed observations. This decoupling between the cliff base and upper cliff face is examined in more detail in Sect. .

3.2 Ice Cliff Boundary Layer

360 Section 3.1 showed that the turbulent velocity field was correlated between the Ground and Cliff stations throughout the observation period, while the coupling of temperature fluctuations and heat fluxes depended strongly on atmospheric stability and, in the case of the horizontal flux, on the opposing local temperature gradients at the two stations. These correlation and quadrant analyses, however, integrate over the full turbulent range and cannot reveal at which temporal scales this coupling

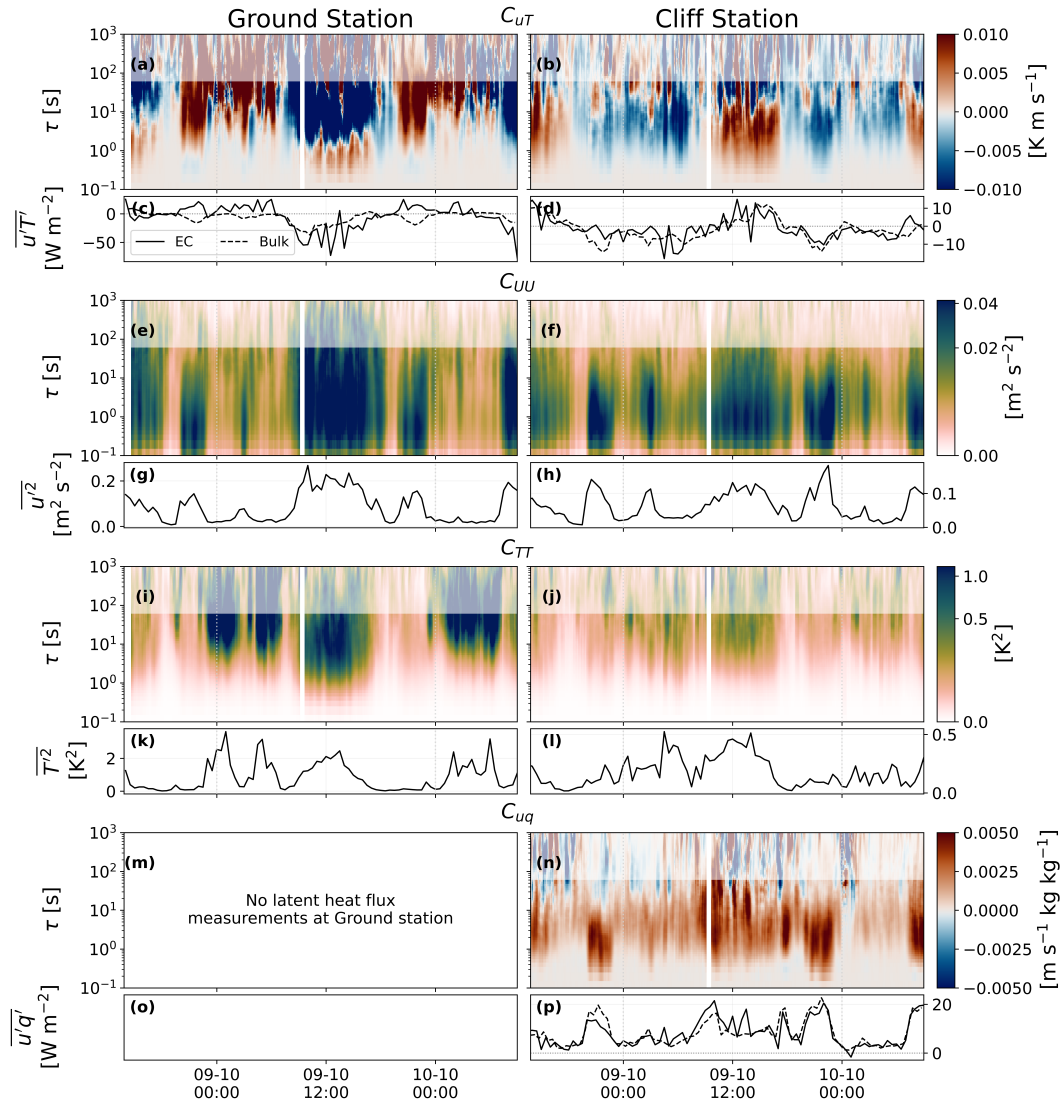


Figure 7. Time series of NO-MRD of turbulent fluxes and variances for the Ground (left) and Cliff (right) stations. Rows show the sensible heat flux C_{uT} (a, b), horizontal wind variance C_{UU} (e, f), temperature variance C_{TT} (i, j), and latent heat flux C_{uq} (n, Cliff only). The white shaded area at the top of each panel indicates the separation between mesoscale (> 60 s) and turbulence (< 60 s) motions. The y-axis shows the time scale τ of the spectral decomposition. The integrated values over the turbulent range are shown in the panels below each MRD plot (sensible heat flux : c, d; horizontal wind variance: g, h; temperature variance: k, l; latent heat flux: o, p). Solid lines indicate EC derived quantities, while dashed lines the bulk flux estimates. Note that the y-axes differ and fluxes match the coordinate system of Fig. 1.



holds, or breaks down. To examine this, non-orthogonal multiresolution flux decomposition (NO-MRD) was applied to resolve
 365 the turbulent fluxes and variances at both stations as a function of time scale τ (Fig. 7).

At the Cliff station, the turbulence structure was coherent and exhibited a pronounced diurnal cycle over the observed period
 (Fig. 7b). At small to intermediate scales ($\tau < 30$ s), the sensible heat flux was consistently negative during nighttime (directed
 toward the ice surface) and positive during daytime (directed away from the ice), a pattern also reflected in the Reynolds-
 averaged flux (Fig. 7d). This scale-resolved view offers a complementary perspective to the quadrant analysis in Sect. 3.1,
 370 which showed that the horizontal flux at the Cliff station was dominated by warm air moving away from the surface and
 cold air moving towards it – a pattern interpreted there as a transition toward a more classical, shear-influenced boundary-layer
 structure. The clear, scale-consistent diurnal cycle seen here supports that interpretation, indicating that this organised exchange
 was not limited to the bulk-averaged flux but persisted coherently across the turbulent range. While mesoscale disturbances
 intermittently extended into the turbulent range, the overall structure remained intact, indicating that turbulence at this station
 375 was closely coupled to the ice surface rather than dominated by external atmospheric variability over the sampled period.

The turbulence characteristics observed at the Cliff station are broadly consistent with the conceptual framework developed
 for turbulent natural convection along vertical walls, despite the opposite thermal configuration of a cold ice wall embedded
 in warmer air. The strong turbulence coherence identified by the NO-MRD analysis, together with the dominance of locally
 generated heat transport, supports the view that turbulent exchange was primarily controlled by wall-bounded buoyancy-driven
 380 processes rather than by the larger-scale atmospheric flow. This agrees qualitatively with the idealized laboratory and numeri-
 cal studies (Hölling and Herwig, 2005; Giometto et al., 2017) discussed in Sect. 1.2, although the present observations cannot
 confirm the detailed boundary-layer structure inferred in those investigations. One aspect of the simulations by Giometto et al.
 (2017) appears particularly relevant. They show that buoyancy-driven natural convection along a vertical wall produces a low-
 level velocity maximum, with turbulence beneath this jet sustained through the interaction of near-wall shear and buoyancy.
 385 Throughout our measurements, the momentum flux $\overline{u'w'}$ remained consistently negative (not shown), indicating downward
 transport of streamwise momentum. In wall-bounded shear flows, such a Reynolds-stress signature is characteristic of mea-
 surements taken below the velocity maximum, suggesting that, if a similar buoyancy-driven jet existed along the ice cliff, the
 eddy-covariance system was located within the shear layer beneath it rather than above it. This would provide a physically
 consistent explanation for the strong local turbulence signatures observed here, although the absence of vertical profile mea-
 390 surements prevents direct confirmation of the jet itself. At the same time, important differences remain between the idealized
 studies and the present field observations. The numerical and laboratory experiments considered smooth, infinitely extended
 vertical walls under controlled forcing, whereas the ice cliff investigated here was embedded within complex three-dimensional
 terrain, influenced by along-cliff flow and unsteady atmospheric forcing. These factors are expected to modify the detailed flow
 structure while preserving the fundamental buoyancy-driven dynamics, making the comparison primarily conceptual rather
 395 than quantitative.

This interpretation is further supported by the latent heat flux (Fig. 7n,p), which showed a similarly coherent behaviour,
 with close agreement across scales and a consistent flux direction below the 60 s averaging threshold. The correspondence
 between the sensible and latent heat flux structures suggests that, during this campaign, both scalars were transported by the



same organised turbulent motions at the Cliff station, reinforcing the picture of a locally coherent, wall-bounded turbulence regime at this location.

The Cliff station, located approximately 20 m above the ground and adjacent to a relatively homogeneous ice surface, was comparatively undisturbed by the hot ash ground below. The Ground station, by contrast, was situated in a geometrically complex setting at the corner between the vertical ice cliff and the ash-covered forefield, a configuration that can promote flow separation or recirculation. Consistent with this, the turbulence structure at the Ground station was more complex and less organised (Fig. 7a). Although a diurnal cycle was still visible, the NO-MRD revealed a persistent sign reversal of the sensible heat flux at very small time scales ($\tau \lesssim 1$ s). This small-scale reversal was not mirrored in the temperature variance (Fig. 7i), which contributed little energy at these scales, and appears instead to be primarily associated with velocity fluctuations (Fig. 7e).

Part of this small-scale behaviour is plausibly linked to the same cliff-induced deflection of warm air identified in Sect. 3.1, where the Ground station's horizontal heat flux was found to be dominated by warm air moving toward the cliff and cold air moving away (Fig. 6). A further, more speculative, explanation may be provided by stratified turbulence theory. Recent work has shown that, at sufficiently small scales, the buoyancy flux can locally reverse sign through processes associated with so-called ramp-cliff structures in the temperature signal, representing a transfer of turbulent potential energy back into turbulent kinetic energy (Bhattacharjee et al., 2026). A potential indication of such structures is the skewness of the temperature fluctuation differences ($\overline{(\Delta T')^3}$). At the Cliff station, this skewness is largest during the period from approximately 10:00 to 16:00, coinciding with the small-scale reversal of the sensible heat flux (Fig. A3).

The partitioning between velocity and temperature variance offers a further, independent perspective on the role of stratification at the two stations (Fig. 7e–l). At the Ground station, periods of low velocity variance coincided with elevated temperature variance, particularly during nighttime. This anti-correlation is consistent with a transfer of turbulent kinetic energy into turbulent potential energy under stable stratification, as has been described elsewhere (Zilitinkevich et al., 2007; Haugeneder et al., 2024). At the Cliff station, this separation between regimes was less pronounced, which may point to a more continuous turbulence production mechanism driven by near-wall processes, though we cannot rule out that this difference simply reflects the more sheltered, less complex flow environment at this station over the sampled period.

Taken together, the scale-resolved turbulence analysis points to a marked contrast between the two measurement locations during this campaign: at the Cliff station, turbulence appeared coherent and boundary-layer-like across scales, consistent with the local surface forcing and with the daytime turbulent coupling identified in Sect. 3.1; at the Ground station, turbulence was more complex and less organised, with disrupted scale interactions that align with the localized, geometry-driven horizontal exchange also seen in the quadrant analysis. As with the microclimatic patterns described above, these results derive from a single, short measurement campaign at one station pair and should be interpreted as characterizing the turbulence regime encountered during this specific period rather than as a general property of LTIC boundary layers. Nonetheless, the consistency between the scale-resolved structure shown here and the bulk correlation and quadrant patterns reported in Sect. 3.1 strengthens the case that the observed contrast between the cliff base and the upper cliff face reflects a genuine physical difference in turbulence regime.



3.3 Applicability of Bulk Aerodynamic Parameterizations

Building on the microclimatic and turbulence-structure contrasts identified in Sect. 3.1 and Sect. 3.2, we now assess whether these differences between the Ground and Cliff stations are also reflected in the performance of the bulk aerodynamic method.

The sensible heat flux at the Cliff station shows a clear diurnal cycle (Fig.7d), consistent in magnitude and timing with previous observations from the flat glacier surface of the Northern Ice Field (Cullen et al., 2007; Mölg and Hardy, 2004). It is notable that both the atmospheric forcing and the sensible heat flux at the Cliff station appear to follow the same diurnal pattern as observed on the flat glacier surface, despite the fundamentally different geometry of the two settings. This pattern is also well reproduced by the bulk method, which captures both the magnitude and temporal variability of the flux (Fig.7d), resulting in a low RMSE of 5.2 W m^{-2} (18%) and a small bias (0.7 W m^{-2}) (see Fig. A4 a). This agreement should be interpreted with some caution, as the roughness lengths used in the bulk calculation were not measured at the cliff itself but adopted from a flat-glacier site on the same ice field (Cullen et al., 2007); given that the surface characteristics of a near-vertical ice cliff (and therefore its aerodynamic roughness) are different from those of a flat glacier surface, this represents a source of uncertainty in the bulk estimates. Nonetheless, within the present, limited dataset, the bulk method performs well despite this simplification, which may be related to the coherent, boundary-layer-like turbulence structure identified at the Cliff station in Sect. 3.2, showing that turbulence there remained closely coupled to the ice surface across scales, broadly analogous to the near-surface exchange regime the bulk parameterization was originally designed to represent.

In contrast, the Ground station exhibits an opposite diurnal cycle (Fig. 7c). During daytime, sensible heat fluxes remain negative, indicating heat transport toward the ice surface and a persistent temperature gradient with warmer air relative to the ice. The main difference compared to the Cliff station lies in the ice surface temperature, which remains colder at the Ground than at the Cliff station throughout the measurement period (Fig. 3 a), maintaining a strong gradient between the air and ice surface temperatures (Fig. 4 a). The bulk method reproduces the daytime sign of the sensible heat flux and captures its overall temporal evolution reasonably well. However, during nighttime the temperature gradient remains unchanged at the Ground Station, with the ice surface consistently colder than the air, and the bulk method therefore continues to predict negative sensible heat fluxes. The eddy-covariance measurements, by contrast, show a sign reversal at this time, indicating counter-gradient transport that a gradient-based bulk formulation cannot, by construction, reproduce. This is consistent with the more complex and less organized turbulence structure identified at the Ground station in Sect. 3.2, where flow separation and recirculation in the corner between the cliff and the ash ground were found to disrupt the classical near-surface exchange regime that the bulk method assumes. Despite a small mean bias (1.9 W m^{-2}), the underestimation of the daytime flux magnitudes together with the nighttime sign reversal results in a relatively large RMSE of 18 W m^{-2} (32%), approximately three times larger, in relative terms, than at the Cliff station (Fig. A4 c).

A additional point to look at for the unusual behaviour at the Ground station may lie in the seasonal evolution of the ice surface temperature. The measured colder ice surface temperatures at the Ground station compared to the Cliff station are somewhat unexpected and may be linked to the timing of the measurements within the seasonal cycle (Fig. 3). Previous work has shown that Kilimanjaro ice cliffs undergo a bimodal annual recession regime governed by solar irradiance, alternating



between extended shaded and strongly sunlit periods (Winkler et al., 2010). As the measurements were conducted close to this transition in October (Winkler et al., 2012), it is plausible that parts of the ice cliff had not yet fully equilibrated to the increased
 470 radiative forcing after several months of shading and that at this time the point measurement of ice surface temperature might be very sensitive to topographic shading of small scale features of the ice cliff (Fig. 1); we note, however, that this explanation cannot be directly tested with the present dataset and remains speculative.

The latent heat flux at the Cliff station (Fig.7p) shows moderate variability, ranging between 0 and approximately 20 W m^{-2} , without a pronounced diurnal cycle. This contrasts with previous observations from flat glacier surfaces, where strong daytime
 475 fluxes away from the surface indicate substantial sublimation (Cullen et al., 2007). Over the sampled period, the bulk-derived latent heat flux shows very good agreement with the eddy-covariance measurements, with consistently positive values and an RMSE of 3.3 W m^{-2} (15%) (Fig. A4b). Due to missing high frequency measurements of moisture, no latent heat flux calculation was possible at the Ground station, so a corresponding comparison at the cliff base is not possible.

Previous studies on Kilimanjaro have evaluated the surface energy balance over flat glacier surfaces (Cullen et al., 2007;
 480 Mölg and Hardy, 2004). A direct comparison with our observations, however, is not possible because neither of our measurement sites provides a complete set of surface energy balance components. While the Cliff station measured the turbulent heat fluxes, no radiation measurements were available. Conversely, the Ground station was equipped with radiative measurements but did not provide latent heat flux observations. Any quantitative energy balance comparison would therefore require combining measurements from the two stations and introducing additional assumptions, making such an analysis overly speculative.
 485 Instead, we restrict the comparison to the turbulent heat fluxes, for which direct observations are available.

From a 19-month record, Mölg and Hardy (2004) report mean October sensible heat fluxes of approximately 10 W m^{-2} directed towards the surface and latent heat fluxes of approximately 40 W m^{-2} directed away from the surface. Similarly, the independent 6-day eddy-covariance campaign of Cullen et al. (2007), conducted in July, measured sensible heat fluxes of approximately 5 W m^{-2} and latent heat fluxes of approximately 40 W m^{-2} , indicating that sublimation represents the
 490 dominant turbulent energy sink over the flat glacier.

We compare the flat glacier observations with those from the Cliff station, as the turbulence there exhibited a more undisturbed flow regime than at the Ground station (Sect.3.2). Sensible heat fluxes were of comparable magnitude, reaching approximately 10 W m^{-2} while reversing direction between daytime and nighttime (Sect. 3.2). Latent heat fluxes, however, remained comparatively weak and stable throughout the campaign, typically between 15 and 20 W m^{-2} , less than half the magnitude
 495 reported in both previous studies representing the flat glacier surface. Although these comparisons necessarily span different seasons, observation periods and experimental configurations, the close agreement between the independent flat-glacier studies suggests that the reduced latent heat flux observed at the LTIC reflects a systematic difference in turbulent exchange rather than methodological variability alone.

At the Cliff station, the reduced latent heat flux together with sensible heat flux magnitudes of comparable size suggest
 500 that, during the sampled period, this LTIC operated closer to a melt-dominated than a sublimation-dominated regime, with ice surface temperatures frequently approaching or reaching the melting point. If representative of longer-term conditions at this site, this would imply that LTICs on Kilimanjaro could exert a disproportionate influence on total glacier ablation relative



to their limited spatial extent. Indeed, Kaser et al. (2010) show higher lateral shrinking than thinning on the plateau glaciers from historical observations and conceptual modeling. A broadly similar transition from a sublimation-dominated regime on flat glacier surfaces to a melt-dominated regime at ice cliffs has been reported for the Antarctic Dry Valleys (Lewis et al., 1998, 1999).

Taken together, the close agreement between the bulk aerodynamic method and the eddy-covariance measurements at the Cliff station, together with the substantially poorer agreement at the Ground station (Fig. A4), mirrors the contrast in turbulence regime established in Sect. 3.2: higher up at the Cliff station, where turbulence remained coherent and locally coupled to the ice surface, a classical surface-layer parameterization performed well despite the near-vertical geometry. In contrast, close to the cliff foot, where turbulence was disrupted by local surface heterogeneity and flow separation, the same parameterization underestimated the observed sensible heat fluxes and failed to reproduce the nighttime transport. This suggests that geometric departure from a flat surface is not, by itself, the primary obstacle to applying bulk methods at LTICs; rather, it is the degree to which the local flow retains a coherent, near-surface-coupled turbulence structure, as assessed here through the scale-resolved analysis in Sect. 3.2.

4 Conclusion

This study combines bulk aerodynamic flux estimates with scale-resolved turbulence analysis to investigate near-surface exchange processes at a land-terminating ice cliff (LTIC). Although previous understanding of turbulent exchange along vertical walls has largely been derived from laboratory experiments and numerical simulations (Hölling and Herwig, 2005; Giometto et al., 2017), direct field observations at near-vertical glacier surfaces have so far been lacking. The present study therefore provides one of the first field-based assessments of the microclimate, turbulence structure, and turbulent heat exchange at an LTIC. The results presented here are derived from a single 42.5-hour eddy-covariance campaign at one station pair, situated at two heights on one south-facing cliff on Kilimanjaro during October. The findings discussed should therefore be interpreted as characterising the flow, turbulence and exchange regime encountered during this specific case, rather than as an established, general description of LTIC boundary layers.

Figure 8 summarizes the conceptual model emerging from the observations collected during this campaign. During daytime (Fig. 8a), strong heating of the ash forefield drives a secondary circulation towards the ice cliff that is redirected upward along the cliff face while the larger-scale flow remains predominantly parallel to the cliff. Under these conditions, coherent turbulence develops along the cliff, supporting upward sensible heat flux ($\overline{w'T'}$) at both measurement heights, whereas local temperature gradients generate horizontal heat flux ($\overline{u'T'}$) in opposite directions at the cliff base and upper cliff face. During nighttime (Fig. 8b), cooling of the surrounding terrain reverses the secondary circulation and the direction of the vertical sensible heat flux, while horizontal exchange remains governed by the local thermal gradients adjacent to the ice surface. Together, these observations provide a physically consistent process-based framework linking the observed microclimate, turbulence structure and turbulent heat exchange at this LTIC.

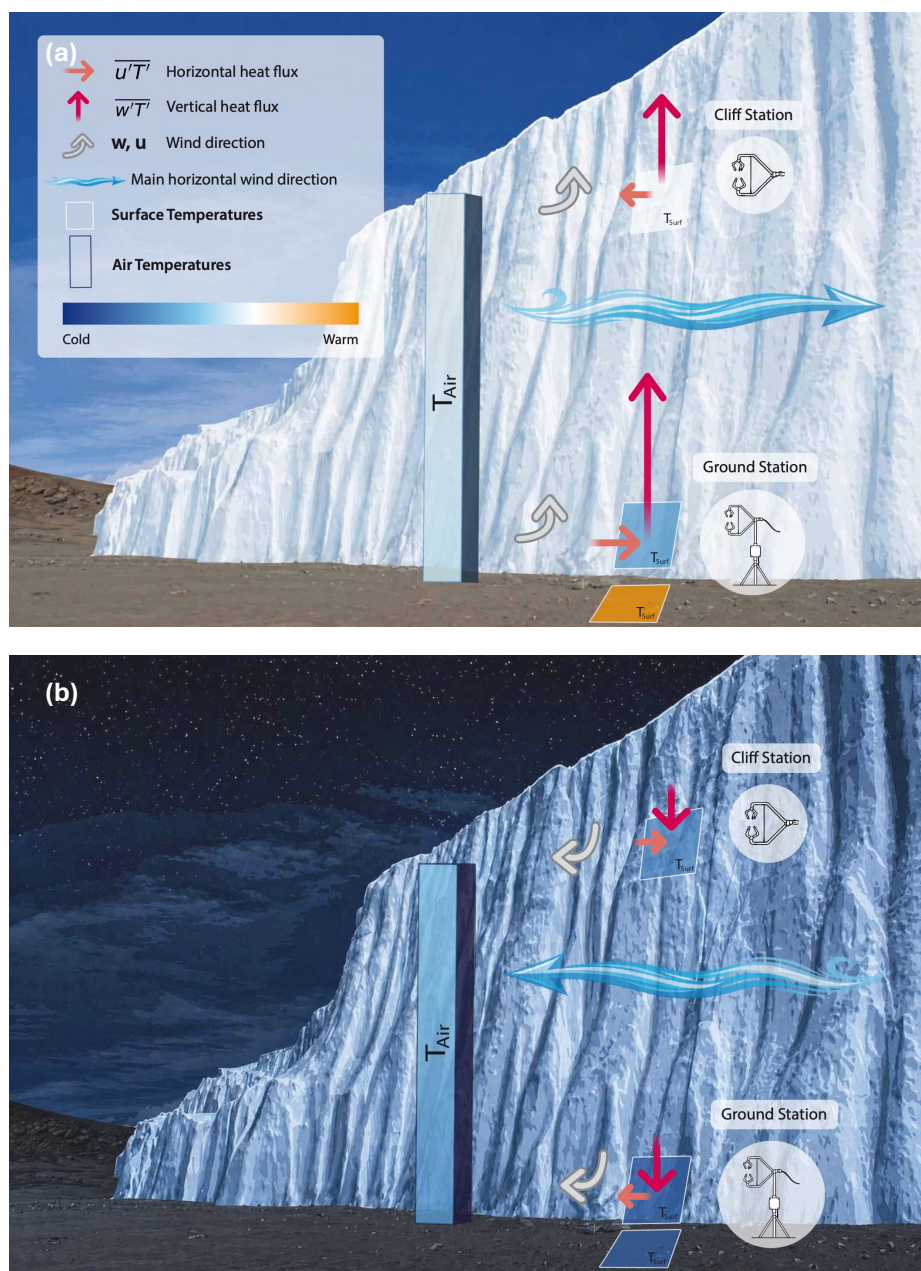


Figure 8. Conceptual illustration of the experimental setup and dominant turbulent heat transport during (a) daytime (unstable) and (b) nighttime (stable) atmospheric conditions. The sketch shows the locations of the Cliff and Ground eddy-covariance stations adjacent to the ice cliff together with the predominant wind direction and the orientation of the horizontal ($\overline{u'T'}$) and vertical ($\overline{w'T'}$) turbulent heat fluxes. Colors indicate relative air and surface temperatures, illustrating the contrasting thermal structure and turbulent exchange under unstable and stable conditions. Symbols and color scales are explained in the legend.



535 Together, our three research questions point to a single, consistent picture: the strong thermal contrast between the warm ash-covered ground and the cold ice surface set up a persistent divide between the cliff foot and the upper cliff that shaped the microclimate, the turbulence regime, and the performance of bulk flux estimates alike.

This contrast is first visible in the microclimatic setting (Research Question i), where the strong thermal contrasts between the warm ash-covered ground and the cold ice surface were associated with pronounced turbulence heterogeneity: the upper
 540 cliff showed comparatively undisturbed flow and turbulence, while the lower cliff was strongly influenced by local surface heterogeneity and large temperature differences. On Kilimanjaro, this is likely amplified by the surrounding volcanic ash, which reaches very high surface temperatures and warms the air through heat conduction and enhanced longwave radiation.

The same divide governed the turbulence structure and transport (Research Question ii). Higher up the cliff, turbulence behaved consistently with a coherent, wall-bounded boundary layer developing along the ice surface, whereas near the cliff
 545 foot, locally generated turbulence, flow separation, and counter-gradient heat transport frequently violated the assumptions of classical surface-layer exchange. This points to a strong influence of local geometry and surface heterogeneity close to the ground, potentially linked to cliff-induced flow deflection and small-scale stratified turbulence associated with ramp-cliff structures. With only two measurement heights, the transition between the two regimes can only be constrained to somewhere between 2 and 20 m above the cliff foot.

550 This same height-dependent coherence carried directly through to how well classical bulk parameterizations could reproduce the observed fluxes (Research Question iii): the bulk aerodynamic method captured the magnitude, sign, and temporal variability of both sensible and latent heat fluxes remarkably well higher up the cliff, despite the unconventional setting and despite several underlying assumptions being formally violated. The more disturbed regime near the cliff foot prevented the same approach from working there. This suggests that geometric departure from a flat surface is not, by itself, the primary obstacle
 555 to applying bulk methods at LTICs, rather, it is the degree to which the local flow retains a coherent, near-surface-coupled turbulence structure, as it did further up the cliff but not at its base. This rests on a single comparison at a single site using roughness lengths derived elsewhere, so further work at other LTICs, and ideally at inclined but non-vertical glacier surfaces, would be needed before drawing broader conclusions about transferability.

The flux estimates further point to a shift, from the sublimation-dominated ablation regime typical of the surrounding flat
 560 glacier surfaces toward a comparatively more melt-dominated regime at the cliff. Turbulent heat loss at the Cliff station appeared markedly smaller than the flat-glacier estimates, and the latent heat flux in particular, the dominant turbulent term driving sublimation on the flat surfaces, was less than half its flat-glacier counterpart in absolute terms, with ice surface temperatures at the cliff frequently approaching or reaching the melting point. If representative of longer-term conditions at this site, this would imply that LTICs on Kilimanjaro could contribute disproportionately to total glacier mass loss relative to their limited spatial
 565 extent, consistent with the hypothesis that decline of the plateau glaciers is driven by ablation at the vertical walls (Kaser et al., 2010). This effect is likely to be most pronounced in very dry environments such as Kilimanjaro or the Antarctic Dry Valleys, whereas its importance for wetter, already melt-dominated glacier systems remains, at present, unconstrained.

The conceptual framework proposed here should be regarded as a first field-based model of turbulent exchange at a LTIC rather than as a general description of LTIC microclimates. Several aspects of the present dataset limit how broadly these



570 findings can be generalized, while at the same time indicating clear priorities for future work. First, the 42.5-hour campaign captured only a single diurnal cycle close to a seasonal transition between shaded and sunlit conditions; longer observations spanning different seasons and, ideally, the full annual shading cycle described for Kilimanjaro cliffs (Winkler et al., 2010) are needed to assess the temporal persistence of the circulation and turbulence regimes identified here. Second, the two-station configuration revealed a clear contrast between the cliff foot and the upper cliff face but could not resolve the vertical transition
575 between these regimes. A denser vertical setup of turbulence measurements would help determine how rapidly this transition occurs and better constrain the depth of the ground-influenced layer. Finally, the present observations originate from a single south-facing cliff on Kilimanjaro, where the exceptionally strong thermal contrast between volcanic ash and ice is likely to enhance the secondary circulation. Extending similar measurements to LTICs with different orientations, surrounding surface types, and climatic settings will be essential to determine whether the mechanisms identified here represent a general feature
580 of near-vertical glacier surfaces or are specific to this environment. Such observations would also provide a stronger basis for evaluating whether bulk aerodynamic parameterizations can be applied more broadly to steep glacier terrain, potentially reducing the need for long-term eddy-covariance measurements at LTICs.

Code and data availability. The code and data used in this study are available at Schroeder et al. (2026)(To be published)

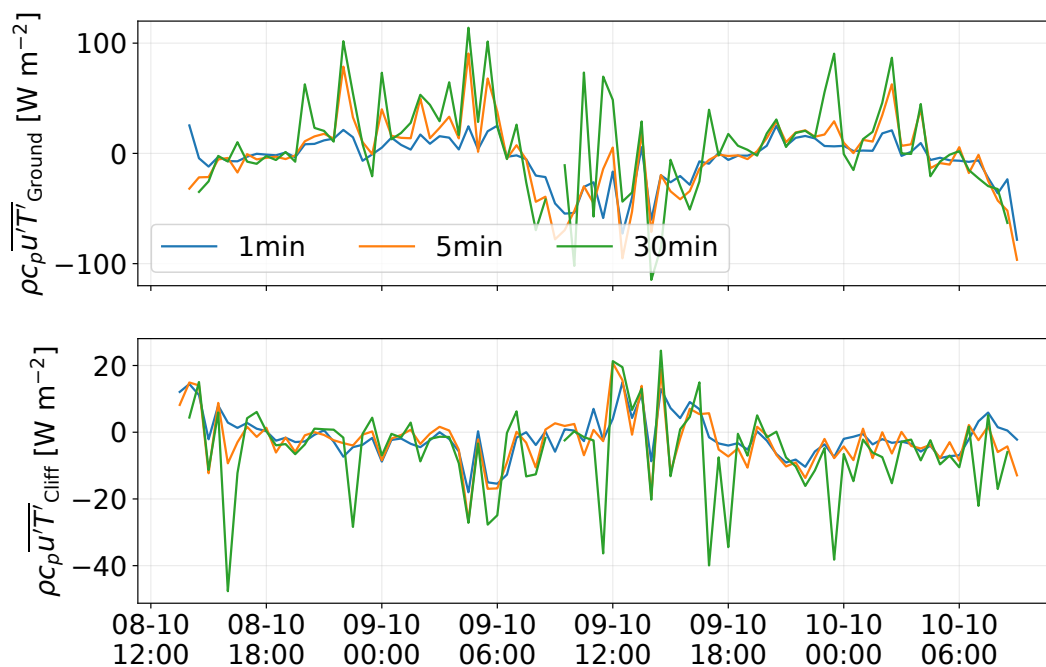


Figure A1. Horizontal sensible heat flux, $\rho c_p \overline{u'T'}$, at the Ground station (top) and Cliff station (bottom), calculated using Reynolds averaging intervals of 1, 5, and 30 min. Fluctuations and covariance products were calculated independently from the high-frequency observations for each interval. All estimates were subsequently averaged into 30-minute reporting intervals. The comparison illustrates the sensitivity of the flux time series to the interval used to define the fluctuations.

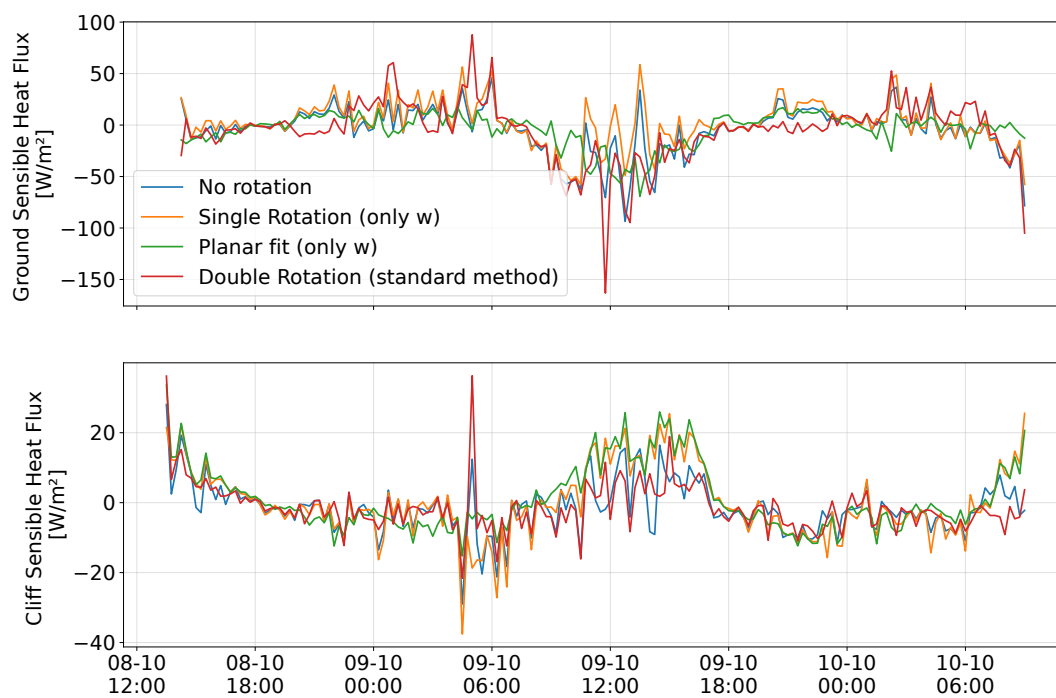


Figure A2. Comparison of sensible heat fluxes calculated using different coordinate-rotation methods for the Ground station (top) and Cliff station (bottom). Shown are fluxes derived without rotation, using a single rotation of the vertical wind component, a planar-fit correction, and the standard double-rotation method.

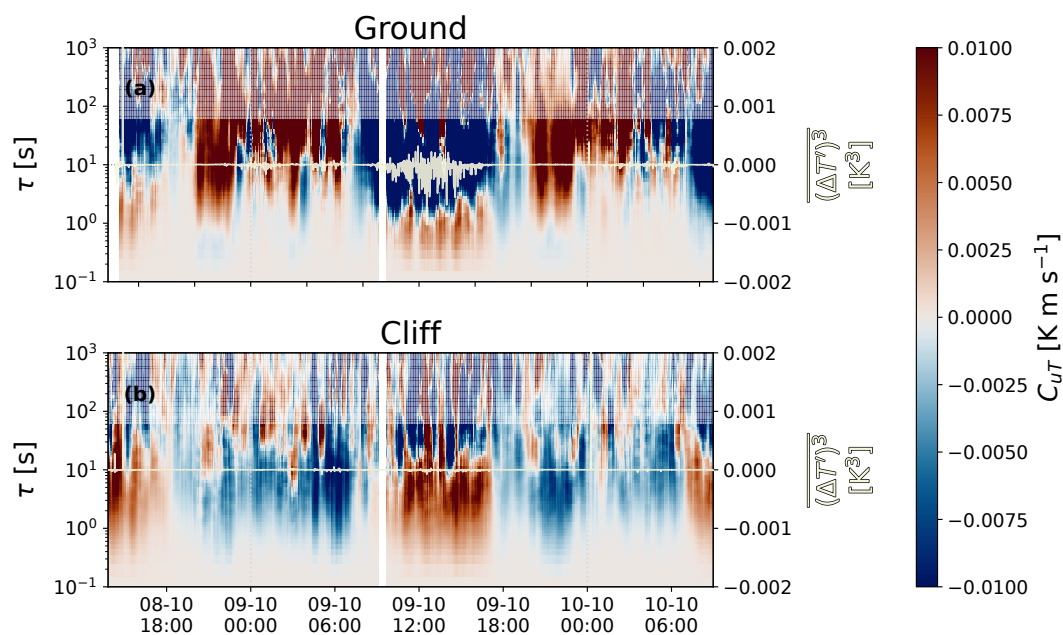


Figure A3. NO-MRD cospectra of the sensible heat flux $\overline{(u'T')}$ for the (a) Ground and (b) Cliff stations (The same as panel (a) and (b) in Fig. 7). The right y-axis further shows the third moment of the temperature fluctuation differences $\overline{(\Delta T')^3}$, a measure for the presence of ramp-cliff structures.

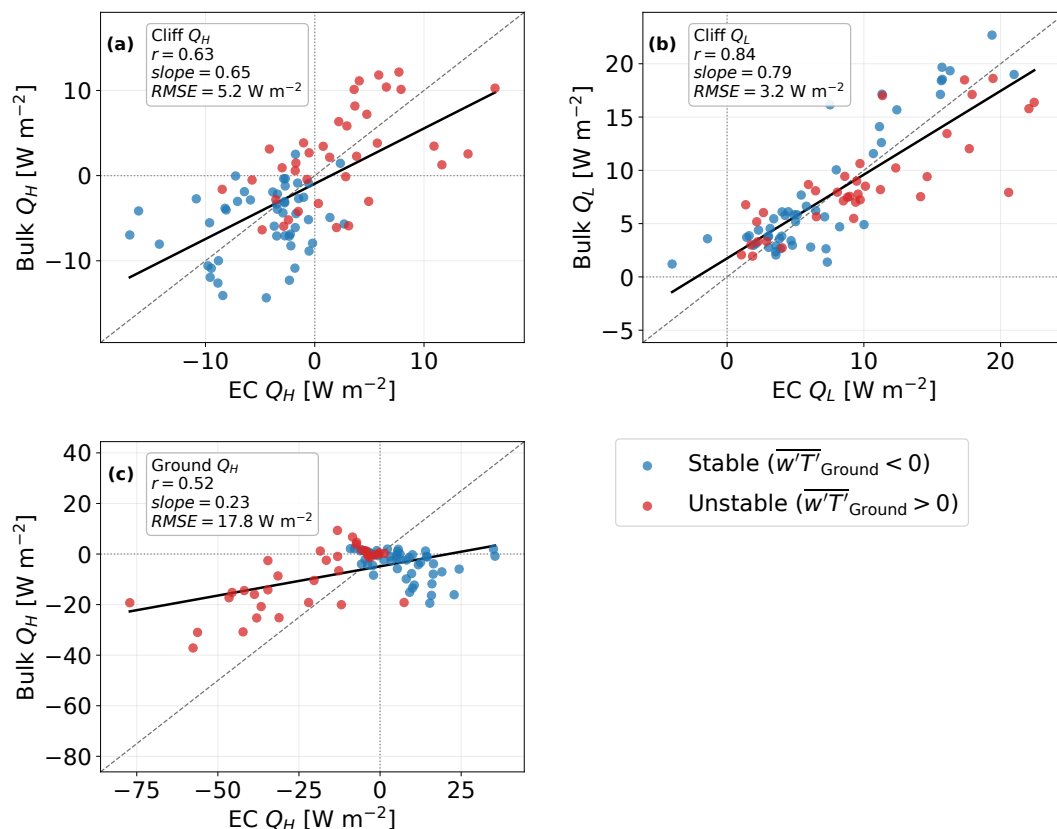


Figure A4. Comparison between bulk aerodynamic and eddy-covariance turbulent heat fluxes. Scatterplots compare bulk-derived and eddy-covariance estimates of (a) sensible heat flux at the Cliff station (Q_H), (b) latent heat flux at the Cliff station (Q_L), and (c) sensible heat flux at the Ground station (Q_H). Blue and red symbols denote periods classified as stable ($\overline{w'T'}_{\text{Ground}} < 0$) and unstable ($\overline{w'T'}_{\text{Ground}} > 0$), respectively, according to the vertical sensible heat flux measured at the Ground station. The dashed line indicates the 1:1 relationship, while the solid line shows the least-squares linear regression using all observations. Pearson correlation coefficients (r) and root-mean-square error (RMSE) are reported in each panel.

Author contributions. MS: data analysis, data curation, study design, figure production and editing, manuscript writing; IS: data analysis, study design, expertise on boundary layer meteorology; MW: design of field survey, field data collection, data curation, data analysis, expertise on Kilimanjaro glaciers; GK: design of field survey, study design, expertise on Kilimanjaro glaciers; JS and JA: expertise on LTIC mass and energy balance; GW: design of field survey, data analysis; RP: study design. All authors were involved in the assessment and contributed to the manuscript draft.

Competing interests. The authors declare there are no conflicts of interest for this manuscript.



590 *Disclaimer.* Large language models were used for suggesting grammatical corrections, stylistic adjustments, and clarity improvements to the human-written text of this manuscript. These AI tools were used under the direct supervision of the authors.

Acknowledgements. The authors would like to thank Thomas Mölg (FAU Erlangen-Nürnberg) and Nicolas Cullen (University of Otago) for framing the measurement concept and Christian "Lenz" Gratzer for his technical skills supporting the field team in the vertical during the October 2010 campaign. We are grateful to Douglas Hardy (University of Massachusetts) for providing meteorological data of AWS1.

595 Ivana Stiperski acknowledges funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (Grant Agreement No. 101001691). This research was funded in whole or in part by the Austrian Science Fund FWF (Grant DOIs 10.55776/P20089 and 10.55776/P36306).



References

- Abermann, J., Steiner, J., Prinz, R., Wecht, M., and Lisager, P.: The Red Rock ice cliff revisited – six decades of frontal, mass and area changes in the Nunatarssuaq area, Northwest Greenland, *Journal of Glaciology*, 66, 567–576, <https://doi.org/10.1017/jog.2020.28>, 2020.
- Bhattacharjee, S., de Bruyn Kops, S. M., and Bragg, A. D.: Mechanism generating reverse buoyancy flux at the small scales of stably stratified turbulence, *Journal of Fluid Mechanics*, 1026, A35, 2026.
- Cheesewright, R.: Turbulent natural convection from a vertical plane surface, 1968.
- Cullen, N., Sirguey, P., Mölg, T., Kaser, G., Winkler, M., and Fitzsimons, S.: A century of ice retreat on Kilimanjaro: the mapping reloaded, *The Cryosphere*, 7, 419–431, 2013.
- Cullen, N. J., Mölg, T., Kaser, G., Steffen, K., and Hardy, D. R.: Energy-balance model validation on the top of Kilimanjaro, Tanzania, using eddy covariance data, *Annals of Glaciology*, 46, 227–233, <https://doi.org/10.3189/172756407782871224>, 2007.
- Evatt, G. W., Mayer, C., Wirbel, A., Abrahams, I. D., and Nicholson, L.: A reassessment of ice cliff dynamics upon debris-covered glaciers, *Annals of Glaciology*, 65, e33, 2024.
- George Jr, W. K. and Capp, S. P.: A theory for natural convection turbulent boundary layers next to heated vertical surfaces, *International Journal of Heat and Mass Transfer*, 22, 813–826, 1979.
- Giometto, M. G., Katul, G. G., Fang, J., and Parlange, M. B.: Direct numerical simulation of turbulent slope flows up to Grashof number, *J. Fluid Mech.*, 829, 589–620, <https://doi.org/10.1017/jfm.2017.372>, 2017.
- Han, H., Wang, J., Wei, J., and Liu, S.: Backwasting rate on debris-covered Koxkar glacier, Tuomuer mountain, China, *Journal of Glaciology*, 56, 287–296, 2010.
- Haugeneder, M., Lehning, M., Stiperski, I., Reynolds, D., and Mott, R.: Turbulence in the Strongly Heterogeneous Near-Surface Boundary Layer over Patchy Snow, *Boundary-Layer Meteorol.*, 190, 7, <https://doi.org/10.1007/s10546-023-00856-4>, 2024.
- Hinzmann, A., Mölg, T., Braun, M., Cullen, N. J., Hardy, D. R., Kaser, G., and Prinz, R.: Tropical glacier loss in East Africa: recent areal extents on Kilimanjaro, Mount Kenya, and in the Rwenzori Range from high-resolution remote sensing data, *Environmental Research: Climate*, 3, 011 003, <https://doi.org/10.1088/2752-5295/ad1fd7>, 2024.
- Hock, R. and Holmgren, B.: A distributed surface energy-balance model for complex topography and its application to Storglaciären, Sweden, *Journal of Glaciology*, 51, 25–36, 2005.
- Howell, J. and Mahrt, L.: Multiresolution flux decomposition, *Boundary-Layer Meteorology*, 83, 117–137, 1997.
- Hölling, M. and Herwig, H.: Asymptotic analysis of the near-wall region of turbulent natural convection flows, *J. Fluid Mech.*, 541, 383–397, <https://doi.org/10.1017/S0022112005006300>, 2005.
- Kaser, G., Hardy, D. R., Mölg, T., Bradley, R. S., and Hyera, T. M.: Modern glacier retreat on Kilimanjaro as evidence of climate change: observations and facts, *International Journal of Climatology*, 24, 329–339, <https://doi.org/10.1002/joc.1008>, 2004.
- Kaser, G., Mölg, T., Cullen, N. J., Hardy, D. R., and Winkler, M.: Is the decline of ice on Kilimanjaro unprecedented in the Holocene?, *The Holocene*, 20, 1079–1091, <https://doi.org/10.1177/0959683610369498>, 2010.
- Ke, J., Williamson, N., Armfield, S. W., and Komiya, A.: The turbulence development of a vertical natural convection boundary layer, *Journal of Fluid Mechanics*, 964, A24, 2023.
- Lewis, K. J., Fountain, A. G., and Dana, G. L.: Surface energy balance and meltwater production for a Dry Valley glacier, Taylor Valley, Antarctica, *Annals of Glaciology*, 27, 603–609, 1998.



- Lewis, K. J., Fountain, A. G., and Dana, G. L.: How important is terminus cliff melt?: a study of the Canada Glacier terminus, Taylor Valley, Antarctica, *Global and Planetary Change*, 22, 105–115, 1999.
- Lu, S. S. and Willmarth, W. W.: Measurements of the structure of the Reynolds stress in a turbulent boundary layer, *Journal of Fluid Mechanics*, 60, 481–511, 1973.
- Miles, E. S., Steiner, J., Buri, P., Immerzeel, W., and Pellicciotti, F.: Controls on the relative melt rates of debris-covered glacier surfaces, *Environmental Research Letters*, 17, 064 004, 2022.
- Mölg, T. and Hardy, D. R.: Ablation and associated energy balance of a horizontal glacier surface on Kilimanjaro, *Journal of Geophysical Research: Atmospheres*, 109, D16 104, <https://doi.org/10.1029/2003JD004338>, 2004.
- Mölg, T., Cullen, N. J., Hardy, D. R., Winkler, M., and Kaser, G.: Quantifying Climate Change in the Tropical Midtroposphere over East Africa from Glacier Shrinkage on Kilimanjaro, *Journal of Climate*, 22, 4162–4181, <https://doi.org/10.1175/2009JCLI2954.1>, 2009.
- Mölg, T., Hardy, D. R., Collier, E., Kropač, E., Schmid, C., Cullen, N. J., Kaser, G., Prinz, R., and Winkler, M.: Mesoscale atmospheric circulation controls of local meteorological elevation gradients on Kersten Glacier near Kilimanjaro summit, *Earth System Dynamics*, 11, 653–672, <https://doi.org/10.5194/esd-11-653-2020>, 2020.
- Reid, T. and Brock, B.: Assessing ice-cliff backwasting and its contribution to total ablation of debris-covered Miage glacier, Mont Blanc massif, Italy, *Journal of Glaciology*, 60, 3–13, 2014.
- Schroeder, M., Stiperski, I., Winkler, M., Kaser, G., Steiner, J., Abermann, J., Wohlfahrt, G., and Prinz, R.: Boundary Layer Characteristics of a Land- Terminating Ice Cliff - Turbulence Measurements from the Summit of Kilimanjaro, Tanzania: Data and Code, <https://doi.org/10.5281/zenodo.20138749>, 2026.
- Steiner, J., Pellicciotti, F., Buri, P., Miles, E. S., Immerzeel, W. W., and Reid, T. D.: Modelling ice-cliff backwasting on a debris-covered glacier in the Nepalese Himalaya, *Journal of Glaciology*, 61, 889–907, 2015.
- Steiner, J., Buri, P., Abermann, J., Prinz, R., and Nicholson, L.: Steep ice – progress and future challenges in research on ice cliffs, *Annals of Glaciology*, 63, 132–136, <https://doi.org/10.1017/aog.2023.41>, 2022.
- Steiner, J., Abermann, J., and Prinz, R.: The terrestrial ice margin morphology in Kalaallit Nunaat (Greenland), *The Cryosphere*, 20, 1797–1814, 2026.
- Stiperski, I. and Rotach, M. W.: On the measurement of turbulence over complex mountainous terrain, *Boundary-Layer Meteorology*, 159, 97–121, 2016.
- Vickers, D. and Mahrt, L.: Quality control and flux sampling problems for tower and aircraft data, *Journal of atmospheric and oceanic technology*, 14, 512–526, 1997.
- Vickers, D. and Mahrt, L.: The Cospectral Gap and Turbulent Flux Calculations, *J. Atmos. Oceanic Technol.*, 20, 660–672, 2003.
- Waterman, T. S., Stiperski, I., Chaney, N., and Calaf, M.: Evaluating anisotropy-based Monin–Obukhov similarity theory over canopies and complex terrain, *Quarterly Journal of the Royal Meteorological Society*, p. e70206, 2026.
- Webb, E. K., Pearman, G. I., and Leuning, R.: Correction of flux measurements for density effects due to heat and water vapour transfer, *Quarterly Journal of the Royal Meteorological Society*, 106, 85–100, 1980.
- Willmarth, W. W. and Lu, S. S.: Structure of the Reynolds stress near the wall, *Journal of Fluid Mechanics*, 55, 65–92, 1972.
- Winkler, M.: Kilimanjaro Ice Cliffs - Morphology, Recession, Micro-Climature, and how they determine Glacier Area Loss, Phd thesis, University of Innsbruck, Austria, <https://www.uibk.ac.at/en/acinn/theses/dissertations/>, 2011.
- Winkler, M., Kaser, G., Cullen, N. J., Mölg, T., Hardy, D. R., and Pfeffer, W. T.: Land-based marginal ice cliffs: Focus on Kilimanjaro, *Erdkunde*, 64, 179–193, <https://doi.org/10.3112/erdkunde.2010.02.05>, 2010.



- Winkler, M., Pfeffer, W. T., and Hanke, K.: KILIMANJARO ICE CLIFF MONITORING WITH CLOSE RANGE PHOTOGRAMMETRY, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXIX-B5, 441–446, <https://doi.org/10.5194/isprsarchives-XXXIX-B5-441-2012>, 2012.
- 675 Zilitinkevich, S. S., Elperin, T., Kleerorin, N., and Rogachevskii, I.: Energy-and flux-budget (EFB) turbulence closure model for stably stratified flows. Part I: Steady-state, homogeneous regimes, Boundary-Layer Meteorology, 125, 167–191, 2007.