General Response to Referee 1

We gratefully thank referee1 for his comments and suggestions to add a more quantitative analysis. We revised all figures additionally showing distributions of the data (see comments to referee 2). We also revised the text ensuring a clearer reference to numbers such as means, correlation coefficients or medians. We also avoid saying that something is a strong or weak correlation, and instead simply report the values in the text. We have added more quantitative analysis according to the specific suggestions or reviewer 2, but should you have particular additional analyses that you would like to see, then please specify those and we can include them where possible.
We revised figures 2, 3, 4, 5, 6, 7, 8, 9 and 10. All suggested figure improvements and adjustments have been made and checked for consistency. Used colours are now colour-blind friendly. Additionally, added three new figures:

- • new Figure 2 describing the multi flux decomposition,
- • new Figure 3 showing the time series of air temperature, wind and the classification scheme for katabatic and disturbed conditions.
- • new figure 13 showing the divergences of the vertical and horizontal heat fluxes.

Furthermore, we added a new table showing estimates on flux footprint area and spitted the original table 1 in two tables – table 2 and table 3.
In the following we respond to all comments and provide the revised figures the responses are referring to at the end of the document.

Specific comments:

• "Sensitivity analysis, however, shows that this increase is no considerable even when reducing the surface roughness by an order of magnitude." A number for what they deem "not considerable" would be helpful.
Response: We have calculated the area enclosed by the footprints for the different conditions and stations. Increasing the roughness from 0.004 to 0.01 results in a decrease of footprint sizes that depends on the flow conditions, but is consistent between the stations. For katabatic flow the footprint size is 88 % of the original, and for the disturbed: 79 %. We now provide the areas of the footprint for two different roughness lengths in Table 1.

• The authors delineate wind regimes as "katabatic situations" and "disturbed situations". Although grammatically correct, I don't feel that "situation" is the best choice of words here. In the caption of Figure 3, the authors use "katabatic conditions" and "disturbed conditions", which feels more appropriate. As an alternate, I suggest "katabatic flows" and "disturbed flows".
Response: we now change the word situations to conditions throughout the manuscript.

• The authors state, "Following these observations, the position of the jet-speed maximum can be estimated by linear interpolation between two heights where momentum fluxes are measured (Grachev et al., 2016). This estimate assumes that the momentum flux decreases linearly, and can be applied confidently only if the jet maximum height happens to be between the two measurement levels." I understand that it won't work if the jet maximum height occurs outside of the two measurement levels, but this reads that they are confident that linear interpolation is appropriate (which they later state provides a crude estimate).
Response: Indeed, the assumption that the momentum profile changes linearly with height is only rough and we use it here as the best guess to estimate of the jet height, following the study of Grachev et al. An independent study that is not part of this work, however, does show confidence in this estimate. Still, we have now changed the wording in the text to make it clear that this is generally indeed a rough estimate.

• "Flux footprints tend to be smaller during disturbed situations", although I don't see this from Figure 3. To my eyes, the areas enclosed (b) are larger than those enclosed in (a). My guess is that these are envelopes of the superposition of all footprints over the day, but I'm uncertain. Additionally, are these footprints of 80% flux contribution? More clarity here would be appreciated.
Response: Indeed, this was an imprecise formulation. The horizontal extent of the footprints for individual periods are smaller in disturbed conditions, however, the larger variability of wind direction during disturbed conditions results in an overall larger area of the climatological footprints. We now also provide more details on the footprint calculations and results.

• "This extreme increase of wind speed with height is confirmed by preliminary numerical simulations (not shown)." It is unclear to me what these numerical simulations are confirming. Two hypotheses are listed previously – is the numerical simulation confirming either of those? Or are the simulations simply confirming that this is possible (that the measurements are not faulty)? Wind shearing in excess of 15 m/s over only 55 cm is very significant for a mountain glacier. In either case, this is an opportunity to provide more detail and build a clearer physical picture of the dynamics at play.
Response: We thank the reviewer for spotting this inconsistency. There was a bug in processing the wind data that resulted in this unphysical result. The corrected analysis shows no strong increase in wind velocity between level 2 and 3. We apologize for this error. It, however, does not affect the remainder of the results as the error was only in the assimilation of the data from the 2D sonic. We have now also skipped the part of the text related to the preliminary numerical results as these are not yet ready for publication. These results are, however, in fact showing the presence of strong winds above the glacier.

• The authors should be more explicit with what they consider a strong correlation. "Sensible

heat fluxes, however, show a strong correlation with the low-level wind speed during disturbed situations". Although not weak, I would argue that -0.42 and -0.47 aren't particularly strong correlations. I'm not sure I follow the justification nor the implications for the analysis at the end of page 16.
Response: We agree that a correlation of 0.47 cannot be considered very strong. We have now recalculated correlation coefficients for wind velocity anomalies and also for new conditions defined for disturbed situations (we use a smaller wind sector that decreases the uncertainty due to flow not aligned with the transect). We revised the paragraph accordingly and no longer stating that something is a high correlation:
Turbulence data reveal higher vertical turbulent sensible heat fluxes during disturbed than during katabatic conditions. Higher heat fluxes coincide with higher air temperatures particularly at the margin station (Fig. 7 d-f). This is also reflected by a mean turbulent heat flux for disturbed conditions (-0.051 K m/s) being significantly higher than during katabatic conditions (-0.037). With the melting surface of the glacier at zero degrees, the increasing near-surface temperature gradients coincided with an increase of downward turbulent heat flux. As already mentioned, near-surface wind speeds during disturbed conditions were typically lower than the daytime average wind speed. Sensible heat fluxes, however, show a much higher correlation with the low-level wind speed (-0.5 and -0.62 for TT1 and TT3) during disturbed conditions than during katabatic flow conditions (-0.15 and -0.18 for TT1 and TT2). For disturbed conditions, no correlation between sensible heat flux and air temperature can be found (-0.001 and 0.16 for TT1 and TT3).

• "During disturbed situations turbulence data showed small spatial difference of turbulent heat exchange at the across-glacier transect". The resulting scatters look similar, but is there any structure in plots of w'T' at TT3 vs w'T' at TT1?
Response: We are now showing the structure of the data of vertical turbulent heat flux through histograms, which more clearly show the small differences between stations for disturbed conditions compared to katabatic conditions when TT3 shows higher fluxes than TT1 and TT2.

• "Fluxes are particularly similar at TT1 and TT3 despite significantly higher air temperatures observed at TT1" How similar is "particularly similar"? Again, a scatter and more site-to-site analysis would aid this discussion.

• "In contrast to the margin station TT1 which shows similar correlations between air temperature and turbulent heat fluxes for both situations, the central station TT3 shows no correlation between air temperatures and heat fluxes". Although -0.2 and -0.21 are similar numbers, neither are strong correlations. One could also argue that 0.06 and 0.12 are similar numbers.
Response: yes, we agree. We changed Figure 6 which now shows the distribution of temperature anomalies for all stations during katabatic and disturbed conditions. We further revised this section, which now reads: *During disturbed conditions turbulence data showed small spatial differences of turbulent heat exchange at the across-glacier transect (Figure 7b). Fluxes are similar for all transect stations despite significantly higher air temperature anomalies observed at TT1 than at TT3 (+1.8°C for TT1 and +1.2°C for TT3; Figure 6b). While air temperatures were lower at TT3 than at TT1, higher wind velocities at the centreline appeared to promote heat exchange there (Figure 7b). This is also confirmed by statistics shown in Table 1. At the central station wind shows higher correlations with turbulent heat fluxes than at the margin station.*

• "Figure 8 illustrates the advection of heat as a function of the deviation of the flow from the dominant katabatic flow direction" – this statement is backwards.
Response: we revised this sentence.

• Figure 8 and some of the following analyses are misleading. When wind direction isn't parallel with the station alignment, heat is no longer being advected between stations. Even if HA is calculated only using wind component V, U must be considered to determine the source of the heat advection. For example: if considering stations TT2 and TT1, if V = 1 m/s and U = 0 m/s, then it reasonable to assume heat is being advected from TT1 to TT2. If V= 1 m/s and U = 0.1 m/s, the source of the advection is slightly further up-glacier than TT1, so the measurement of HA is more inaccurate, as it assumes the up-glacier conditions are the same as those at TT1. This becomes a far more uncertain if V = 1 m/s and U = 5 m/s, for example. A clearer analysis of uncertainties and error here (and in figure 9) would be helpful. Currently, much of the information in Figure 8, along with the statement "Horizontal heat advection HA increased with temperature differences and V-component along the transect line" are guaranteed results considering that is how HA is defined. I wonder if factoring in these uncertainties would improve correlation coefficients between HA and w'T', as although 0.31 is a higher correlation than 0.19, I wouldn't call either of them a strong correlation.
Response: We agree that imperfect alignment with the transect would lead to partially erroneous conclusions of where the air is coming from. The conditions in which V = 1 m/s and U = 5 m/s would indeed mean that the along-transect component is negligible and the wind is coming from almost perpendicular direction to the transect. These kinds of conditions have now been a priory filtered out of our analysis as we only examine a sector that is more or less aligned with the transect when we examine heat advection. We therefore limited the analysis of heat advection and horizontal heat divergences between stations to a smaller wind sector of 60°. Beyond this, the uncertainty related to not perfectly aligned flows is hard to be quantified in a reliable way.

• "Second, the transect stations reveal a trend for both situations from more frequently measured positive and small momentum fluxes at the margin to larger and more frequently measured negative momentum fluxes at the central station." Distributions would be helpful in justifying this. I don't see this trend in the katabatic situation.

Response: we added distributions to Figure 10 which shows the shift of the curve towards more negative momentum fluxes and positive horizontal heat fluxes at TT3 than at TT1 (see below).
• higher flux divergence of turbulent heat fluxes during disturbed situations." If all of the scatter in y is projected onto a single line across the x-axis, do (a vs. d), (b vs. e), and (c vs. f) really look so different? How much higher are the flux divergences?

Response: we now directly compare the distributions of flux divergences during katabatic conditions against disturbed conditions in Figure 10 (shown later in this response document). This shows that we have a flatter distribution for FD during disturbed conditions with a higher value at the peak of the distribution.
• "During westerly flow situations turbulence data at the centerline of the glacier (TT3) show a strong increase of downward vertical sensible heat fluxes with increasing downward momentum fluxes (negative values) (Fig. 10c)." This relationship is not apparent. I don't visually see any correlation between the colourbar (vertical sensible heat fluxes) with the y-axis (momentum fluxes).

Response: we added now a new figure 12 showing this relationship between strong increase of downward vertical sensible heat fluxes with increasing downward momentum fluxes (negative values). We revised the text accordingly:

We are not only interested in changes in the turbulent structure when changing from katabatic to disturbed conditions but also on the effect of heat advection on the turbulent heat fluxes. Turbulence data of katabatic and disturbed conditions reveal some similarities along the transect stations but also pronounced differences between the different flow conditions (Fig. 10 a, b). First, the three transect stations show a similar trend for both conditions with an increase of the vertical turbulent heat flux (Fig. 7 a, b) and heat flux divergence (Figure 10 a, b) from the margin station towards the central station. Second, the transect stations reveal a trend for both conditions from more frequently measured positive and small momentum fluxes at the margin to larger and more frequently measured negative momentum fluxes at the central station (Fig. 10 a, b). On the other side, the largest differences are the much higher magnitudes of turbulent fluxes of momentum and heat as well as higher flux divergence of turbulent heat fluxes during disturbed conditions.

In order to assess the effect of heat advection on the heat exchange processes during disturbed conditions we focus our analysis on flow characteristics during those conditions (Fig. 10; Fig. 12). During westerly flow conditions turbulence data at the centreline of the glacier (TT3) show a strong increase of downward vertical sensible heat fluxes with increasing downward momentum fluxes (negative values) (Fig. 12b). The strongest vertical turbulent heat fluxes coincided with peak vertical heat divergence (Fig. 10 d). At the more wind-exposed centreline, negative momentum fluxes and the strong vertical heat flux divergence (Fig. 10 b) indicate that no pronounced katabatic jet is present below the lowest measurement level and that measurements were conducted within a stable atmospheric layer with increasing wind velocities with height featuring strong flux gradients close to the surface. Strong turbulent momentum and sensible heat fluxes combined with strong flux divergence at TT3 suggest very efficient turbulence transfer towards the surface in case of advection.

• "While the mid-transect station TT2 evidences predominantly negative momentum fluxes with a considerably smaller flux divergence and smaller turbulent heat fluxes than observed at the centerline: : :" Certainly the maximum flux divergence is smaller, but how do the distributions/means compare? Is there any structure to the scatter plots? A similar analysis would be helpful in arguing that the turbulent heat fluxes are larger at the centerline. Is this comparison being done quantitatively or by eye? Along a similar vein, some of the conclusions do not seem to fall from the work done in the paper.

Response: we revised Figure 10 now showing the structure of the data by presenting the histograms. This figure supports the statement that the mid-transect station TT2 evidences predominantly negative momentum fluxes with a considerably smaller flux divergence and smaller turbulent heat fluxes than observed at the centreline. It also shows the strong differences in the flux divergence between katabatic and disturbed conditions.

• "Local turbulence profiles of momentum and heat revealed a strong contribution of heat advection to the local heat budget". Where was this done explicitly? The advective term is higher, but how strong is its contribution to the local heat budget (as a percentage, say)? What are the other components in the budget?

Responds: we now also show the horizontal flux divergence calculated only for the narrow wind sector of 250°-290° which ensures that the flow was aligned with the transect. This figure shows that both horizontal and vertical flux divergences are at the same order of magnitude but the vertical heat flux divergence is larger, in particular at the central station.

• "Strongest horizontal advection of heat was promoted by large horizontal gradients of air temperature along the transect, coinciding with maximum heat exchange towards the glacier surface." I'm not sure this is the conclusion that Figure 9 leads me to. At least in the case of TT2 & TT3, R(w'T',V)=0.56, but R(w'T',HA)=0.31. This implies to me that maximum heat exchange is more dependent on wind speed, but since HA = HA(V), elevated HA is somewhat correlated to elevated w'T', although is not the cause. Again, performing an uncertainty analysis on HA given wind direction/speed could help make this distinction clearer.

Responds: We have now limited our analysis of heat advection to a narrow 60° wind sector.

• "Furthermore, the steepness of the surrounding terrain plays a decisive role for the sheltering of peripheral areas from heat advection from the surrounding terrain." Where does this conclusion come from?
Response: This conclusion is based on the analysis of turbulence data profiles suggesting less developed flow at the peripheral areas during disturbed conditions compared to the central stations. The sign of momentum and horizontal heat fluxes suggest the presence of a very low-level jet below the lower measurement height at TT1, but a well-developed flow at TT3. We updated the discussion to have a more in-depth discussion of the sheltering effect: *The topographic setting which is typical for alpine glaciers are likely to play a significant role in the sheltering of the site closest to the glacier margin. Steep moraine sides and sharp slope transitions at the glacier margin strongly affect the local boundary layer flow (i.e. lee-side flow separation) reducing the ability of the flow hitting the glacier edge to influence the stable glacier boundary layer. Contrary, well developed flows at the glacier line and associated higher wind speeds appear to promote turbulent mixing close to the surface allowing the rush-in of high-speed fluid from the outer region into the near-surface atmospheric layer, as shown by Mott et al., (2016) for a wind tunnel experiment with warm air advection over a melting snow surface.*

Other aspects to tidy up:
• Occasionally, variables are not written in math mode/italicized (for example: w'T' on line 164, labels in all figures/tables).
Response: Yes, we agree and revised all figures accordingly showing the correct in math mode labels.

• x'y' and noverline{x'y'} are used interchangeably, but should all be changed to the latter as they do not mean the same thing.

Response: we agree with the referee. We revised all figures showing the correct in math mode labels including overbars.

• Inconsistent labels on figures throughout (for example: "Height z (m)" & "Z (m)" are both used to denote height – Figure 5 even has both. Likewise with "wind speed U (m/s)" and "U (m/s)". Other labels such as (Fig 2 c,f) "Momentum, flux u'w' (K m s^{- 1})" Contain all of these inconsistencies, an extra comma, and the wrong units).
Response: we revised all figures and ensured consistency.

• A comma instead of a period in "6,3 km" in line 86

Response: we revised this.
• Throughout this paper, the figures are neither colourblind-friendly, nor are they B&W printer-friendly. They are also not saved in a .pdf format, so are low resolution. Figures 2, 4, and 5 are challenging to interpret as the colours appear very similar. Brown and grey, for example, are difficult to distinguish between. I would suggest a different colour palette and to make it consistent with Figure 3. -The dates of Figure 3 are not listed in chronological order.
Response: we revised all figures including color schemes and legends.

• When appropriate, I would suggest making axis limits self-consistent. For example, Figure 4 (a&b), (c), (d), and (e) all have different x-axis limits. The same applies for Figure 4 (a/c) and (b/d) and Figure 9.
Response: we revised all figures ensuring self-consistent x- and y axis.

• I don't feel that diverging colourmaps are appropriate for the data presented in Figure 6, 9, or 10.
Response: we revised all figures including color schemes and legends.

• Units need to be reviewed in all figures. To mention a couple: In Figure 6, T_a/T_mean does not have units of C. Perhaps (C/C) is what is intended here. In Figure 8, (b) has incorrect units on the y-axis, and the x-axis has no units. Figure 10 has incorrect units on the y-axis and no units on the x-axis. Table 1 has units for RH but no other variables.
Response: we revised all figures including color schemes, legends, labels and units. We also changed T_a/T_mean to anomalies allowing a better physical interpretation including units.

• The citations are not consistent with the journal's citation guide. Some journal names are cited in italic, and abbreviated journal names should have periods following them, i.e. "J Atmos Ocean Technol". The citations should be checked for consistency throughout. This journal is cited as both "Cryosphere" and other times "The Cryosphere", not all journal titles are abbreviated appropriately, etc.
Response: we revised the citations style to be consistent with the journal's citations style.

Response to Referee 2 - Jono Conway:

General Response: We thank Jono Conway for his very valuable comments which helped significantly to improve the representation of the results and the informative value of the figures. We revised figures 2, 3, 4, 5, 6, 7, 8, 9 and 10 and added two figures (which are now Figure 2 and Figure 13). All suggested figure improvements and adjustments have been made and checked for consistency. Used colours are now colour-blind friendly. Additionally, added three new figures:

- new Figure 2 describing the multi flux decomposition,
- new Figure 3 showing the time series of air temperature, wind and the classification scheme for katabatic and disturbed conditions.
- new figure 13 showing the divergences of the vertical and horizontal heat fluxes.

Furthermore, we added a new table showing estimates on flux footprint area and spitted the original table 1 in two tables – table 2 and table 3.

In the following we respond to all comments and provide the revised figures the responses are referring to at the end of the document.

General comments

1. The manuscript would benefit from the addition of some context for the general meteorological conditions during campaign, especially timeseries of temperature and wind speed/ direction during the 5 selected days. This would provide the reader with a more intuitive introduction to the meteorology between relationships are discussed in later figures. These figures should also include an indication of time periods defined as 'katabatic' and 'disturbed' as this is unclear.

Response: We agree and have now added the time series of temperature anomalies, the wind velocity, deviation of wind direction from 200° (prevailing Katabatic wind direction) and the classification between katabatic and disturbed flows for two of the measurement days to demonstrate conditions during katabatic and disturbed situations. We decided not show the data for all five days as this would make the figure too unclear.

2. In the discussion section, the authors should reflect further on the (potential) implications for measurements and modelling of turbulent heat fluxes, wind speed and air temperature distributions on other glaciers. Along with this the authors could provide more recommendations for future research.

Response: Yes, we agree with the referee and will add a discussion on implications for modelling an measuring the distribution of turbulent heat fluxes, temperature and wind speed. A postdoc based at Innsbruck is currently doing 240m and 48m resolution LES simulations of these days with WRF which will allow us to include some specific experiences relevant to combining and comparing measurements such as these with modelling efforts. In terms of future research, we now include lessons learned from our instrumental campaign and some specific research goals we would want to explore in a follow up campaign if funding were available.

3. Specific comments to improve the paper are provided below, but in general the paper is very well written, and figures well presented. My only concern with the analysis presented is the use of ratios to normalise temperature and wind speed in Figure 6, 7 and Table 1, and I would suggest the authors instead use anomalies (in K and ms-1, respectively). This is especially important for temperature, where the fractional

difference for the same change in temperature (in C) become smaller as daily mean temperature (in C) increases. If the authors wish to retain the current method, the theoretical basis for using ratios needs more explanation. The discussion of temperature differences between sites and situations is also very hard to compare with the current figures (see specific comments), but a change to anomalies and addition of timeseries of from each site should address this. While the use of scatter plots makes it a little hard to interpret the density of data in certain figures, the ability to use colour warrants this approach. For some figures (Fig 9 and 10), histograms added along the x and y axes would enable the reader to see differences in the distribution that are discussed in the text (e.g. https://matplotlib.org/3.1.0/gallery/lines_bars_and_markers/scatter_hist.html).
In short, with some changes to clarify ambiguities of method and the presentation of additional results to support some statements, this manuscript will make a good addition to the literature.

Response: We followed Jono Conway suggestion to use anomalies and adapted Figure 7 and 8, as well as statistics shown in table 1. We further followed the suggestion to add histograms to figures 8, 10 and 11 which much better describe the distribution of the data and allows a better comparison between the data (i.e. between station or flow types). Figures are shown further below under specific comments.

Specific comments:

- 41 – the sensitivity of melt rate to air temperature is not only controlled by net longwave and turbulent heat flux, but also controlled by snowfall-albedo feedbacks – consider changing "controlled" to 'strongly affected' or similar.

Response: yes, we agree. We replace "controlled" by "strongly affected".

- 48 – 'several studies' – worth adding additional references to this sentence or rewording.

Response: we reworded the sentence.

- 49 – "near-surface warming" – it is unclear what is meant here – the katabatic models discussed in the previous sentence predict enhanced turbulent heat fluxes due to increased wind speed, not temperature. Please revise.

Response: to be clear that these are different processes we changed the corresponding sentences to read: *Zhong and Whiteman (2008) claim that near-surface warming induced by katabatic flow could also be caused by along-slope warm-air advection, while Pinto et al., (2006) identify the entrainment of potentially warmer air down to the surface driven by stronger turbulent mixing. Furthermore, some studies highlighted the effect of katabatic flows in laterally decoupling the local atmosphere from its surrounding, thus lowering the climatic sensitivity of glaciers to external temperature changes (Shea and Moore, 2010; Sauter and Galos, 2016; Mott et al., 2019).*

- 122 – please list the model numbers of the other instrumentation, including the young anemometers, the 2d sonic anemometer and the air temperature, rh and pressure sensors. Please also note if the t/rh sensors were passively or actively ventilated and if any corrections were made to raw data aside from the eddy-covariance data.

Response: yes, we add the model numbers and the information that the RH/T sensor was actively ventilated.

- 127 – it would be useful to expand further on the choice of 1-minute averaging period, as this departs significantly from often-used averaging periods of ~30 minutes. Perhaps present some of the analysis mentioned or comment on the effect of the short averaging period on, e.g. average heat fluxes.

Response: We have now added a plot showing the results of the MRD which highlights our choice of the averaging time, and have expended the text to provide more information.

The turbulence data were processed as follows: multi-resolution flux decomposition (MRD) was used to determine the optimal averaging time for the turbulence data (Vickers and Mahrt, 2003). MRD works as a wavelet transform that decomposes the signal into dyadic scales while preserving Reynolds averaging rules. The appropriate averaging time is usually taken to be that time scale at which the contribution to the flux (at its inter-quantile ranges) first crosses over zero (Vickers and Mahrt, 2003). The MRD analysis of the heat flux for the four examined stations during the period of the campaign (Figure 2) shows that due to its stable nature, the dominant turbulent contribution to the flux comes at scales smaller than 1 min, while the scales larger than 1 min already show a strong contribution of the (sub)mesoscale motions. The exception here is station TT1 which exhibits a higher median contribution to the turbulent flux up until a 5 min scale. Following the approach of Vickers and Mahrt (2003) however, we choose the appropriate averaging time scale to be that where the upper quantile crosses over zero, for comparability reasons we therefore block average the data from all stations with an averaging time of 1 minute

- 147-155 – please clarify the criteria used to define katabatic vs disturbed conditions as there are several different versions given in this paragraph and the figure captions – i.e. did disturbed situation require wind shift from just W/NW or also E sector?

Response: disturbed situation also include flow from easterly sector, but these were very rare. Now the analysis of horizontal heat flux and horizontal heat flux divergence was limited to the small wind sector of 290°+/- 30° which is flow along the transect (see revised methods below). This is also indicated in Figure 2 and 9.

- please define whether 'time periods' on line 149 means 1-min or 30-min periods.

Response: it refers to each 1-minute average.

- Line 150 says that disturbed required WD shift of >50 degree over 30 mins, yet Figure 2 has many disturbed situations with average WD around 200 degrees?
- Figure 2 caption says katabatic required consistent WD during 30-min period – are there time periods that are excluded from the analysis as they do not fit either criteria?
- Are the data sub-set solely on one station (tt3), or classified individually based on WD at each station?

Response: the subsets are classified based on the wind direction and velocity measured at TT3. This has now been more clearly stated in the text and the deviations for stations other than TT3 were discussed (see above).

- Perhaps adding a timeseries of each case-study day, showing periods defined as katabatic and disturbed at TT3 would be useful.

Response: we fully agree that as it is stated in the text is confusing. We revised the method section to be clearer about the two different classification schemes used for analysis based on 1-minute averages and on 30-minute averages. Two slightly different schemes are used to allow a stricter classification for smaller averaging times as we expect more homogenous flow conditions during shorter time periods. We further show a time series now demonstrating the stricter classification scheme (see above).

- 223 – 'Flux footprints tend to be smaller during disturbed situations." Figure 3 shows a larger overall footprint area – perhaps worth clarifying that footprints for individual periods are smaller but the more varied orientation during disturbed conditions results in a larger overall footprint, if this is the case.

Response: Yes, we agree and added this to the text and have also added the information on the actual area enclosed by the footprints for the different conditions. We have also calculated the area enclosed by the footprints for the different conditions and stations. Increasing the roughness from 0.004 to 0.01 results in a decrease of footprint sizes that depends on the flow conditions, but is consistent between the stations. For katabatic flow the footprint size is 88 % of the original, and for the disturbed: 79 %. We now provide the areas of the footprint for two different roughness lengths:

Table 1: Estimates on flux footprint area in m^2 for surface roughness of z0 = 0.004 m and z0 = 0.01 m. Flux footprint areas are provided for disturbed and katabatic flow conditions and for the three transect stations TT1, TT2 and TT3.

With z0 = 0.004

	TT1	TT2	TT3
katabatic	$2.88 *10^3$	$2.31*10^3$	$3.43*10^3$
disturbed	$6.35*10^3$	$6.5*10^3$	$8.42*10^3$

With z0 = 0.01

	TT1	TT2	TT3
katabatic	$2.5 *10^3$	$2.04*10^3$	$3.03*10^3$
disturbed	$5.01*10^3$	$5.1*10^3$	$6.67*10^3$

(decrease of footprint size with increasing roughness between 0.004 and 0.01 is Katabatic: 88 % of the original, disturbed: 79 %)

- 227 – Do you think the different instrumentation contributes significantly to the differences observed between level 3 and the lower two levels?

Response: We have now skipped this part of the text as wind data in the original version had some errors. Now, there is no strong increase in wind velocity between level 2 and 3.

- 227 – Do you mean a secondary larger-scale wind system above level 2? If so, please clarify.

Response: This part is skipped from the text as wind data in the original version had some errors. Now, there is no strong increase in wind velocity between level 2 and 3.

- 234 – "This extreme increase of wind speed with height is confirmed by preliminary numerical simulations (not shown)". As the reader cannot assess this without presenting the data, please remove or modify this sentence.

Response: we agree, we removed this sentence.

- 259 – 'higher streamwise momentum fluxes" please revise – I presume you mean "larger negative streamwise momentum fluxes"?

Response: yes, we agree, we revised this part accordingly.

- 268 – 'on 2018-08-20' – I presume you mean on all case-study days? Please revise

Response: thanks! Yes, this is true – we revised it.

- 277 – 'the temporal variability of flux profiles increased significantly for disturbed situations' – it is very hard to assess this statement from Figure 5 – please add further statistics to describe the mean and variability of the fluxes or reword.

Response: we have to admit that this is not very clear and removed this sentence.

- Figure 6 – consider moving TT3 to the x axis on these plots as it is functioning here as a common variable (hence is more like the 'independent' variable).

Response: we revised figure 6 (now Figure 8) now showing kernel distributions for all stations for katabatic and disturbed conditions. We revised the text accordingly.

- Figure 6 – it is hard to assess the density of points in the scatter plot – consider using a transparency for the points so that more dense data shows as darker shades.

Response: Please see comment above.

- Figure 6 – the colour scale for disturbed conditions would be better to avoid white tones as the are hard to read. Scale used in Figure 9 would be better.

Response: please see comment above.

- 308-332 – there are many statements in this section at are not clearly supported by the data presented in Figure 6. The addition of timeseries of WD/WS and temperature from multiple sites would be of great benefit here.

Response: we are now showing the time series of 2 days, for stations TT1 and TT3. We now also show the mean temperature anomaly for each station and condition.

- 310 – "significant increase in the near-surface air temperature of several degrees (Fig. 6d-f)" – this cannot be ascertained from the current figure 6 as the units are normalised. Please use anomalies as suggested in general comments section or provide additional results to support this statement.

Response: we now show the anomalies indicating the change in temperature which provides a clearer picture.

- 314 – "Local air temperatures at the higher altitude station TT4 showed the lowest sensitivity to changes in wind direction at TT3
- ." It is unclear how the data support this statement – please clarify and revise.

Response: this is shown by the smallest temperature anomaly for disturbed flow. We revised the text accordingly:

Local air temperatures at the higher altitude station TT4 showed the lowest sensitivity to changes in wind direction at TT3, which is reflected by the smallest mean temperature anomaly for disturbed flows. Wind direction data at TT4 (not shown) suggest that the katabatic flow seemed to persist at the higher-altitude station TT4 when at the same time all transect stations already evidenced a westerly flow. Data thus suggest that the station TT4 was more sheltered from westerly flows than stations located at lower parts of the glacier.

- 315 – "The katabatic flow seemed to persist at the higher altitude station TT4 when at the same time all transect stations already evidenced a westerly flow (Fig. 6b)." It is unclear how the data support this statement – please clarify and revise.

Response: Yes, it is true the figure 6 (now Figure 8) does not show this because we always show the wind direction deviation based on TT3 measurements. As we want to stick with that we changed the sentence now to: *Wind direction data at TT4 (not shown) suggest that the katabatic flow seemed to persist at the higher-altitude station TT4 when at the same time all transect stations already evidenced a westerly flow.*

- 317 – "Air temperatures at the glacier tongue (WT1) appeared to be strongly affected by up-valley flows (Fig. 6f)." It is unclear how the data support this statement – please clarify and revise.

Response: we removed this sentence.

- 326 – "explain a larger spatial variability of the air temperature" – It is unclear how the data support this statement – please clarify and revise.

Response*:* We agree with the Referee that spatial differences are quite similar between the two flow conditions. We therefore decided to remove this sentence.

- 329 – Are the cooler temperatures during katabatic flows affected by diurnal changes in temperature? Ie. are katabatic conditions more common during cooler periods at night time?

Response: Our analysis is only focused on the daytime hours, as mentioned in the text, and therefore we only examine daytime temperatures. We do also observe katabatic flows in the afternoon – we can therefore not link cooler air temperatures to diurnal changes.

- Table 1 – what is UT ?

Response: We thank the referee for detecting this inconsistency – UT is named V elsewhere in the text - *wind velocity component along the transect V (wind speed component along the Transect)*

- 342 – 'all four turbulence stations' do you mean 'all three turbulence stations' or 'all 6 turbulence sensors'. Also please list what height data is from

Response: We revised the text now referring to three across glacier transect stations. We also added a more detailed list of heights etc.

Each tower measured wind properties at three heights above the ice surface (1.7 m (level 1) and 2.35 m (level 2) and 2.9 m (level 3)), as well as air temperature, relative humidity and pressure at level 1. The temperature and humidity sensors were actively ventilated. At the four turbulence towers (TT1-TT4) the wind sensors at level 1 and 2 were Campbell CSAT3 sonic anemometers, sampling at a frequency of 20 Hz, while as the fifth tower (WT1), with at these levels was recorded with two Young anemometers. At all towers the level 3 wind sensor was a two-

dimensional sonic anemometer. Air temperature, relative humidity and air pressure was measured at each station at measurement level 1 with a 1-minute resolution.

- showed small spatial differences' – this is very hard to interpret from Figure 7 – a histogram of differences between fluxes at different stations would support this.

Response: we now add histograms to Figures 7. The distributions nicely show that spatial differences of turbulent heat fluxes are particularly small for disturbed flows and are higher for katabatic flows.

- 362 – "despite significantly higher air temperatures observed at TT1" – this is not shown and needs to be supported by additional results – perhaps a histogram of temperature differences between each site in different conditions.

Response: a histogram of air temperatures is now shown in Figure 7 and Figure 8. Additionally, mean anomalies of air temperature are given for TT1 and TT3 showing higher air temperature anomalies at TT1 for disturbed situations.

- Figure 8 – does this figure include all periods from the 5 days, or only disturbed periods? Please clarify in the caption. Please also add units and level used for HA calculation.

Response: we revised Figure9 accordingly.

- 423 – "Similar to heat advection, peak vertical turbulent heat fluxes coincided with peak V-component at the centerline." - to what extent is this due to the correlation between mean wind speed and vertical fluxes? Please discuss.

Response: we revised the discussion of correlations between HA, wind and vertical turbulent heat fluxes: *We are interested in the efficiency of the horizontal heat transport to warm near-surface air layers and thus to indirectly promote turbulent heat exchange towards the ice surface contributing to the surface energy balance. We therefore analyzed the relationship between horizontal heat advection HA (TT1-TT2 and TT2-TT3), the vertical turbulent heat flux and the V-component along the transect, illustrated in Fig. 9. Additionally, correlation coefficient R between those variables are provided (Table 1). Note that for this analysis we considered only data for the 60° wind sector (see methods, disturbed conditions). Consistent with small correlations between air temperature and $\overline{w'T'}$, correlations between HA and $\overline{w'T'}$ are rather small for all stations. Highest correlation was found at TT3 (0.31). Peak vertical turbulent heat fluxes coincided with peak V-component at the centreline. Correlation coefficients $R_{(w'T',UT)}$ were higher between TT2 and TT3 (0.56). Turbulent heat fluxes showed slightly smaller mean values at TT1 (Figure 9b), coinciding with significantly smaller wind speeds (Figure 9a). Furthermore, the correlation between wind speed and vertical turbulent heat flux at the peripheral station was smaller (-0.5) than at the centreline (-0.62). Thus, at the centerline (TT3) strong winds not only promote stronger heat advection (Figure 9a) but also promote maximum downward turbulent heat exchange (Figure 9b). Heat advection appears to enhance turbulent heat exchange towards the glacier surface by enhancing near-surface temperature gradients. Consequently, at the glacier centreline (TT3) stronger winds enhance both the heat advection and the turbulent heat exchange.*

- 424 – “Correlation coefficients R(w´T´,UT) were high between TT1-TT2 and TT2-TT3 station pairs with a slightly higher value for stations closer to the centerline.” It is unclear how this relates to the data presented in Table 1. Please revise.

Response: please see the revised text above.

- Figure 9 - consider adding histograms to each axis. It is currently very difficult to compare the distribution of points between different conditions and sites.

Response: we added histograms to Figures 9 and 10. We now show heat advection as a function of V component and vertical heat flux (now Figure 10). Showing both stations in one plot allows a much better comparison of the distribution of the data. In Figure 11 we now present all stations in one plot. Panel c additionally presents the data from station TT3 but for katabatic and disturbed situations to allow a direct comparison.

- 509 - The steep moraine sides are likely to play a role in the sheltering of the site closest to the glacier margin, especially considering the sharp slope transitions and short distances involved. Thus, the flow hitting the glacier edge may not be well developed and still be affected by lee-side flow separation etc, reducing its ability to influence the stable glacier boundary layer. This may be worth discussing further here.

Response: we thank Jono Conway for his thoughtful comments and revised the conclusion now reading: *The topographic setting which is typical for alpine glaciers are likely to play a significant role in the sheltering of the site closest to the glacier margin. Steep moraine sides and sharp slope transitions at the glacier margin strongly affect the local boundary layer flow (i.e. lee-side flow separation) reducing the ability of the flow hitting the glacier edge to influence the stable glacier boundary layer. Contrary, well developed flows at the glacier line and associated higher wind speeds appear to promote turbulent mixing close to the surface allowing the rush-in of high-speed fluid from the outer region into the near-surface atmospheric layer, as shown by Mott et al., (2016) for a wind tunnel experiment with warm air advection over a melting snow surface.*

- 528 – as the study only presents data from 5 days, it would be more meaningful to say “during five days that displayed a distinct disruption of down-glacier flow during a three-week period in summer 2018.” Or similar.

Response: we followed this suggestion and revised this part of the manuscript.

- 541 – ‘induced by strong westerly winds’ – while this makes sense, the origin of the flow is still speculative so please revise.

Response: we revised this paragraph not speculating about the origin of the flow.

- 552 – ‘At the peripheral areas stronger exposure’ – shouldn’t this be ‘weaker exposure’.

Response: Yes, we changed that to weaker exposure.

- 552 – As wind direction is not presented for TT1 it is impossible to assess if the ‘preservation of a very-shallow low-level katabatic jet’ is supported by the results. Figure 1 shows the WD is aligned at all levels at TT3 during disturbed situations – in order to support a katabatic jet at TT1 the wind direction would need to be maintained down-slope. The BL could still be decoupled at TT1 because of the strong thermal stratification, but this does not necessarily mean that a katabatic jet will exist at TT1. Please revise.

Response: Yes, the referee is right at this point and we try to be more clear that the turbulence data (positive momentum fluxes) indicate a wind jet below the lowest measurement level but data do not allow to distinguish between a glacier flow or slope flow*: At the peripheral area weaker exposure to the westerly winds might promote the preservation of a very shallow low-level jet which potentially decouples near-surface turbulence from higher atmospheric levels (Parmhed et al., 2004). Although no wind direction measurements are available at heights below 1.7 m, positive momentum fluxes at the lowest measurement height indicate the existence of such a shallow low-level jet height which might be connected to a glacier flow or a thermal flow originating from the moraine slopes.*

- 575 – "the frequency of such flows at other glaciers is not known" – this comment highlights that fact that the frequency of these flows has not been presented in the current study. This would be an easy and useful addition to the results.

Response: During the entire 3 weeks of data 20 % of the data fulfilled the conditions of disturbed conditions. 45% of the data is categorized as katabatic conditions. We added this information to the method section.

Editorial comments:

- Temporal changes

Response: we changed change to changes.

- 121 – 'while as the fifth tower (WT1), with at these' –> 'while at the fifth tower (WT!), these'

Response: thanks, we revised this.

- 125 – suggest changing 'methodology' to 'data processing'

Response: we changed methodology to data processing and also change turbulence towers to instrumentation

Response to JE Sicart:

Response: Dear Jean Emmanuel, thanks for your comments. The time period is quite short but those measurements were associated with a lot of effort which we could not afford for longer time period. Yes, horizontal turbulent fluxes are significant and are larger than the vertical fluxes. When looking at the fluxes we always use the rotated flux which is called streamwise flux. That is why for disturbed conditions u'T' which is along the transect shows the same tendencies for the stations as does u'w' suggesting that we are most probably above a local jet height at TT1 and below it at TT2 and TT3. We also add here a plot showing vertical heat flux against horizontal heat flux u'T' for disturbed and katabatic conditions. The horizontal heat flux is larger for katabatic flows than for disturbed ones.

We now also show the horizontal flux divergence calculated only for the narrow wind sector of 260°-320° which ensures that the flow was aligned with the transect. This figure shows that both horizontal and vertical flux divergences are at the same order of magnitude but the vertical heat flux divergence is larger, in particular at the central station.

We analysed stability parameter z/L and plot it against the vertical heat flux, We can detect a tendency of higher turbulent heat fluxes for weaker stability (i.e. during disturbed flows that are more near-neutrally stratified). The decrease of stability during disturbed flows is associated with higher wind speeds and therefore higher friction velocity.

Spatio-temporal flow variations driving heat exchange processes at a mountain glacier

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Abstract. Multi-scale interactions between the glacier surface, the overlying atmosphere and the surrounding alpine terrain are highly complex. The high heterogeneity of boundary layer processes that couple these systems drives temporally and spatially variable energy fluxes and melt rates. A comprehensive measurement campaign, the HEFEX (Hintereisferner Experiment), was conducted during the summer of 2018. The aim of this experiment was to investigate spatial and temporal dynamics of the near-surface boundary layer and associated heat exchange processes close to the glacier surface during the melting season. The experimental setup of five meteorological stations was designed to capture the spatial and temporal characteristics of the local wind system on the glacier and to quantify the contribution of horizontal heat advection from surrounding ice-free areas to the local energy flux variability at the glacier. Turbulence data suggest that the temporal changes in the local wind system strongly affect the micrometeorology at the glacier. Low-level katabatic flows were persistently measured during both night time and daytime and were responsible for consistently low near-surface air temperatures with small spatial variations at the glacier. Local turbulence profiles of momentum and heat revealed strong changes of the local thermodynamic characteristics at the glacier when westerly flows disturbed the prevailing katabatic flow forming across-glacier flows. Warm air advection from the surrounding ice-free areas significantly increased near-surface air-temperatures at the glacier, resulting in strong horizontal temperature gradients from the peripheral zones towards the centreline of the glacier. Despite generally lower near-surface wind speeds during the across-glacier flow, peak horizontal heat advection from the peripheral zones towards the centreline and strong transport of turbulence from higher atmospheric layers downward resulted in enhanced turbulent heat exchange towards the glacier surface at the glacier centreline. Thus, at the centreline of the glacier the exposure to strong larger-scale westerly winds promoted heat exchange processes at the glacier surface potentially contributing to ice melt. On the contrary, at the peripheral zones of the glacier turbulence data indicate that stronger sheltering from the larger-scale flows allowed the preservation of a katabatic jet, which suppressed the efficiency of the across-glacier flow to drive heat exchange towards the glacier surface by decoupling low-level atmospheric layers from the flow aloft. To explain the origin of the across-glacier flow would however require large eddy simulations.

1 Introduction

Mountain glaciers are important contributors to the regional and global hydrological cycle (e.g., Bahr and Radić, 2012) as well as sea-level rise (e.g., Radić and Hock, 2011). Thus, it is crucial to understand their mass balance and its climatic drivers. Winter precipitation, avalanching (e.g., Kuhn, 1995; Sold et al., 2013; Mott et al., 2019), wind transport (e.g., Dadic et al., 2010), regional climate (e.g., Kaser et al., 2004) and micrometeorology (e.g., Kuhn, 1985; Denby and Greuell, 2000; Escher-Vetter, 2002; Oerlemans and Van Den Broeke, 2002; Strasser et al., 2004; Nicholson et al., 2013; Petersen et al., 2013; Conway and Cullen, 2016; Mott et al., 2019) have been found to be driving factors for the survival of mountain glaciers, in the face of generally increasingly unfavorable conditions. The specific contribution of various climatic drivers to the prevalent rapid mass losses of mountain glaciers has been studied using energy balance models (e.g. Mölg et al., 2009; Klok and Oerlemans, 2002). Although shortwave radiation is the main driver for snow and ice melt, the sensitivity of the melt rate to temperature is strongly affected by the net longwave radiation and the turbulent heat fluxes (e.g. Oerlemans, 2001; Cullen and Conway, 2015). Recent studies could, however demonstrate insufficient representation of the variability of energy fluxes on mountain glaciers (e.g. MacDougall and Flowers, 2011; Prinz et al., 2016; Sauter and Galos, 2016). Potentially large bias in snowmelt predictions were also shown to be induced by the evolution of small-scale flow systems in alpine catchments (Mott et al., 2015; Dadic et al., 2013; Helbig et al., 2017; Schlögl et al.,2018a, b). Recent studies already highlighted that complex wind systems at glaciers, with strong spatial and temporal variations of the katabatic flow and interactions with cross-valley flows, drive large variations in the local air temperature field (Petersen and Pellicciotti, 2011) and in turbulent heat exchange (Sauter and Galos, 2016). Contrary, Oerlemans and Grisogono, (2002) suggest that deep glacier winds act as heat pump for the glacier surface by generating shear and enhancing turbulent mixing close to the glacier surface. Furthermore, Zhong and Whiteman (2008) claim that near-surface warming could also be caused by along-slope warm-air advection induced by katabatic flows, while Pinto et al., (2006) identify the entrainment of potentially warmer air down to the surface driven by stronger turbulent mixing. Furthermore, some studies highlighted the effect of katabatic flows in laterally decoupling the local atmosphere from its surrounding, thus lowering the climatic sensitivity of glaciers to external temperature changes (Shea and Moore, 2010; Sauter and Galos, 2016; Mott et al., 2019).

The effect of katabatic wind systems on the local air temperatures over glaciers has been intensively studied and parameterizations for turbulent fluxes have been suggested (e.g., Oerlemans and Grisogono, 2002; Petersen et al., 2013). However, the complex interaction between different boundary layer processes on glacier mass balance has gained little attention so far. Recently, experimental and numerical studies on turbulent fluxes in the stable boundary layer of snow or ice (Daly et al., 2010; Mott et al., 2013; Curtis et al., 2014; Mott et al., 2016; Mott et al., 2017; Lapo et al., 2019) identified cold-air pooling, boundary layer decoupling and advective heat transport as important counteracting processes altering the local air temperature and heat exchange processes. Advective transport of sensible heat has been shown to increase the local air temperature, strongly contributing to the net available melt energy for snow and ice (Essery et al., 2006; Mott et al., 2011; Harder et al., 2017; Schlögl et al., 2018a, b). The numerical simulations of Sauter and Galos (2016) showed that insufficient characterization of these temperature advection processes caused incorrect local sensible heat flux estimates. They showed that cross-valley flows in particular strongly drive the advection of warmer air from surrounding ice-free areas towards the glacier. The increase in local air temperatures enhance the turbulent heat exchange towards the glacier surface, particularly at the peripheral zones of the glacier.

The concurrent existence of counteracting processes such as katabatic flows, horizontal warm air advection and boundary layer decoupling increases the complexity of atmospheric boundary layer dynamics on glaciers, and the interaction between them is not well understood. Warm air advection may disturb the katabatic flow at some areas of the glacier altering thermal conditions and enhancing downward heat exchange towards the glacier surface (Ayala et al., 2015). In the presence of advective heat transport, however, shallow internal boundary layers may enhance local atmospheric stratification close to the snow surfaces resulting in atmospheric decoupling of the air adjacent to the snow cover from the warm air above (Mott et al., 2017). The collapse of near-surface turbulence subsequently limits the amount of sensible and latent heat than can be transmitted from the atmosphere to the snow surface (Mott et al., 2018). Understanding the interplay of these processes is important for correctly interpreting the climatic significance of glacier mass balance studies that typically use interpolated fields for turbulent flux estimations.

2 Methods

2.1 Field site

The Hintereisferner is a valley glacier located in the Ötztal Alps, Austria. It has been classified as one of the ‘reference glaciers’ by the World Glacier Monitoring Service, with observations dating back to the year 1952/53, and continuing to the present day as part of a comprehensive catchment monitoring program (Strasser et al., 2018). The mass balance of the glacier has been extensively studied for decades (e.g., Hoinkes, 1970; Kuhn et al., 1999; Marzeion et al., 2012). In addition to traditional glaciological mass balance measurements, numerous ALS (Airborne Laser Scanning) flight campaigns were carried out near the end of each mass balance year since 2001 (Klug et al., 2018). Hintereisferner has also been used for development and testing of instruments, methods and models (Kuhn et al., 1999) and for investigating glacier and valley winds (Obleitner, 1994).

Hintereisferner is a classical valley glacier approximately 6.3 km long (in 2018) with an elevation difference of approximately 1200 m (www.wgms.ch). The glacier tongue is located in a northeast-orientated valley surrounded by steep slopes (Fig. 1b). In the central part of the glacier tongue the Langtaufererjoch-valley discharges into the main valley, marking the former confluence of a tributary glacier. Hintereisferner is located in the “inner dry Alpine zone”(Frei and Schär, 1998), among the driest regions of the entire European Alps. Like many glaciers in the Eastern Alps the Hintereisferner has experienced strong shrinkage during recent decades. Between 2001 and 2011 the area of the glacier decreased by 15 % (Abermann et al., 2009; Klug et al., 2018).

2.2 Instrumentation

The HEFEX micrometeorological measurement campaign was conducted during three weeks in August 2018. Measurement towers were installed on the 1. and 2. August and removed on 22. August. The measurement network consisted of five 3-m tripod towers (Fig. 1a), located at an along- and an across-glacier transect to capture the spatial variations of the atmospheric flow system at the glacier and associated heat exchange processes. Floating tripods were chosen to allow the towers to migrate with the melting ice surface and maintain the same sensor height over the length of the experiment.

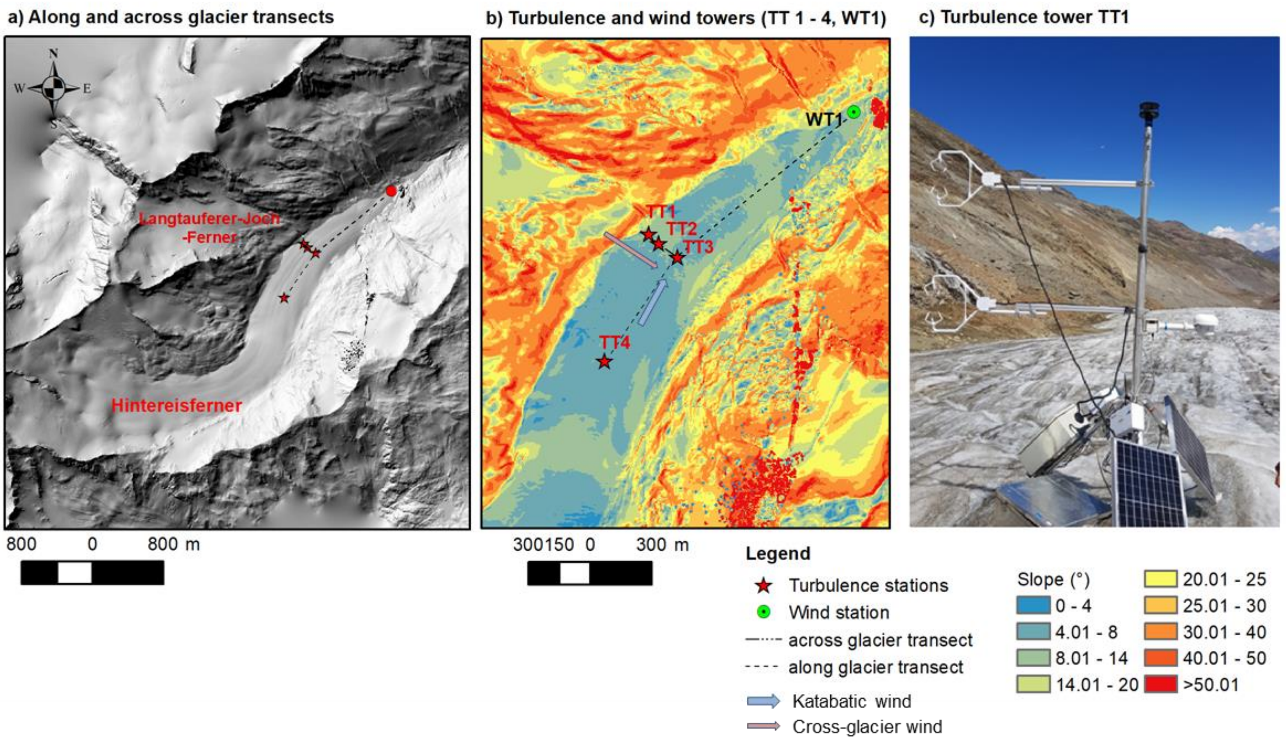

Figure 1: Experimental test site Hintereisferner with an along- and across-glacier transect of five meteorological towers (a, b). Four of these towers, the turbulence towers (TT1 – TT4), were additionally equipped with two turbulence sensors (c). The wind station WT1, installed at the glacier tongue was equipped with three wind sensors. The hillshade (a) and slope maps (b) were produced based on a terrestrial laser scan of the glacier surface (August 2018), which was combined with an airborne LiDAR scan (September 2013) covering a larger area including the surrounding of the glacier.

The across-glacier transect consisted of three turbulence towers installed from the peripheral zones of the glacier towards the centreline (TT1, TT2, TT3) at 2700 m asl (Fig. 1). The location of the across-glacier transect coincides with where the valley of Langtaufererjochferner discharges into the valley of the Hintereisferner glacier (Fig. 1a). In this area, thermal flows from the surrounding area were hypothesized to influence the surface of Hintereisferner. The distances between towers TT1 and TT2 were 65 m and 110 m between TT2 and TT3. One turbulence tower (TT4) was installed at an up-glacier location at the glacier centreline (at 2761 m asl), with a horizontal distance of 620 m to TT3. The fifth station (WT1) was installed at the glacier tongue. All stations were installed at comparatively flat areas of the glacier with slope angles varying between 6 and 8°. Measurement towers were installed directly at the ice surface. Due to pronounced changes in the ice surface caused by strong ice melt during the measurement campaign, frequent visual inspection and small adjustments to the location of the towers were essential for good data quality. This mainly consisted of repositioning the tower feet to ensure the tower stability and re-levelling the sensors. Post-processing of data, i.e. correction of data for height changes and rotation of the mast further ensured data quality (see details below).

Each tower measured wind properties at three heights above the ice surface (level 1: 1.7 m , level 2: 2.35 m and level 3: 2.9 m), as well as air temperature, relative humidity and pressure at level 1. The temperature and humidity sensors (HC2A-S3 Rotronic) were actively ventilated and together with air pressure (CS100 Campbell scientific) measured with a one-minute resolution. At the four turbulence towers (TT1-TT4) the wind sensors at level 1 and 2 were CSAT3 and CSAT3b sonic anemometers (Campbell scientific), sampling at a frequency of 20 Hz, while as the fifth tower (WT1), these levels were recorded with two Young wind monitor (05103) propeller anemometers. At all towers the level 3 wind sensor was a two-dimensional wind sonic anemometer (Gill instruments).

2.3 Data processing

The turbulence data were processed as follows: multi-resolution flux decomposition (MRD) was used to determine the optimal averaging time for the turbulence data that eliminates the influence of non-turbulent (sub)mesoscale motions (Vickers and Mahrt, 2003). MRD is a wavelet transform that decomposes the signal into dyadic scales while preserving Reynolds averaging rules. According to Vickers and Mahrt (2003) the appropriate averaging time is taken to be that time scale at which the contribution to the flux (at its inter-quantile ranges) first crosses over zero.

The MRD analysis of the heat flux for the four examined stations during the period of the campaign (Figure 2) shows that due to its stable nature, the turbulent contribution to the flux is found at scales smaller than 1 min, while scales larger than 1 min already show a strong contribution of the (sub)mesoscale motions. The exception here is station TT1 which exhibits a higher median contribution to the turbulent flux up until a 5 min scale. Following the approach of Vickers and Mahrt (2003) however, we choose the appropriate averaging time scale to be that where the upper quantile crosses over zero and for comparability reasons we therefore block average the data from all stations with an averaging time of one minute.

Prior to block averaging, the data in each one-minute averaging period were rotated using double rotation (Stiperski and Rotach 2016) and detrended (Aubinet, 2012). Double-rotation is preferred over a planar fit method due to continual changes to the surface of the glacier and movement of the stations. The rotation method ensures that z component corresponds to the local slope normal direction, while the x component is oriented into the mean wind direction. Thus, the momentum flux $(\overline{u'w'})$ and streamwise heat fluxes $(\overline{u'T'})$_are facing into the mean wind direction. Data were also corrected for repositioning of the stations and possible rotations during the campaign caused by strong melting of the glacier surface and associated changes in surface structure of the glacier. Finally, to calculate the advective terms, we rotated the coordinate system in such a way that *x* direction is facing down the glacier ($\overline{U} > 0$) and y direction is oriented along the across-glacier transect towards the glacier margin ($\overline{V} > 0$).

Climatological flux footprints were calculated for each station, for katabatic and non-katabatic flows, using the two-dimensional footprint parametrization of Kljun et al. (2015), with a boundary layer height of 100 m and surface roughness of 0.004 m (Greuell and Smeets, 2001; Fitzpatrick et al., 2019; Nicholson and Stiperski, 2020). We use this model as a first guess for the flux source area only, given a number of uncertainties. First, the model was not specifically designed for use in sloping terrain, second, our dataset is not allowing us a reliable estimate of the boundary layer height, and third, estimation of surface roughness for katabatic flow is challenging. Indeed, a higher surface roughness would cause footprint area to decrease. Sensitivity analysis, however, shows that this decrease is not considerable even when increasing the surface roughness by an order of magnitude (Table 1). Increasing the roughness length from 0.004 to 0.01 (cf. Smith et al., 2020) results in a decrease of footprint sizes that depends on the flow conditions, but is consistent between the stations (a reduction to 88 % of the original footprint for katabatic flows and to 79 % for disturbed flows).

Table 1: Estimates on flux footprint area in m^2 for surface roughness of z0 = 0.004 m and z0 = 0.01 m. Flux footprint areas are provided for disturbed and katabatic flow conditions and for the three transect stations TT1, TT2 and TT3.

With z0 = 0.004

	TT1	TT2	TT3
katabatic	$2.88 *10^3$	$2.31*10^3$	$3.43*10^3$
disturbed	$6.35*10^3$	$6.5*10^3$	$8.42*10^3$

With z0 = 0.01

	TT1	TT2	TT3
katabatic	$2.5 *10^3$	$2.04*10^3$	$3.03*10^3$
disturbed	$5.01*10^3$	$5.1*10^3$	$6.67*10^3$

(decrease of footprint size with increasing roughness between 0.004 and 0.01 is Katabatic: 88 % of the original, disturbed: 79 %)

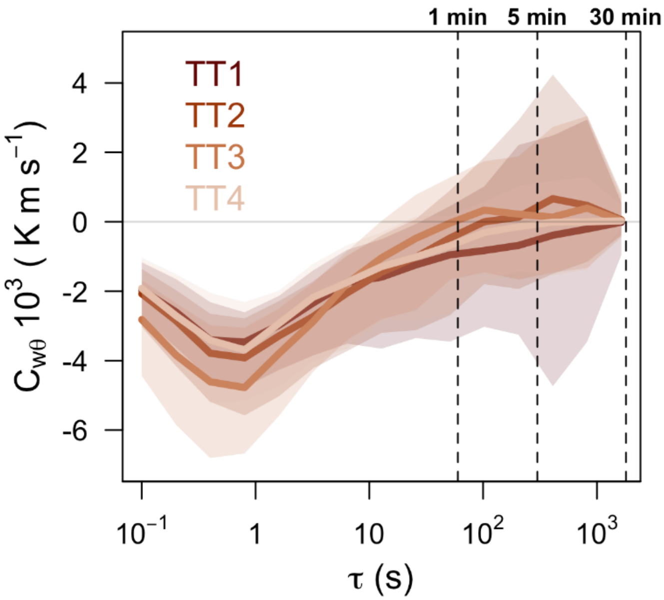

Figure 2: Multi-resolution flux decomposition of buoyancy flux as a function of time scale t for the four examined stations. Shown are median (full line) and interquantile ranges (shading).

As we are interested in the interplay of katabatic flow with other local circulation patterns, in this study we focus on five days in August 2018 that meet three criteria: (1) good data quality at all the stations, (2) predominantly clear sky conditions and (3) flow is characterized by a significant shift of wind direction from katabatic down-glacier flow direction to a westerly or north-westerly flow during the day. In order to allow a comparison between air temperature evolution and wind velocity differences during different days we calculated the anomalies of 1-minute air temperatures and wind velocities from the respective daytime averages of all transect stations between 10 AM – 6 PM.

While a 1-minute averaging period was chosen to calculate turbulent fluxes, a 30-minute averaging period was used for wind profiles. The classification varies for averaging time periods of 1 and 30 minutes. The data analysis based entirely on 1-minute averages used the following classification (as applied in Fig. 3): (1) Pure katabatic conditions are defined as flows with persistent flow direction from southwest (defined as 200° at station TT3) and wind velocities larger than 3 m/s. (2) Disturbed conditions are defined by a deviation of wind direction of more than 60° and less than 120° from the dominant katabatic flow direction. This limits the flow sector to +/- 30° from the flow perfectly aligned with the transect (wind direction 290°). Following these criteria, the analysis of turbulence data was performed for the following five days: 4, 5, 11, 15 and 20 August (referred to as day 1-5). During these days, persistent katabatic flow was disturbed by westerly winds. Following this classification, 45% of the data are classified as katabatic conditions and 20% as disturbed conditions. 30 minute-averaged data used for profiles in Fig. 4 and 6 were classified using the following criteria: Pure katabatic flows are defined as flows with persistent flow direction from southwest (defined as 200° at station TT3) and wind velocities larger than 3 m/s for the entire 30-minute averaging time period. All other flows were classified as disturbed flows without lower and upper limit of wind direction. Note that the upper turbulence sensor (CSAT, level 2) at TT2 was not working until 7 August, due to a faulty cable which had to be replaced. During this period turbulence profiles were analyzed for stations TT1 and TT3.

Horizontal heat advection for disturbed conditions was calculated between transect stations TT1 and TT2 (distance of 65 m) and TT2 and TT3 (distance 114 m). We only calculated heat advection at the lowest level above ground as air temperature was measured only at this height (see Fig. 1c). In order to calculate heat advection along the transect we introduced a new coordinate system that is defined along the transect. Therefore, heat advection *HA* was calculated as passive advection of temperature *T (y, t)* carried along by the mean y flow component $\bar{V}$ using finite differences: $HA = -\frac{\Delta T}{\Delta y}\bar{V}$. Here the flow component $\bar{V}$ is defined as the mean wind velocity component along the transect and was calculated as the mathematical average of the *y* wind component between the pairs of stations.

The vertical flux divergence v*FD* of the vertical sensible heat flux $(\overline{w'T'})$ was calculated between the two measurement levels as:

$$vFD = \frac{\Delta\, \overline{w'T'}}{\Delta z}$$

Similarly, the horizontal flux divergence h*FD* of the streamwise sensible heat flux $(\overline{u'T'})$ was calculated between two stations as:

$$hFD = \frac{\Delta\, \overline{u'T'}}{\Delta x}$$

According to Denby (1999) and Grachev et al. (2016) profiles of streamwise momentum $(\overline{u'w'})$ and streamwise heat $(\overline{u'T'})$ flux provide an approximation of the vertical location of the jet height because typical turbulence profiles observed in the presence of low-level jets show a change in sign of the streamwise momentum flux (negative below and positive above) and heat flux (positive below and negative above) at the wind speed maximum. Following these observations, the position of the jet-speed maximum can be estimated by linear interpolation between two heights where momentum fluxes are measured (Grachev et al., 2016). This estimate assumes that the streamwise momentum flux decreases linearly, and can be applied confidently only if the jet maximum height happens to be between the two measurement levels. We use this indirect estimate of jet maximum height from the turbulence profiles at the across-glacier transect to examine the change of katabatic flow depth across the glacier and its disturbance by heat advection from the glacier surroundings. In this case the fluxes are not rotated into the new coordinate system but are streamwise.

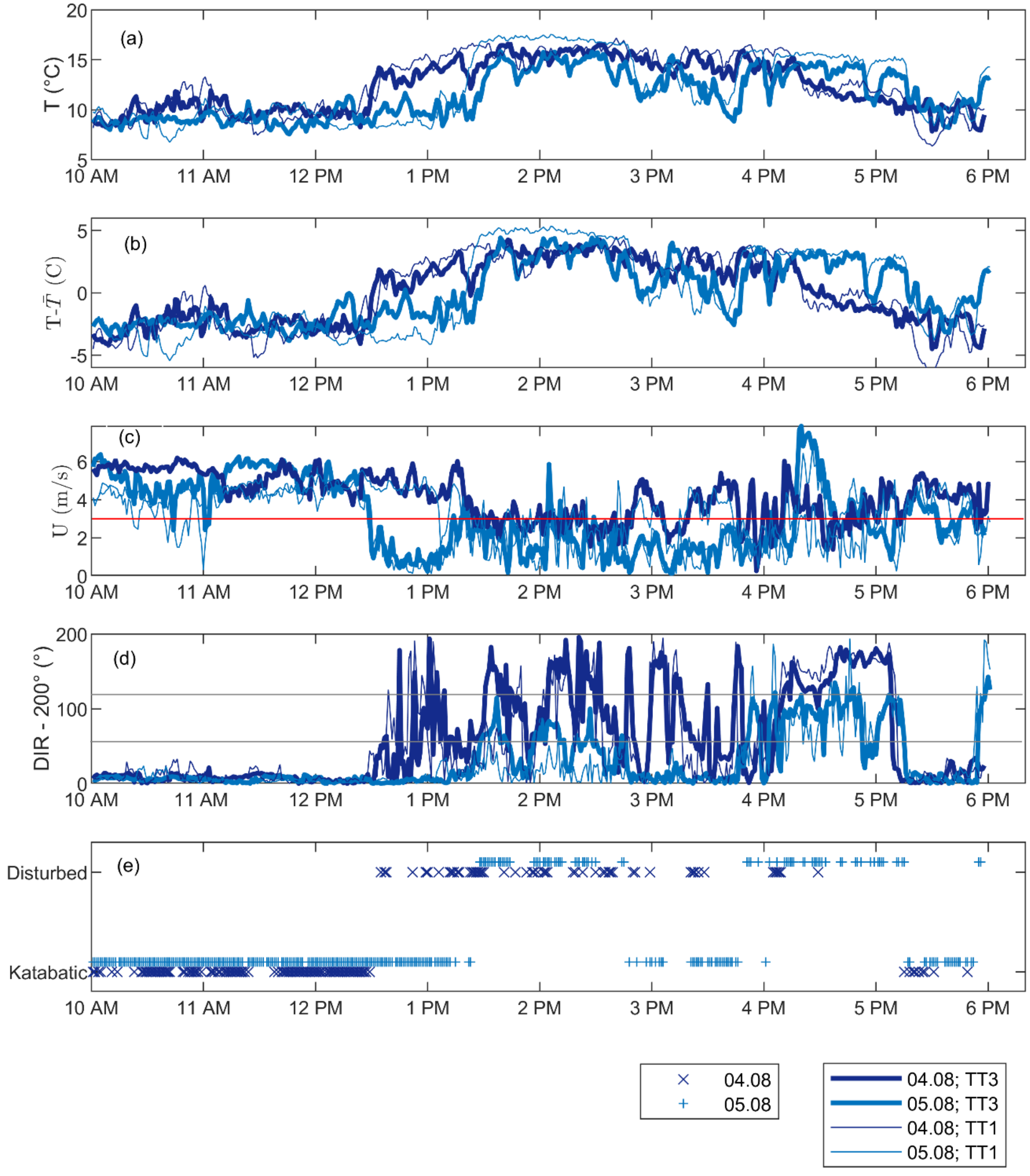

Figure 3: 1-minute averages of a) air temperature, b) air temperature anomalies, c) wind velocity, d) wind direction deviation from the prevailing katabatic wind direction (200°) for stations TT1 and TT3 and e) of classification of katabatic and disturbed flow based on station TT3. The solid line indicates the lower limit of 3 m/s for katabatic flow classification in c) and the lower

and upper limit of the deviation of wind direction from dominant katabatic flow direction to be classified as disturbed flow in d). Data is shown for days 1 and 2 (04.08 and 05.08).

3 Results

3.1 Mean flow characteristics across the glacier

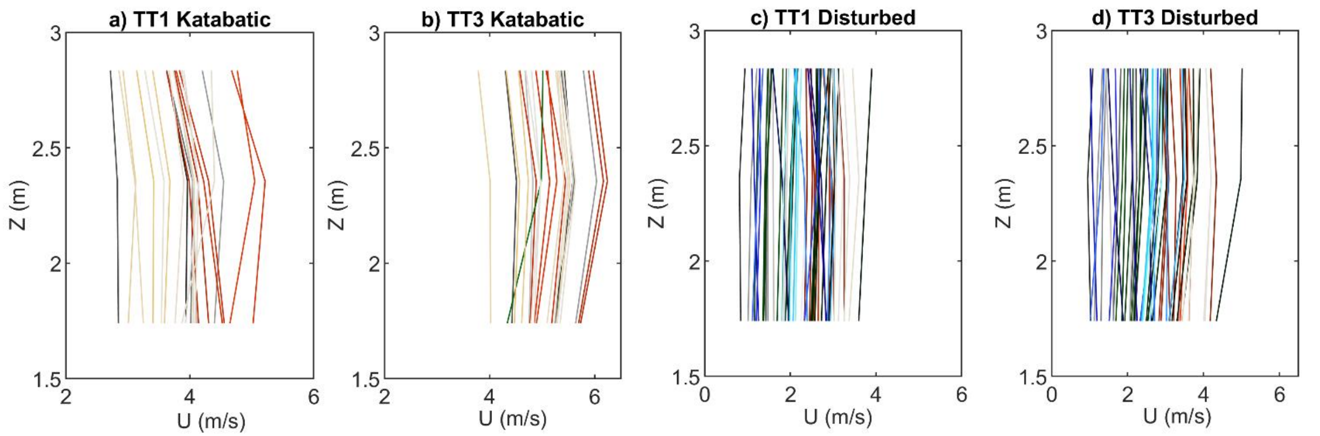

Figure 4: 30-minutes averaged profiles of wind speed for katabatic (a, b) and disturbed (c, d) conditions *during five days in August 2018 obtained from the mobile wind tower and station TT3. Note that data was only considered as pure katabatic with mean wind speeds larger than 3 m/s. Due to long averaging tim of 30 minutes the classification is different to the 1-minute classification. Colours indicate different measurement days (grey=day1, red=day 2; green=day3; blue=day 4; brown=day5).*

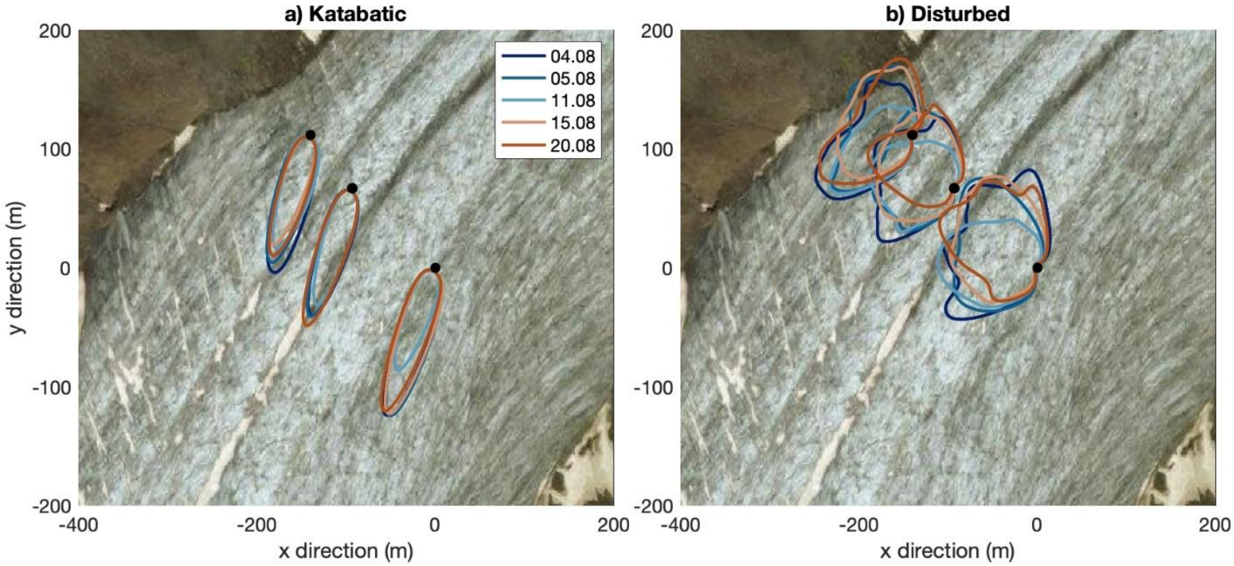

Figure 5: Climatological flux footprints for transect stations TT1-TT3 and for a) katabatic and b) disturbed conditions. Background images © Microsoft BingTM Maps Platform Arial screen shot(s) reprinted with permission from Microsoft Corporation.

Profiles of mean wind speed at TT1 and TT3 is shown in Fig. 4. Furthermore, climatological flux footprints for all three transect stations are presented in Fig. 5 describing the upwind area where 80% of measured fluxes measured at level 1 are generated. The areas of the footprints are provided in Table 1. During periods defined as pure katabatic flow, wind directions are quasi constant at all stations, while wind direction is much more variable during periods of disruption of the katabatic flow (Fig. 5). This results in highly consistent flux footprints during katabatic flows (Fig. 5a). Footprints vary between a few tens of meters to approximately 100 m and are largest at the centreline (Table 1) consistent with the highest wind speed observed there. During disturbed conditions footprints show a dominance of westerly to north-westerly flows but with a high temporal variability at all stations. Although the footprints for individual periods are smaller in their horizontal extent their orientation is more varied during disturbed conditions results in a larger overall footprint (Tab. 1). Still, the flux footprints for all periods are found over the ice and only extend marginally to the rock at TT1 for NNW wind directions. We can also see that the footprints of TT1 and TT2 overlap during disturbed periods justifying the calculation of horizontal flux divergence there, but not between TT2 and TT3.

Wind speed profiles differ substantially between pure katabatic and disturbed conditions (Fig. 4). For katabatic conditions wind speed profiles indicate a distinct low-level wind speed maximum within the lowest 2.9 m above the surface (Fig. 4a, b). The shape of wind speed profiles suggests low-level jets between 1.7 and 2.3 m, with observed wind speed maxima between 4 and 6 m/s. In contrast, profiles during disturbed conditions show smaller wind speeds within the lowest 2.9 m above ground

(Fig. 4c, d). The wind speed gradients are small, and wind speed increases with height with less evidence of low-level jets within the height range of our measurements.

Persistent katabatic flows at the centreline are also indicated by largest footprints at TT3 and decreasing footprints towards the glacier margin (Fig. 5; Table 1). Wind speed profile characteristics are typically similar for TT1 and TT3 (Fig. 4), although there are some periods when the stations at the glacier margins TT1 do not show a significant decrease in wind speed at level 3 or even showed an increase in wind speed at this level. This different behaviour might be explained by disturbances from the non-glacierized surrounding at these two stations. Indeed, wind speed at the marginal station tends to show more variability, especially at level 3, than in the more centrally located station.

During disturbed conditions (Fig. 4 c, d) wind profiles at all sites show a much stronger temporal variability of wind direction also indicated by strong variation of the footprint (Fig. 5b). The horizontal extent of flux footprints tends to be smaller during disturbed conditions. Based on the predominantly measured westerly to north-westerly wind direction we assume that these westerly flows were connected to a large-scale westerly circulation that developed over the day and disturbed the katabatic flow (Whiteman and Doran, 1993). A second explanation could be a thermal flow originating from the Langtalerjochferner or the development of cross-valley circulations caused by the curvature of the valley (cf. Weigel and Rotach 2004) at the lower parts of the glacier.

3.2 Turbulence profiles and flux footprints of pure katabatic flows and disturbed conditions across the glacier

Vertical profiles of streamwise momentum fluxes for stations TT1 and TT3 (Fig. 6) are shown to demonstrate spatial and temporal patterns along the across-glacier transect. As not all three transect stations were properly working during the five days of interest we present data from stations TT1 and TT3 in Fig. 7 to compare air flow and jet height evidence along the across-glacier transect.

During the katabatic flow conditions, streamwise momentum fluxes measured at the centreline stations (TT3) clearly changed from a negative (downward) to a positive flux (upward) between the lower and the upper sensor (Fig. 6b) suggesting a jet height between the two measurement heights of 1.7 and 2.3 m above the ice surface. Jet heights are found to be more consistent at TT3. Furthermore, profiles of streamwise momentum fluxes at the centreline show a steeper gradient of streamwise momentum flux in the layer below the wind-speed maximum than observed at the margin station where the lower measurement level was predominantly located approximately at the jet height. At the margin station TT1 strong temporal variability of streamwise momentum flux profiles indicates jet heights lower and higher than level 1 and 2. Streamwise momentum fluxes at station TT1 show more frequently positive fluxes at both measurement levels indicating that measurements were conducted above a primary low-level jet height. Well-developed katabatic flows at the centreline also showed higher wind speeds and larger negative streamwise momentum fluxes particularly at the lower measurement level.

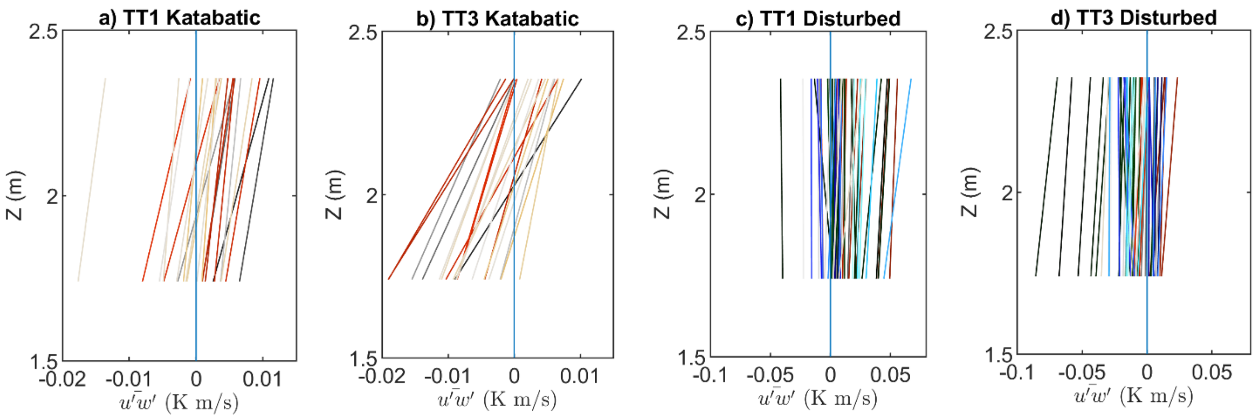

Figure 6: Profiles of 30 minutes averages of wind speed (U) streamwise momentum flux ($\overline{u'w'}$) measured during pure katabatic flow and during disturbed flow conditions at transect stations TT1 and TT3. Note that only 30-minute averaged data was considered as pure katabatic if data showed katabatic flow during the entire 30 minutes periods. Colours indicate different measurement days (grey=day1, red=day 2; green=day3; blue=day 4; brown=day5).

There are considerable differences in the turbulence characteristics observed for disturbed conditions. First, streamwise momentum fluxes were much higher for the disturbed conditions indicating a significantly stronger turbulence and transport of momentum. Second, streamwise momentum fluxes do not frequently change sign between the two measurement levels. In combination with the small vertical flux divergence between the two measurement levels turbulence data during disturbed conditions indicate that measurements at these heights were conducted within a statically stable layer not much affected by a katabatic jet. We also observed similarities in the turbulence structure between the two different conditions. Similar to katabatic conditions, streamwise momentum fluxes at the lowest are predominantly negative at the centreline, but were fluctuating between negative and positive directions at the margin station. The strong temporal variations of the sign of the streamwise momentum flux at the margin station suggest the presence of an intermittent flow with a windspeed maxima below the turbulence measurement levels for specific time periods. No measurements of wind speed profiles at high enough resolution close to the ground are available, however, to test this hypothesis for the station close to the glacier margin.

3.3 Evolution of air temperature and heat exchange connected to prevailing wind conditions

3.3.1 Mean air temperature, wind velocity and relative humidity

The focus of this section is on the change of the local thermodynamic characteristics at the glacier driven by local flow conditions. Figure 7 presents near-surface air temperature and wind velocity anomalies for katabatic and disturbed flow conditions measured at stations at the across-glacier transect (TT1, TT2, TT3) and the along-glacier transect (TT4, TT3, WT1).

During katabatic conditions air temperature anomalies stayed at low values with higher air temperatures along the centreline of the glacier (TT3, TT4) than at the margin stations TT2 and TT1. Stations located approximately at the centreline (TT3, TT4 and WT1) of the glacier featured highest positive wind velocity anomalies during katabatic flows (Fig. 7b).

As soon as the katabatic flow was disturbed by the westerly wind, local wind directions became much more variable (deviations from katabatic wind direction ranging 60° – 120°). The change in wind directions evidenced by all across-glacier transect stations coincided with a significant increase in the near-surface air temperature of several degrees (Fig. 7c) and a decrease in relative humidity of 9 to 13 % on average (Table 2). Near-surface wind speeds during disturbed conditions were typically close or lower than the daytime average wind speed at all stations (Fig. 7d). The change in air temperatures showed strong spatial differences, with strongest air temperature rise in the peripheral areas (TT1, +2.1°C) and significantly smaller temperature rise along the glacier centreline with +0.8°C at TT3 and only +0.1°C at TT4 (Fig. 7b). Similarly, the drying out of the near-surface air is stronger in the peripheral zone than at the centreline (Table 2). Local air temperatures at the higher altitude station TT4 showed the lowest sensitivity to changes in wind direction at TT3, which is reflected by the smallest mean temperature anomaly for disturbed flows (Fig. 7b). Wind direction data at TT4 (not shown) suggest that the katabatic flow persisted at the higher-altitude station TT4 when at the same time all transect stations already evidenced a westerly flow. Data thus suggest that the station TT4 was more sheltered from westerly flows than stations located at lower parts of the glacier. Measurements reveal a higher impact of near-surface air warming during westerly flows on stations located in areas close to the glacier margin such as in the peripheral areas (TT1, TT2) and at the glacier tongue (WT1) (Fig. 7b).

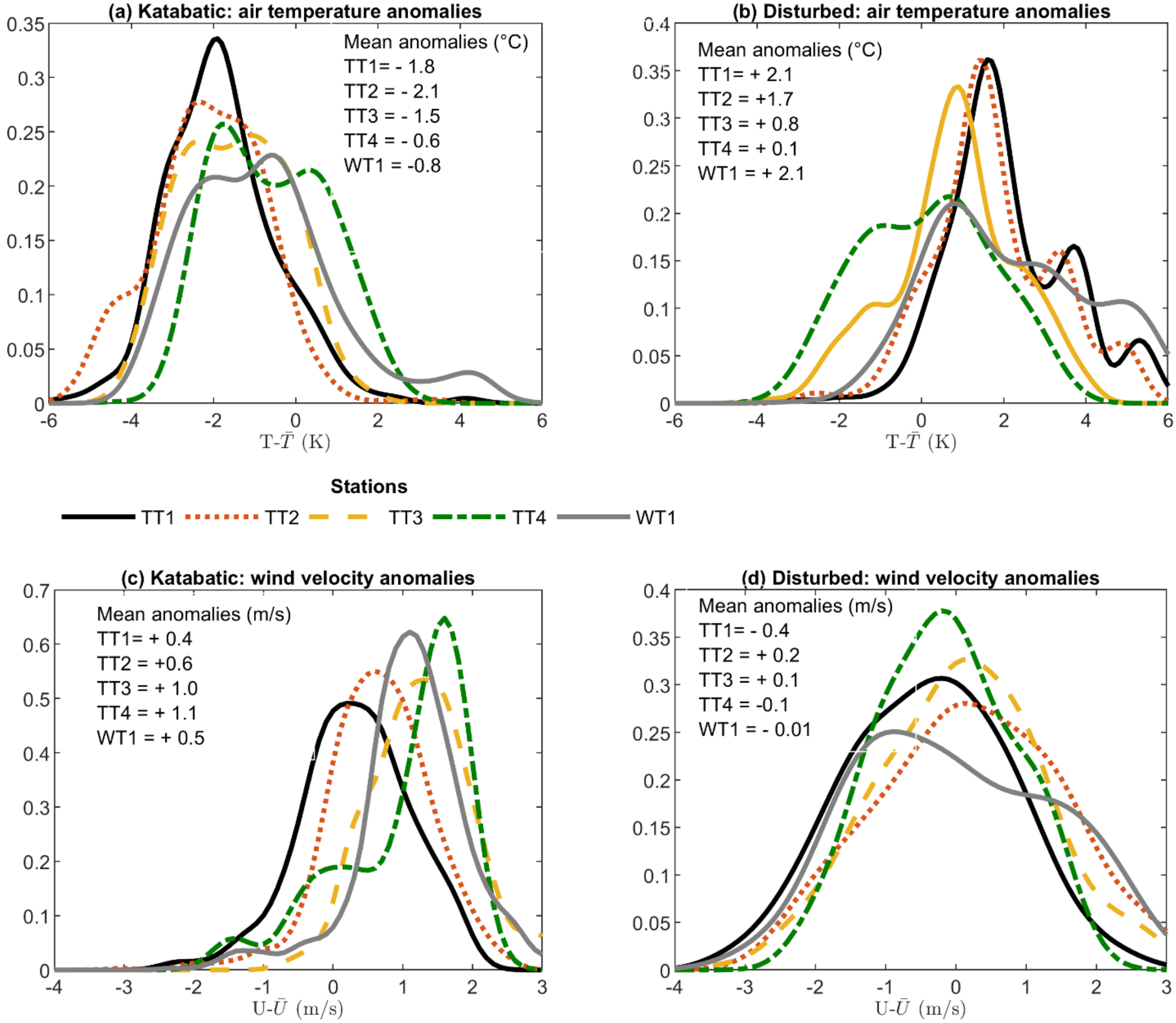

Figure 7: Anomalies of air temperatures and wind velocities from mean daytime averages of the transect ensemble mean for stations TT1, TT2, TT3, TT4 and WT1 are shown for katabatic and disturbed conditions.

1000 Note that the wind system often changed between katabatic and disturbed flows within short time periods of a few minutes. During these intermittent conditions, short-term south-westerly flows (defined as katabatic flow direction) showed higher air temperatures than typically observed during persistent katabatic flow conditions, which were most probably still influenced by the disturbed flow. This might partly explain the larger scatter of air temperatures for the katabatic flow direction.

The strong sensitivity of the mean air temperature to the presence or the disturbance of an along glacier katabatic wind indicates that well-developed katabatic winds decouple the local near-surface air temperature at the glacier from the warmer surrounding air. This is well reflected by significantly lower air temperatures during well-developed katabatic flows. Measurements also suggest that the local disturbance by the across-glacier flows promote the advection of warm air towards the glacier with strongest effects at the peripheral zones of the glacier.

Table 2: Averaged values of normalized air temperatures and wind velocities and of turbulent vertical heat flux (w'T') at stations TT1 and TT3. Correlation coefficients between 1) vertical turbulent heat flux and horizontal heat advection, 2) between vertical turbulent heat flux and y- wind speed component along the transects, 3) horizontal heat advection and y-wind speed component along the transects. Values are provided for Katabatic (K) and disturbed (D) conditions and for stations TT1 and TT3.

	Mean								**Correlation Coefficients**		
	U - U_{mean}		**T - T_{mean}**		**RH (%)**		**w'T'**		**HA, w'T'**	**w'T', V**	**HA, V**
conditions	K	D	K	D	K	D	K	D	**D**	**D**	
TT1	+0.98	-0.33	-2.24	+1.6	80	67	-0.035	-0.041	0.18	0.17	0.6
TT3	+0.94	-0.32	-1.38	+1.2	79	70	-0.037	-0.051	0.43	0.56	0.66

Table 3: Correlation coefficient between 1) vertical turbulent heat flux and wind velocity anomalies and (2) between vertical turbulent heat flux and air temperature anomalies. Values are provided for Katabatic and disturbed conditions and for stations TT1 and TT3.

	Correlation Coefficients											
	w'T' , U-U_{mean}											
	KATABATIC						**DISTURBED**					
	d 1	d 2	d 3	d 4	d 5	mean	d1	d 2	d 3	d 4	d 5	mean
TT1	-0.38	-0.02	-0.15	-0.27	-0.01	**-0.15**	-0.65	-0.32	-0.44	-0.56	-0.54	**-0.5**
TT3	-0.15	-0.30	-0.20	- 0.01	-0.6	**-0.18**	-0.7	-0.58	-0.63	-0.53	-0.67	**-0.62**

w'T' , T-T_{mean}												
	KATABATIC						**DISTURBED**					
	d 1	d 2	d 3	d 4	d 5	mean	d1	d 2	d 3	d 4	d 5	mean
TT1	-0.04	-0.11	-0.35	-0.84	-0.1	**-0.29**	0.27	0.07	-0.05	-0.40	0.10	**-0.001**
TT3	0.01	-0.01	-0.28	0.04	-0.06	**-0.03**	0.21	0.29	0.24	-0.09	0.13	**0.16**

3.3.2 Vertical heat exchange

In order to address how increasing air temperatures during disturbed conditions affect local heat exchange processes, potentially promoting ice melt (Fig. 8 a, b) we analyzed turbulent sensible heat fluxes at all three turbulence stations installed at the across-glacier transect (TT1-TT3). In glaciology it is conventional to give heat fluxes in terms of gains and losses with respect to the glacier surface, such that a downward flux, termed negative in atmospheric science is given as a positive flux in glaciology as it represents an energy contribution to the glacier surface. We are following the convention of atmospheric science, where a negative sensible heat flux indicates a flux directed towards the glacier surface. As most turbulent flux parameterizations assume a linear relationship between turbulent fluxes and wind speed, we plotted turbulent sensible heat fluxes against wind velocity and air temperature anomalies measured at stations TT1 – TT3 in Fig. 8 (a-d). Furthermore, the logarithm of stability parameter z/L is plotted against the sensible heat flux and wind velocity anomaly for katabatic and disturbed flows in Fig. 8 (e, f).

Turbulence data reveal higher vertical turbulent sensible heat fluxes during disturbed (-0.051 K m/s) than during katabatic conditions (-0.037) (Fig. 8 a-d) coinciding with higher air temperatures particularly at the margin station (Fig. 8 a, b). With the melting surface of the glacier at zero degrees, the increasing near-surface temperature gradients coincided with an increase of downward turbulent heat flux. As already mentioned, near-surface wind speeds during disturbed conditions were typically lower than the daytime average wind speed (Fig. 7). Sensible heat fluxes, however, show a much higher correlation with the low-level wind speed (correlation coefficient -0.5 and -0.62 for TT1 and TT3) during disturbed conditions than during katabatic flow conditions (-0.15 and -0.18 for TT1 and TT2). For disturbed conditions, no correlation between sensible heat flux and air temperature can be found (-0.001 and 0.16 for TT1 and TT3). There are some situations when katabatic conditions coincided with higher air temperatures. Most of those situations, however, also coincided with negative wind velocity anomalies. This again indicates that these individual katabatic flow conditions with high air temperatures can be rather characterized as intermittent flows than well-developed katabatic flows as discussed above.

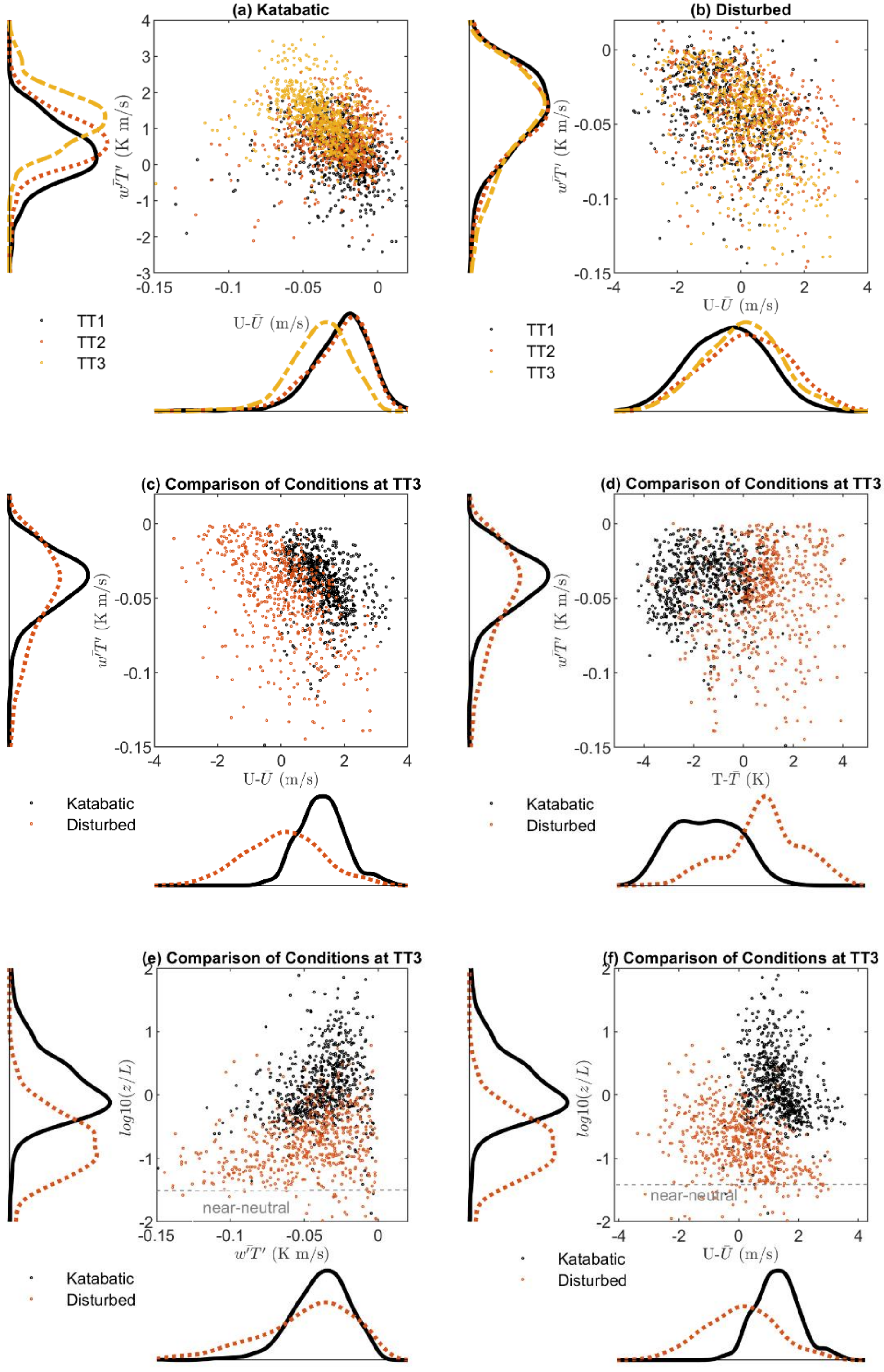
(a) Katabatic
(b) Disturbed
(c) Comparison of Conditions at TT3
(d) Comparison of Conditions at TT3
(e) Comparison of Conditions at TT3
(f) Comparison of Conditions at TT3
$w'T'$ (K m/s)
U-$\bar{U}$ (m/s)
T-$\bar{T}$ (K)
$log10(z/L)$
TT1
TT2
TT3
Katabatic
Disturbed
near-neutral

Figure 8: Vertical heat flux plotted against anomalies of wind speed from mean daytime wind speed shown for stations TT1 – TT3 for katabatic conditions a) and disturbed conditions (b). Vertical turbulent heat flux plotted against anomalies of wind speed from mean daytime wind speed (c) and against anomalies of air temperature from mean daytime air temperature (d) shown for station TT3 for katabatic and disturbed conditions. Vertical turbulent heat flux (e) and normalized wind speed (f) plotted against the Logarithm of Stability parameter z/L at TT3 during katabatic and disturbed flows.

During disturbed conditions turbulence data showed small spatial differences of turbulent heat exchange at the across-glacier transect (Fig. 8b). Fluxes are similar for all transect stations despite significantly higher air temperature anomalies observed at TT1 than at TT3 (+1.8°C for TT1 and +1.2°C for TT3; Fig. 7). While air temperatures were lower at TT3 than at TT1, higher wind velocities at the centreline appeared to promote heat exchange there (Fig. 9b). This is also confirmed by statistics shown in Table 3. At the central station wind shows higher correlations with turbulent heat fluxes than at the margin station.
Stability parameter z/L shows much higher stability for katabatic flow conditions than for disturbed conditions when z/L is often close to neutral (Fig. 8 e,f). The magnitude of the vertical turbulent heat fluxes tends to increase with weaker stability (i.e. during disturbed flows that are more near-neutrally stratified).

3.3.3 Lateral heat advection

Measurements of air temperatures suggested a strong influence of warm air advection during north-westerly flows disturbing the katabatic flow at the glacier and forming an across-glacier flow. In a next step we quantify the horizontal warm air advection HA for across-glacier flow conditions. A transect consisting of three stations was aligned in a north-westerly orientation allowing the calculation of HA between neighbouring stations during across-glacier flows. Figure 9 illustrates the deviation of the flow from the dominant katabatic flow direction plotted against advection of heat. The colour of each data point indicates air temperature differences between neighbouring stations TT1-TT2 and TT2-TT3 (Fig. 10 a, b) and mean V-component in the direction of the transect (Fig. 9 c, d). Positive horizontal differences in air temperature result from warmer air temperatures at the margin stations and a decrease towards the centreline. We defined a negative V–component along the transect directing from TT1 to TT3 (Fig. 9 c, d). Thus, a negative advective heat flux indicates the advection of warm air from the peripheral zones of the glacier towards the glacier centreline (positive air temperature differences and negative V-component). Positive values of heat advection correspond to conditions when colder air was advected along the TT1-TT3 transect (negative V-component and negative temperature gradient). Conditions with positive V-component along the transect were excluded from this analysis as these were conditions when wind direction was east to southeast. For these situations the transect was not properly aligned.

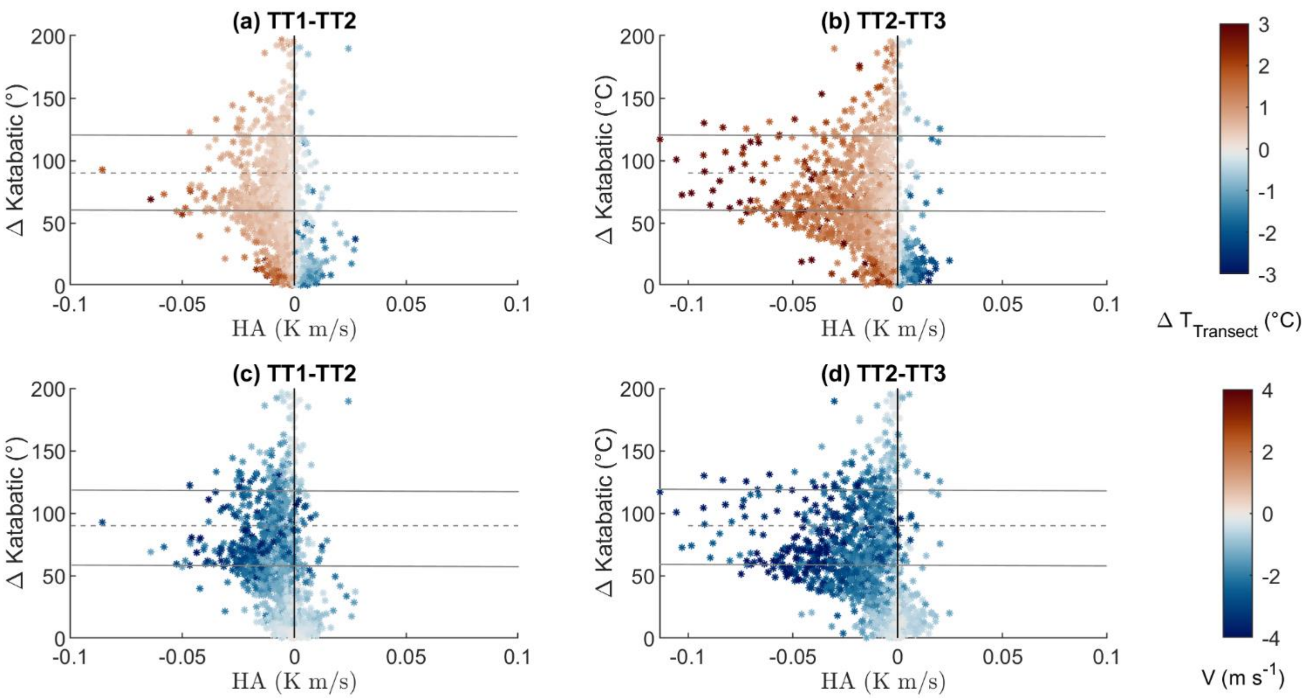

Figure 9: Horizontal advection of heat (HA) calculated between stations TT1 and TT2 (a) and TT2 and TT3 (b) from the first level above ground are plotted against deviation from katabatic wind direction for 5 selected days with periods of clear deviation from the dominant katabatic flow direction. Colour codes indicate the measured air temperature difference between stations TT1 and TT2 and TT2 and TT3 (a, b) and the wind velocity component along the transect V (wind speed component along the Transect) (c, d). Note that all data (katabatic and disturbed flows) are shown here. Positive values of air temperature difference indicate higher air temperatures at the station closer to the glacier margin. Negative wind velocity component indicate wind from station TT1 to TT3. The dashed line indicates the deviation of the wind direction 90 degree from the dominant katabatic flow which is the orientation of the transect. The solid lines indicate the 60° wind sector the following heat advection analysis for disturbed conditions is based on.

Strong positive horizontal air temperature gradients along the transects occurred for westerly to north-westerly winds (60 – 90° deviation from katabatic). Horizontal heat advection HA increased with temperature differences and V-component along the transect line and increased from the peripheral stations towards the centreline station TT3. Therefore, peak HA at the centreline can be explained by stronger temperature difference between the middle and the central station (TT2 and TT3) than between the two more peripheral stations. Furthermore, strongest temperature differences between all stations concurred with peak V-components in the direction of the transect of more than 4 m/s. These V-components increased towards the centreline.

On the contrary, the small V-components at the peripheral station TT1 indicates that the margin stations are more sheltered from the synoptic westerly wind than the station at the centreline.

Negative air temperature gradients (colder air temperatures at the peripheral areas, blue colors) were only measured during short time intervals. For some cases, warm and cold air advection even occurred during intermittent flow conditions (changing between south-westerly and north-westerly flow directions within short time) but with much smaller wind velocities than observed during well-developed katabatic flow conditions. The heat advection during these intermittent conditions, however, was much weaker.

We are interested in the efficiency of the horizontal heat transport to warm near-surface air layers and thus to indirectly promote turbulent heat exchange towards the ice surface contributing to the surface energy balance. We therefore analyzed the relationship between horizontal heat advection HA (TT1-TT2 and TT2-TT3), the vertical turbulent heat flux and the V-component along the transect, illustrated in Fig. 10. Additionally, correlation coefficient R between those variables are provided in Table 2. Note that for this analysis we considered only data for the 60° wind sector (see methods, disturbed conditions). Consistent with small correlations between air temperature and $\overline{w'T'}$, correlations between HA and $\overline{w'T'}$ are rather small for all stations. Highest correlation was found at TT3 (0.43). Peak vertical turbulent heat fluxes coincided with peak V-component at the centreline. Correlation coefficients $R_{(w'T',V)}$ were higher between TT2 and TT3 (0.56). Turbulent heat fluxes showed slightly smaller mean values at TT1, coinciding with significantly smaller wind speeds (Figure 9b). Furthermore, the correlation between wind speed and vertical turbulent heat flux at the peripheral station was smaller (-0.5) than at the centreline (-0.62). Thus, at the centreline (TT3) strong winds not only promote stronger heat advection ($R_{(HA,V)}$=0.65; Table 2; Figure 11a) but also promote maximum downward turbulent heat exchange (Figure 11b). Heat advection appears to enhance turbulent heat exchange towards the glacier surface by enhancing near-surface temperature gradients. At the same time, atmospheric stability during disturbed conditions tended to be smaller for high wind velocity situations (although the scatter of the data is large), favouring stronger turbulent heat exchange. Consequently, at the glacier centreline (TT3) stronger winds enhanced both the heat advection and the turbulent heat exchange.

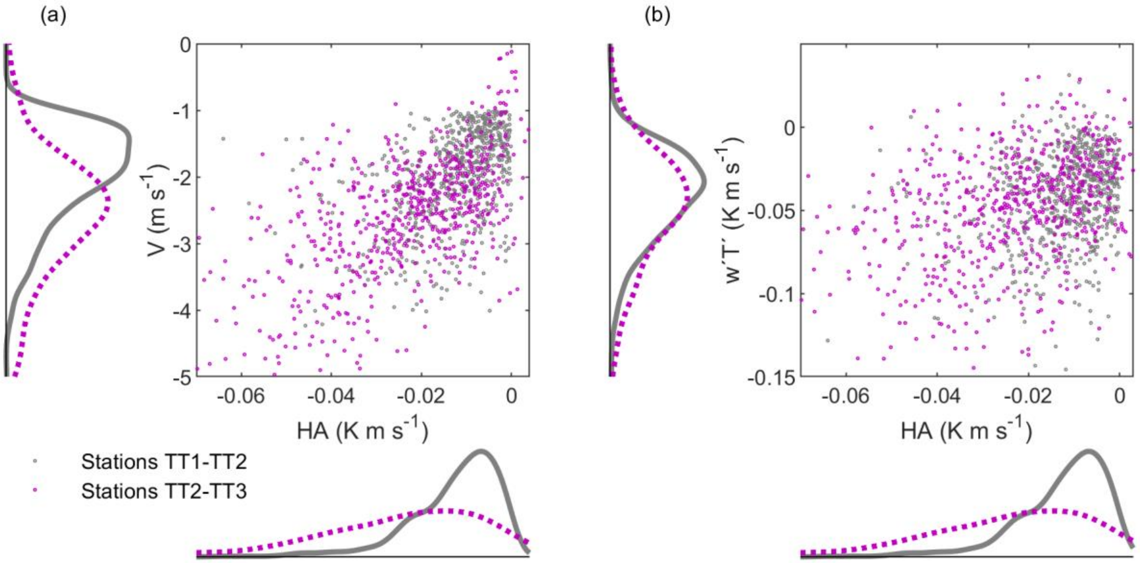

Figure 10: Horizontal advection of heat (HA) between stations TT1 and TT2 and TT2 and TT3 plotted against measured wind speed component along the transect V (a) and turbulent vertical heat flux (b) for disturbed conditions. Note that for this analysis we considered only data with evidence of horizontal heat advection along the transect (U-component along the transect larger than 1 m/s and positive air temperature differences).

4 Discussion

In the presence of katabatic winds, similarity-based scaling parameterizations used to link the surface energy balance to the flow or the estimation of surface turbulent fluxes from turbulence measurements are not valid (Nadeau et al., 2013; Oldroyd et al., 2014; Grachev et al., 2016). This is because the jet height imposes a strong control on the turbulent structure of the katabatic flow (e.g., Denby and Smeets, 2000; Stiperski et al., 2020a) so that turbulent fluxes in katabatic flows vary strongly with height as a function of the jet height location. Therefore, an estimation of the contribution of turbulent fluxes to the energy balance at the glacier surface is challenging and inferring turbulent surface fluxes from measured fluxes at a certain height will lead to strongly biased surface energy balance calculations. Analysis of streamwise momentum flux profiles during katabatic and disturbed conditions showed that in the presence of a low-level wind jet turbulent fluxes typically have their local minimum at the jet height and increase below the jet height in line with strong vertical gradients there (Fig. 4, 6). Thus, the magnitude of measured turbulent fluxes strongly depends on the measurement location relative to the jet height. A more detailed analysis on the existence of a jet height during disturbed conditions is needed to assess the effect of heat advection during prevailing westerly flows on the heat exchange towards the glacier surface. Figure 11 shows the streamwise momentum flux as a function of the vertical sensible heat flux divergence vFD at the across-glacier transect stations TT1, TT2 and TT3 for katabatic and disturbed conditions. Vertical flux divergence was calculated between the two measurement levels. Positive momentum fluxes are a sign of decreasing wind speed with height, suggesting the presence of a local wind speed maximum below the respective measurement height. On the contrary, negative momentum fluxes suggest that measurements were performed in a layer with increasing wind speed with height (see also Fig. 4). Katabatic flows typically coincide with strong vertical flux divergences due to strong gradients in wind velocity and air temperature. While these high vertical flux divergences are typically observed in layers where wind speeds strongly increase with height, very small vertical divergences might indicate either a constant flux layer in the absence of a low-level jet (negative momentum flux), that measurements are conducted close to or above the wind speed maximum (small or positive momentum fluxes) or that strong stability is responsible for strong turbulence suppression (Stiperski et al. 2020a).

We are not only interested in changes in the turbulent structure when changing from katabatic to disturbed conditions but also on the effect of heat advection on the turbulent heat fluxes. Turbulence data of katabatic and disturbed conditions reveal some similarities along the transect stations but also pronounced differences between the different flow conditions (Fig. 11 a, b). First, the three transect stations show a similar trend for both conditions with an increase of the vertical turbulent heat flux (Fig. 9 a, b) and heat flux divergence (Figure 12 a, b) from the margin station towards the central station. Second, the transect stations reveal a trend for both conditions from more frequently measured positive and small momentum fluxes at the margin to larger and more frequently measured negative momentum fluxes at the central station (Fig. 11 a, b). On the other side, the largest differences are the much higher magnitudes of turbulent fluxes of momentum and heat as well as higher vertical flux divergence of turbulent heat fluxes during disturbed conditions.

In order to assess the effect of heat advection on the heat exchange processes during disturbed conditions we focus our analysis on flow characteristics during those conditions (Fig. 10; Fig. 12; Fig. 13). During westerly flow conditions turbulence data at the centreline of the glacier (TT3) show a strong increase of downward vertical sensible heat fluxes with increasing downward momentum fluxes (negative values) (Fig. 13b). The strongest vertical turbulent heat fluxes coincided with peak vertical heat divergence (Fig. 11d). At the more wind-exposed centreline negative momentum fluxes and positive streamwise turbulent heat fluxes (Fig. 12a) and the strong vertical and horizontal heat flux divergence (Fig. 11b; Fig. 13) indicate that no pronounced katabatic jet is present below the lowest measurement level and that measurements were conducted within a stable atmospheric layer with increasing wind velocities with height featuring strong flux gradients close to the surface. While the vertical flux divergence is increasing towards the centreline, the horizontal flux divergence is similar between all stations and is smaller than the vertical flux divergence (Fig. 13). Strong turbulent momentum and sensible heat fluxes (Fig. 12b) combined with strong vertical flux divergence at TT3 (Fig. 11) suggest very efficient turbulence transfer towards the surface in case of advection.

Contrary to the centreline, momentum fluxes measured at the more peripheral stations TT2 and TT1 show a trend towards a higher frequency of positive momentum fluxes and negative streamwise turbulent heat fluxes with decreasing distance to the glacier margin (Fig. 11b; Fig. 12a). While the mid-transect station TT2 evidences predominantly negative momentum fluxes with a considerably smaller flux divergence and smaller turbulent heat fluxes than observed at the centreline (Fig. 11 b), the peripheral station TT1 predominantly show positive momentum fluxes suggesting that the lower measurement level was already located above a low-level jet or close to the jet height which typically features a local flux minimum and small flux gradient. These positive momentum fluxes measured at TT1 coincided with smaller peak turbulent heat fluxes and heat flux divergence than measured at TT3 at the same time. This supports conclusions of Grachev et al. (2016) that turbulent fluxes in the layer below the wind-speed maximum vary with height more rapidly than in the layer above the katabatic jet.

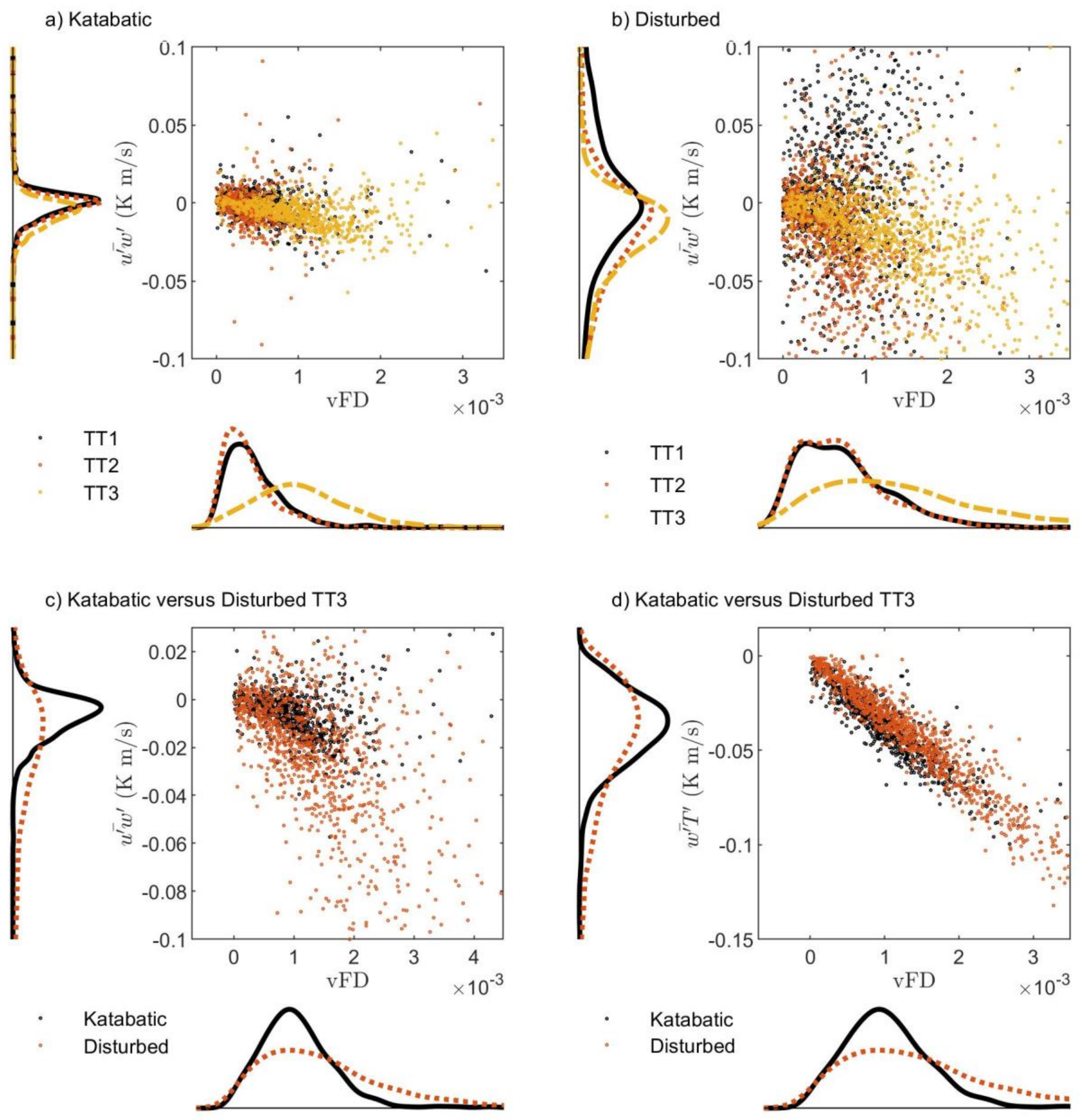

Figure 11: Vertical flux divergence plotted against streamwise momentum flux for stations TT1, TT2, TT3 are shown for katabatic (a) and disturbed conditions *(b). To allow a better comparison of fluxes during different flow conditions the vertical*

flux divergence (vFD) is plotted against streamwise momentum flux (c) and against vertical turbulent heat flux (d) for station TT3 for katabatic and disturbed flow in.

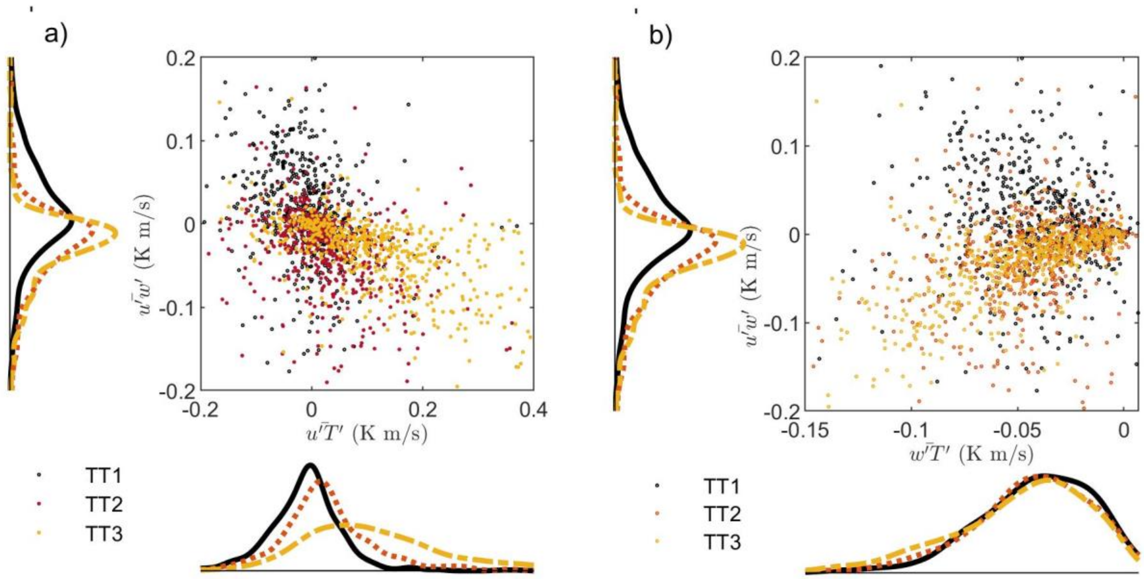

Figure 12: Streamwise horizontal turbulent heat flux plotted against streamwise momentum flux for stations TT1, TT2 and TT3 (a). Vertical turbulent heat flux plotted against streamwise momentum flux for stations TT1, TT2 and TT3 (b). Data are only shown for disturbed conditions and the 60°wind sector from 260° to 320°.

The more frequently measured positive streamwise momentum fluxes at TT1 and strongly negative momentum fluxes at TT2 and TT3 suggest that the flow at the centreline is more developed than the flow at the margin. Also, lower-level measurements at TT3 revealed significantly higher fluxes than at the peripheral stations where measurements are supposed to be conducted above a very shallow low-level jet. Therefore, the strong increase of the wind speed component towards the centreline (Fig. 8 a, b) and the potential formation of a very low-level jet height at the margin stations (TT1) suggest strong differences between the flow development at the centreline and in the peripheral zone of the glacier. One possible explanation for the occurrence of the low-level jet at TT1 is the formation of a shallow stable internal boundary layer (SIBL) at the peripheral areas of the glacier when the warm air crosses the peripheral area of the glacier induced by the step of surface characteristics between ice-free surrounding and the glacier (Mott et al., 2015). SIBLs favour the formation of very low-level jets (Mott et al., 2015) as the high static stabilities of SIBLs over ice are associated with reduced wind velocities near the ground. Above the shallow SIBL the flow field is characteristic of the upstream conditions despite the detachment of the larger-scale flow from the snow surface and its displacement to higher atmospheric levels. An alternative explanation might be that the stronger sheltering of the peripheral areas to the strong westerly winds allowed the preservations of a very shallow katabatic flow (below 1.7 m above ground) close to the glacier surface, which is not captured by measurement sensors above. Furthermore, wind and turbulence characteristics also infer a much stronger exposure of the central station to the across-glacier wind than the more sheltered margin station. Stronger exposure at the central line might allow a stronger disturbance of the katabatic flow. This is in contrast to earlier numerical results of Sauter and Galos (2016) who suggested that well-developed katabatic flows at the centreline of glaciers prevent warm air advection from the surrounding. This conclusion seems not to be valid for synoptic winds strong enough to disturb the katabatic flow along the centreline.

The topographic setting which is typical for alpine glaciers are likely to play a significant role in the sheltering of the site closest to the glacier margin. Steep moraine sides and sharp slope transitions at the glacier margin strongly affect the local boundary layer flow (i.e. lee-side flow separation) reducing the ability of the flow hitting the glacier edge to influence the stable glacier boundary layer. On the contrary, well developed flows at the glacier line and associated higher wind speeds appear to promote turbulent mixing close to the surface allowing the rush-in of high-speed fluid from the outer region into the near-surface atmospheric layer, as shown by Mott et al., (2016) for a wind tunnel experiment with warm air advection over a melting snow surface.

Turbulence measurements thus highlight the strong consequences of the development of across-glacier flows for the energy balance at the glacier surface, although a thorough analysis of the origin of this flow requires a numerical modelling approach. The increasing wind velocity towards the centreline of the glacier promotes efficient heat exchange towards the glacier surface. Furthermore, measurements confirm that vertical heat fluxes measured below the jet height or in absence of the latter are significantly higher than measured at the jet height or just above where fluxes typically show its minimum. Turbulence in the layer above the wind speed maximum, as observed at the margin of the glacier, is largely decoupled from the flow below and the underlying surface. Turbulence measured above the katabatic jet is thus no longer communicating with the surface (Denby 1999; Grachev et al., 2016; Mott et al., 2016). In case of the presence of an across-glacier flow, the very low-level wind speed maximum that potentially exists at the margin areas of the glacier might thus prevent heat exchange towards the glacier surface, partly decoupling the warmer air aloft. On the contrary, the higher low-level wind velocities at the more wind-exposed centreline and the associated increase in turbulence close to the surface might promote heat exchange towards the glacier surface promoting ice melt there.

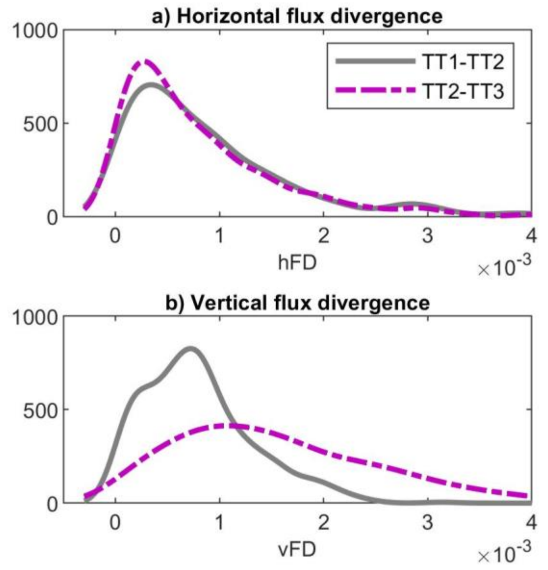

Figure 13: Kernel distribution of streamwise horizontal (hDF) and vertical (vDF) heat flux divergence shown only for disturbed conditions and the 60° wind sector (260°-320°).

5 Conclusion

This study presents a unique set of turbulence data measured at a mid-latitude mountain glacier (Hintereisferner, Austria) evidencing a frequent disruption of down-glacier flow. The experiment was designed to capture near surface air flow dynamics and associated turbulent exchange processes at an along- and across-glacier transect. The high-density network of five meteorological stations and eight turbulence sensors allowed us to investigate governing micrometeorological heat exchange processes close to the glacier surface during both katabatic and non-katabatic dominated atmospheric flow conditions.

Measurements highlight the complex dynamics of boundary layer flows at a mountain glacier strongly affecting the local meteorology and glacier-atmosphere exchanges, with vertical profiles of wind speed and turbulent fluxes varying strongly for different flow conditions. We measured persistent low-level katabatic flows during daytime driving consistently cold air temperatures close to the glacier surface with small spatial differences along the glacier. The across-glacier transect of stations showed katabatic jet maximum height and wind velocity maxima decreasing from the centreline towards the glacier margin. Turbulent heat exchange was especially driven by stronger wind velocities at the glacier centreline.

The measurement days analyzed showed a disturbance of the well-developed glacier wind by the evolution of an across-glacier flow. These predominantly westerly to north-westerly flows measured at the glacier were associated with strong advection of heat with the larger scale flow. The horizontal heat advection was indicated by a significant rise in the near-surface air temperature which was greatest at the glacier margin. Local turbulence profiles of momentum and heat revealed strong heat advection from the glacier margin towards the glacier centreline. Strongest horizontal advection of heat was promoted by large horizontal gradients of air temperature along the transect, coinciding with maximum heat exchange towards the glacier surface. The evolution of the across-glacier flow also coincided with an increasing turbulence from the peripheral zone towards the centreline. Turbulence measured along the across-glacier transect suggested different flow characteristics during disturbed conditions between the peripheral zone and the centreline of the glacier. Profiles of momentum inferred a very low-level wind speed maximum below the lowest measurement level at the margin station potentially suppressing the heat exchange from the higher atmospheric layers towards the glacier surface. In contrast, at the centreline of the glacier turbulence profiles suggested well-developed flow with high wind velocities promoting strong turbulence close to the glacier surface.

At the peripheral area weaker exposure to the westerly winds might promote the preservation of a very shallow low-level jet which potentially decouples near-surface turbulence from higher atmospheric levels (Parmhed et al., 2004). Although no wind direction measurements are available at heights below 1.7 m, positive streamwise momentum fluxes at the lowest measurement height indicate the existence of such a shallow low-level jet height which might be connected to a glacier flow or a thermal flow originating from the moraine slopes. At the centreline, westerly wind conditions coincided with an increase in low-level turbulent mixing and heat exchange towards the glacier surface. In case of large-scale flows that are strong enough to disturb the katabatic wind on the glacier, we find the greatest increases in low-level heat exchange towards the glacier surface at the wind-exposed areas of the glacier, in our case at the centreline. This contrasts with previous studies (e.g. Sauter and Galos, 2016) that concluded that the heat exchange increases mostly at the peripheral areas of the glacier due to strongest heat advection. These earlier findings however, appear to be only valid for conditions when the katabatic flow at the centreline of the glacier was preserved. Furthermore, the steepness of the surrounding terrain plays a decisive role for the sheltering of peripheral areas from heat advection from the surrounding terrain. Steeper terrain might thus lead to a stronger sheltering of peripheral areas from a disturbance of the katabatic flow by larger-scale flows associated with strong winds and lateral heat advection.

Our experiments highlight the difficulty of experimentally characterizing the micro-meteorological conditions over glaciers and its potential effect on the energy balance of the glacier surface. Even flux profiles at multiple locations at the glacier provide only local scale information and turbulence sensors only allow measurements at a certain distance away from the glacier surface. In the case of shallow katabatic jet formation, the vertical flux divergence is high and the knowledge of the exact local jet height is critically important for the interpretation of turbulence profiles. Turbulence measurements close to the jet height or even above will provide underestimated values of momentum and vertical heat fluxes not reflecting the turbulence characteristics at the glacier surface. These measurements do not necessarily provide meaningful information about heat exchange through the atmospheric layer adjacent to the ice surface. It is therefore critically important to apply measurement techniques that allow measuring turbulence at the lowest meter above the glacier surface. Eddy-covariance sensors with smaller path lengths as used by Mott et al. (2017) can measure turbulent fluxes in the lowest 0,5 meter above the surface. High-resolution Fibre-Optic Temperature Sensing (Thomas et al., 2012) can be applied to measure the two-dimensional thermal structure of the surface layer at high resolution. A different very promising approach is the use of an Infrared camera pointing at a synthetic projection screen. The surface temperature of the screen is used as a proxy for air temperature (Grudzielanek et al., 2015). The high frequency of the measurements (10 Hz) combined with eddy covariance measurements will allow to infer turbulent sensible heat fluxes in very high spatial resolution (less than 0,1 m resolution) and very close to the glacier surface. As such measurements were conducted during the HEFEX campaign ongoing research will provide more insight into the temporal dynamics of the katabatic flow.

Furthermore, the origin of the across-glacier flow and differences of the exposure to strong westerly winds at different parts of the glacier could not be ascertained due to limited number of stations at higher elevations on the glacier and in the near-by surroundings. Numerical methods such as large eddy simulations are required to complement our experiments to investigate the dynamics of the across-glacier flow and its development. In the framework of a current research project associated with the HEFEX campaign LES simulations with WRF are done at the Hintereisferner area on 240m and 48m resolution. These simulations will allow us to combine and compare measurements such as these with modelling efforts. For glacier mass and energy balance studies, a dynamical downscaling (Gerber et al., 2018) of regional scale atmospheric models to very high resolutions would help to better capture boundary layer dynamics at the glacier and their effect on temporal and spatial dynamics of heat exchange processes at the glacier. Although measurements suggested the impact of across glacier flows on the local energy balance to be non-negligible, the frequency of such flows at other glaciers is not known.

6 Data availability

Data used in this paper will be made available upon request to the first author.

7 Author Contributions

RM, IS and LN designed the field experiment and RM, IS, and LN conducted field experiments. RM and IS analysed the data. RM prepared the manuscript with contributions from all Co-authors,

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References

Abermann, J., Lambrecht, A., Fischer, A., and Kuhn, M.: Quantifying changes and trends in glacier area and volume in the Austrian Ötztal Alps (1969-1997-2006), The Cryosphere, 3, 205–215, https://doi.org/10.5194/tc-3-205-2009, 2009.

Aubinet, M., Vesala, T., and Papale, D. (Eds): Eddy Covariance: A Practical Guide to Measurement and Data Analysis, Springer, Berlin, 460 pp., 2012.

Ayala, A., Pellicciotti, F., and Shea, J. M.: Modeling 2 m air temperatures over mountain glaciers: Exploring the influence of katabatic cooling and external warming, J. Geophys. Res. Atmos., 120, 3139–3157, https://doi.org/10.1002/2015JD023137, 2015.

Bahr, D. B. and Radic, V.: Significant contribution to total mass from very small glaciers, The Cryosphere, 6, 763–770, https://doi.org/10.5194/tc-6-763-2012, 2012.

Conway, J. P., and Cullen, N. J.: Cloud effects on surface energy and mass balance in the ablation area of Brewster Glacier, New Zealand, The Cryosphere 10, 313–328. doi: 10.5194/tc-10-313-2016, 2016.

Cullen, N. J., and Conway, J. P.: A 22-month record of surface meteorology and energy balance from the ablation zone of Brewster Glacier, New Zealand, J. Glaciol. 61, 931–946. doi: 10.3189/2015JoG15J004, 2015.

Curtis, J. A., Flint, L. E., Flint, A. L., Lundquist, J. D., Hudgens, B., Boydston, E. E., and Young, J. K.: Incorporating Cold-Air Pooling into Downscaled Climate Models Increases Potential Refugia for Snow-Dependent Species within the Sierra Nevada Ecoregion, CA, PLoS ONE, 9, e106984 https://doi.org/10.1371/journal.pone.0106984, 2014.

Dadic, R., Mott, R., Lehning, M., and Burlando, P.: Wind influence on snow depth distribution and accumulation over glaciers, J. Geophys. Res., 115:F01012 doi: 10.1029/2009JF001261, 2010.

Dadic, R., Mott, R., Lehning, M., Carenzo, M., Anderson, B., and Mackintosh, A.: Sensitivity of turbulent fluxes to wind speed over snow surfaces in different climatic settings, Adv. Water Resour., 55, 178–189, https://doi.org/10.1016/j.advwatres.2012.06.010, 2013.

Daly C, Conklin DR, Unsworth MH.: Local atmospheric decoupling in complex topography alters climate change impacts, Int. J. Climatol. 30, 1857– 1864, 2010.

Denby, B.: Second order modeling of turbulence in katabatic flows, Bound. Lay. Meteorol., 92 (1), 67-100, 1999.

Denby, B., Greuell, W.: The use of bulk and profile methods for determining surface heat fluxes in the presence of glacier winds, J. Glaciol., 46(154), 445-452. doi:10.3189/172756500781833124, 2000.

Denby, B. and Smeets, C.J.P.P.: Derivation of turbulent flux profiles and roughness lengths from katabatic flow dynamics, J. Atmos. Sci., 39, 1601–1612, 2000.

Escher-Vetter, H.: Zum Gletscherverhalten in den Alpen im zwanzigsten Jahrhundert, in: Klimastatusbericht 2001, Deutscher Wetterdienst, Offenbach, 51–57, 2002.

Essery, R., Granger, R., and Pomeroy, J. W.: Boundary-layer growth and advection of heat over snow and soil patches: Modelling and parameterization, Hydrol. Process. 20, 953–967. doi: 10.1002/hyp.6122, 2006.

Fitzpatrick, N., Radić, V., and Menounos, B.: A multi-season investigation of glacier surface roughness lengths through in situ and remote observation, The Cryosphere, 13, 1051–1071, https://doi.org/10.5194/tc-13-1051-2019, 2019.

Frei, C. and Schär, C.: A precipitation climatology of the Alps from high-resolution rain-gauge observations, Int. J.Climatol., 18, 873–900, https://doi.org/10.1002/(SICI)1097-0088(19980630)18:8<873::AID-JOC255>3.0.CO;2-9, 1998.

Gerber, F., Besic, N., Sharma, V., Mott, R., Daniels, M., Gabella, M., Berne, A., Germann, U., and Lehning, M.: Spatial variability in snow precipitation and accumulation in COSMO–WRF simulations and radar estimations over complex terrain, The Cryosphere, 12, 3137–3160, https://doi.org/10.5194/tc-12-3137-2018, 2018.

Grachev, A.A., Leo, L.S., Sabatino, S.D., Fernando, H.J.S., Pardyjak, E.R. and Fairall, C.W.: Structure of turbulence in katabatic flows below and above the wind-speed maximum, Bound. Lay. Meteorol., 159(3), 469–494, 2016.

Greuell, W., and Smeets, P.: Variations with elevation in the surface energy balance on the Pasterze (Austria), J. Geophys. Res., 106(D23), 31717– 31727, doi:10.1029/2001JD900127, 2001.

Grudzielanek, A.M., Cermak, J.: Capturing Cold-Air Flow Using Thermal Imaging, Bound. Lay. Meteorol., 157**,** 321–332, https://doi.org/10.1007/s10546-015-0042-8, 2015.

Harder, P., Pomeroy, J. W., and Helgason, W.: Local scale advection of sensible and latent heat during snowmelt, Geophys. Res. Lett. 44, 9769–9777. doi: 10.1002/2017GL074394, 2017.

Helbig, N., Mott, R., Herwijnen, A., Winstral, A., and Jonas, T.: Parameterizing surface wind speed over complex topography, J. Geophys. Res. Atmos., 122, 651– 667, doi:10.1002/2016JD025593, 2017.

Hoinkes, H.: Methoden und Möglichkeiten von Massenhaushaltsstudien auf Gletschern, Zeitschrift für Gletscherkunde und Glazialgeologie, 6, 37–90, 1970.

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, Int. J. Climatol., 24, 329–339, https://doi.org/10.1002/joc.1008, 2004.

Kljun, N., Calanca, P., Rotach, M.W., and Schmid, H.P.: A simple two-dimensional parameterisation for Flux Footprint Prediction (FFP), Geosci. Model Dev. 8, 3695-3713, 2015.

Klok, E., Oerlemans, J.: Model study of the spatial distribution of the energy and mass balance of Morteratschgletscher, Switzerland, J. Glaciol., 48(163), 505-518. doi:10.3189/172756502781831133, 2002.

Klug, C., Bollmann, E., Galos, S. P., Nicholson, L., Prinz, R., Rieg, L., Sailer, R., Stötter, J., and Kaser, G.: Geodetic reanalysis of annual glaciological mass balances (2001–2011) of Hintereisferner, Austria, The Cryosphere, 12, 833–849, https://doi.org/10.5194/tc-12-833-2018, 2018.

Kuhn, M.: The mass balance of very small glaciers, Zeitschrift für Gletscherkunde und Glazialgeologie, 31, 171–179, 1995.

Kuhn, M., Dreiseitl, E., Hofinger, S., Markl, G., Span, N., and Kaser, G.: Measurements and Models of the Mass Balance of Hintereisferner, Geografiska Annaler: Series A, Physical Geography, 81, 659–670, https://doi.org/10.1111/1468-0459.00094, 1999.

Lapo, K., Nijssen, B., & Lundquist, J. D.: Evaluation of turbulence stability schemes of land models for stable conditions, J. Geophys. Res: Atmosph., 124, 3072– 3089. https://doi.org/10.1029/2018JD028970, 2019.

MacDougall, A.H. and Flowers, G.E.: Spatial and Temporal Transferability of a Distributed Energy-Balance Glacier Melt Model., J. Climate, 24, 1480–1498, https://doi.org/10.1175/2010JCLI3821.1, 2011.

Marzeion, B., Jarosch, A. H., and Hofer, M.: Past and future sea-level change from the surface mass balance of glaciers, The Cryosphere, 6, 1295–1322, https://doi.org/10.5194/tc-6-1295-2012, 2012.

Mott, R., Egli, L. T., Grünewald, Dawes, N., Manes, C., Bavay, M., et al.: Micrometeorological processes driving snow ablation in an Alpine catchment, The Cryosphere 5, 1083–1098. doi: 10.5194/tc-5-1083-2011, 2011.

Mott, R., Gromke, C. T., and Grünewald, Lehning, M.: Relative importance of advective heat transport and boundary layer decoupling in the melt dynamics of a patchy snow cover, Adv. Water Resour. 55, 88–97. doi: 10.1016/j.advwatres.2012.03.001, 2013.

Mott, R., Daniels, M., and Lehning, M.: Atmospheric flow development and associated changes in turbulent sensible heat flux over a patchy mountain snow cover, J. Hydrometeor. 16, 1315–1340. doi: 10.1175/JHM-D-14-0036.1, 2015.

Mott, R., Paterna, E., Horender, S., Crivelli, P., and Lehning, M.: Wind tunnel experiments: cold-air pooling and atmospheric decoupling above a melting snow patch, *Cryosphere* 10, 445–458. doi: 10.5194/tc-10-445-2016, 2016.

Mott, R., Schlögl, S., Dirks, L., and Lehning, M.: Impact of extreme land surface heterogeneity on micrometeorology over spring snow cover, *J. Hydrometeor*. 18, 2705–2722. doi: 10.1175/JHM-D-17-0074.1, 2017.

Mott, R., Vionnet, V., and Grünewald, T.: The Seasonal Snow Cover Dynamics: Review on Wind-Driven Coupling Processes, *Front. Earth Sci.* 6:197. doi: 10.3389/feart.2018.00197, 2018.

Mott, R., Wolf, A., Kehl, M., Kunstmann, H., Warscher, M., and Grünewald, T.: Avalanches and micrometeorology driving mass and energy balance of the lowest perennial ice field of the Alps: a case study, The Cryosphere, 13, 1247–1265, https://doi.org/10.5194/tc-13-1247-201, 2019.

Mölg, T., Cullen, N. J., and Kaser, G.: Solar radiation, cloudiness and longwave radiation over low-latitude glaciers: Implications for mass balance modelling, J. Glaciol., 55, 292–302, 2009.

Nadeau, D.F., Pardyjak, E.R., Higgins, C.W., Huwald, H. and Parlange, M.B.: Flow during the evening transition over steep Alpine slopes, Q.J.R. Meteorol. Soc., 139: 607-624. doi:10.1002/qj.1985, 2013.

Nicholson, L. I., Prinz, R., Mölg, T., and Kaser, G.: Micrometeorological conditions and surface mass and energy fluxes on Lewis Glacier, Mt Kenya, in relation to other tropical glaciers, The Cryosphere, 7, 1205–1225, https://doi.org/10.5194/tc-7-1205-2013, 2013.

Nicholson, L., Stiperski, I.: Comparison of turbulent structures and energy fluxes over exposed and debris-covered glacier ice, submitted to Journal of glaciology. https://doi.org/10.1017/jog.2020.23.

Obleitner, F.: Climatological features of glacier and valley winds at the Hintereisferner (Ötztal Alps, Austria), Theor Appl Climatol (1994) 49: 225. https://doi.org/10.1007/BF00867462, 1994.

Oerlemans, J.: Glaciers and Climate Change, Lisse, Balkema, 148 pp., 2001.

Oerlemans, J. and Grisogono, B.: Glacier winds and parameterisation of the related surface heat fluxes, Tellus A, 54, 440–452, https://doi.org/10.1034/j.1600-0870.2002.201398.x, 2002.

Oerlemans, J. and Van Den Broeke, M.: Katabatic flows over ice sheets and glaciers, Tellus A, 54, 440–452, https://doi.org/10.1034/j.1600-0870.2002.201398.x, 2002.

Oldroyd, H. J., Katul, G., Pardyjak, E. R., & Parlange, M. B.: Momentum balance of katabatic flow on steep slopes covered with short vegetation, Geophysical Research Letters, 41, 4761–4768. http://doi.org/10.1002/2014GL060313, 2014.

Parmhed, O., Oerlemans, J., & Grisogono, B.: Describing surface fluxes in katabatic flow on Breidamerkurjökull, Iceland, Quarterly Journal of the Royal Meteorological Society, 130, 1137–1151. http://doi.org/10.1256/qj.03.52, 2004.

Petersen, L., Pellicciotti, F., Juszak, I., Carenzo, M., and Brock, B.: Suitability of a constant air temperature lapse rate over an Alpine glacier: testing the Greuell and Böhm model as an alternative, Ann. Glaciol., 54, 120–130, https://doi.org/10.3189/2013AoG63A477, 2013.

Petersen, L., and Pellicciotti, F.: Spatial and temporal variability of air temperature on a melting glacier: Atmospheric controls, extrapolation methods and their effect on melt modeling, Juncal Norte Glacier, Chile, *J. Geophys. Res.*, 116, D23109, doi:10.1029/2011JD015842, 2011.

Pinto, J. O., Parsons, D. B., Brown, W. O. J., Cohn, S., Chamberlain, N., & Morley, B.: Coevolution of down-valley flow and the nocturnal boundary layer in complex terrain, Journal of Applied Meteorology and Climatology, 45, 1429– 1449. http://doi.org/10.1175/JAM2412.1, 2006.

Prinz, R., Nicholson, L. I., Mölg, T., Gurgiser, W., and Kaser, G.: Climatic controls and climate proxy potential of Lewis Glacier, Mt. Kenya, The Cryosphere, 10, 133-148, https://doi.org/10.5194/tc-10-133-2016, 2016.

Radić, V. and Hock, R.: Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise, Nat. Geosci., 4, 91–94, https://doi.org/10.1038/ngeo1052, 2011.

Sauter, T. and Galos, S. P.: Effects of local advection on the spatial sensible heat flux variation on a mountain glacier, The Cryosphere, 10, 2887-2905, https://doi.org/10.5194/tc-10-2887-2016, 2016.

Schlögl, S., Lehning, M., and Mott, R.: How are turbulent heat fluxes and snow melt rates affected by a changing snow cover fraction? *Front. Earth Sci*. 6:154. doi: 10.3389/feart.2018.00154, 2018a.

Schlögl, S., Lehning, M., and Mott, R.: Representation of horizontal transport processes in snow melt modelling by applying a footprint approach, *Front. Earth Sci.* 6:120. doi: 10.3389/feart.2018.00120, 2018b.

Shea, J. M. and Moore, R. D.: Prediction of spatially distributed regional-scale fields of air temperature and vapor pressure over mountain glaciers, J. Geophys. Res., 115, D23107, https://doi.org/10.1029/2010JD014351, 2010.

Smith, T., Smith, M.W., Chambers, J.R., Nicholson, L., Mertes, J., Quincey, D.J., Carrivick, J.L., Sailer, R., & Stiperski, I.: A scale-dependent model for changing aerodynamic roughness of ablating glacier ice. J. of Glaciology, https://doi.org/10.1017/jog.2020.56, 2020.

Sold, L., Huss, M., Hoelzle, M., Andereggen, H., Joerg, P., & Zemp, M.: Methodological approaches to infer end-of-winter snow distribution on alpine glaciers, *Journal of Glaciology*, *59*(218), 1047-1059. doi:10.3189/2013JoG13J015, 2013.

Stiperski, I., & Rotach, M. W.: On the measurement of turbulence over complex mountainous terrain, *Boundary-Layer Meteorology*, 159(1), 97– 121, 2016.

Stiperski, I., M. Calaf, and M. W. Rotach: Scaling, Anisotropy, and Complexity in Near-Surface Atmospheric Turbulence. *Journal of Geophysical Research: Atmospheres*, 144, doi:10.1029/2018JD029383. http://doi.wiley.com/10.1029/2018JD029383, 2020a.

Stiperski, I., Holtslag, A.A.M., Lehner, M., Hoch, S., Whiteman, C.D.: On the turbulence structure of deep katabatic flows on a shallow mesoscale slope, *Q. J. of the Royal Meteorol. Soc*., 146, 1206– 1231, https://doi.org/10.1002/qj.3734, 2020b..

Strasser, U., Corripio, J., Pellicciotti, F., Burlando, P., Brock, B., and Funk, M.: Spatial and temporal variability of meteorological variables at Haut Glacier d'Arolla, Switzerland, during the ablation season 2001: measurements and simulations, *J. Geophys. Res*. 109:D03103. doi: 10.1029/2003JD003973, 2004.

Strasser, U., Marke, T., Braun, L., Escher-Vetter, H., Juen, I., Kuhn, M., Maussion, F., Mayer, C., Nicholson, L., Niedertscheider, K., Sailer, R., Stötter, J., Weber, M., and Kaser, G.: The Rofental: a high Alpine research basin (1890–3770 m a.s.l.) in the Ötztal Alps (Austria) with over 150 years of hydrometeorological and glaciological observations, Earth Syst. Sci. Data, 10, 151–171, https://doi.org/10.5194/essd-10-151-2018, 2018.

Thomas, C.K., Kennedy, A.M., Selker, J.S. *et al.:* High-Resolution Fibre-Optic Temperature Sensing: A New Tool to Study the Two-Dimensional Structure of Atmospheric Surface-Layer Flow, *Boundary-Layer Meteorol.*, **142,** 177–192, https://doi.org/10.1007/s10546-011-9672-7, 2012.

Vickers D, Mahrt L.: The cospectral gap and turbulent flux calculations, J Atmos Ocean Technol 20:660–672. doi: 10.1175/1520-0426(2003)20<660:TCGATF>2.0.CO;2, 2003.

Weigel, A.P. and Rotach, M.W.: Flow structure and turbulence characteristics of the daytime atmosphere in a steep and narrow Alpine valley, Q.J.R. Meteorol. Soc., 130: 2605-2627. doi:10.1256/qj.03.214, 2004.

Whiteman, C.D. and Doran, J. C.: The Relationship between Overlying Synoptic-Scale Flows and Winds within a Valley. *J. Appl. Meteor.*, 32, 1669–1682, https://doi.org/10.1175/1520-0450(1993)032<1669:TRBOSS>2.0.CO;2, 1993.

Zhong, S., & Whiteman, C.: Downslope Flows on a Low-Angle Slope and Their Interactions with Valley Inversions. Part II: Numerical Modeling, *Journal of Applied Meteorology and Climatology*, *47*(7), 2039-2057, 2008.