Referee Anonymous:

RC1 General comment: This paper sets out to examine the interaction between katabatic and across-glacier glacier flows, and how this contributes to turbulent heat exchange. To my knowledge, this is one of the largest and best quality datasets exploring this complex interaction. I found the writing compelling, but I'm not certain I would have reached all the same conclusions by looking at the data. Apart from computing fluxes, the quantitative analysis contained in this work did not extend much beyond correlation coefficients. Given the volume and complexity of the data and day-to-day variability, almost all figures presented could benefit greatly from more quantitative analyses. Because of this, it is not clear which conclusions are truly substantiated by their data and which are a product of statistical outliers influencing qualitative analysis. This work could also benefit from more robust analysis of magnitudes and sources of possible uncertainties.

General Response: 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:

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 %)

- 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.

Revised figures referred to in this document:

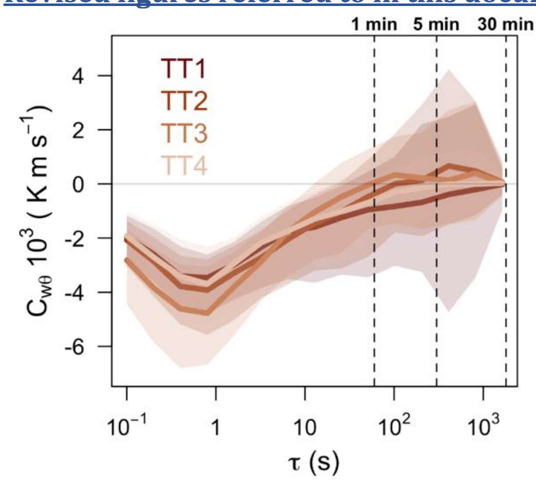


Figure: Multi-resolution flux decomposition of buoyancy flux as a function of time scale t for the four examined stations.

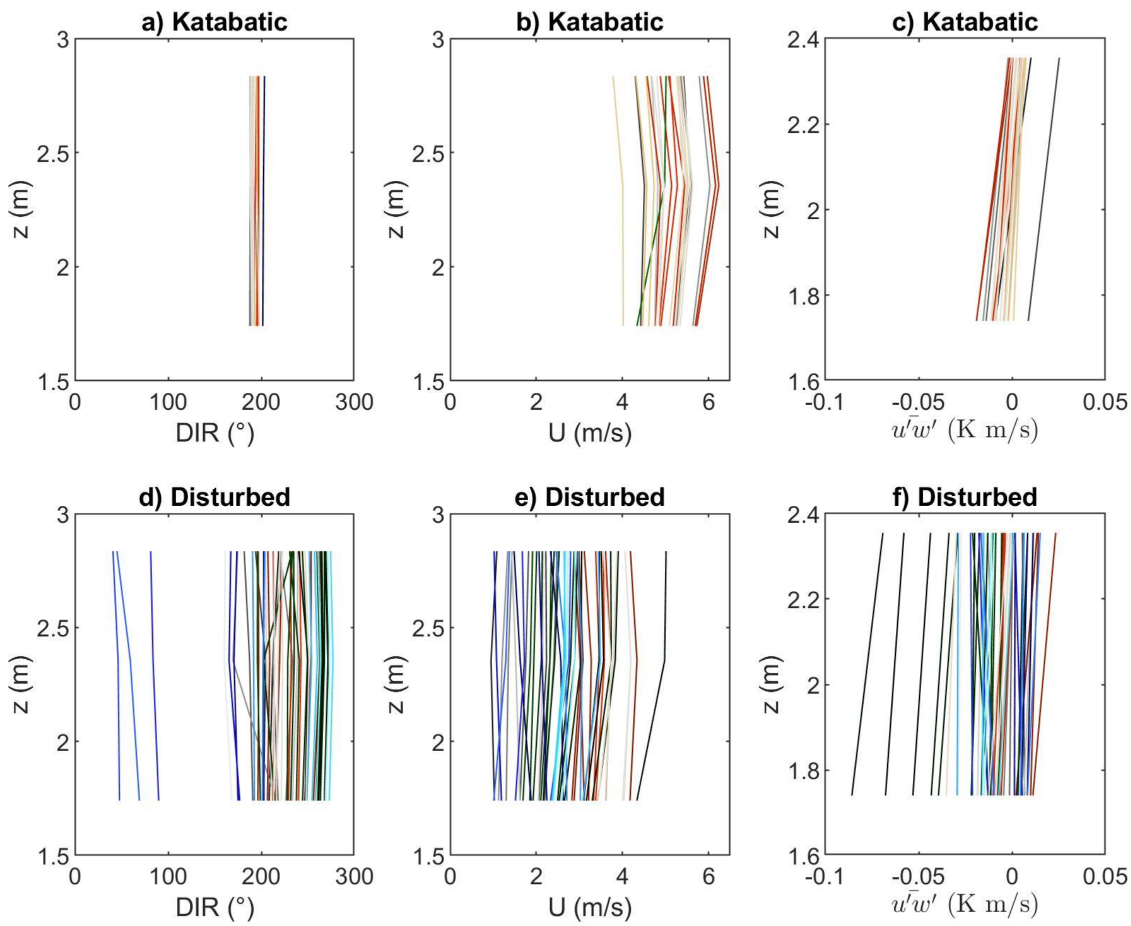


Figure 2: 30 minutes averaged profiles of wind direction (a, d) and wind speed (b, e) for katabatic (a-c) and disturbed (d-f) conditions *during five days in August 2018 obtained from the mobile wind tower and station TT3. Streamwise momentum fluxes are shown for two measurement levels obtained from station TT3 (c, f). 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 1-minute classification. Colours indicate different measurement days (grey=day1, red=day 2; green=day3; blue=day 4; brown=day5).*

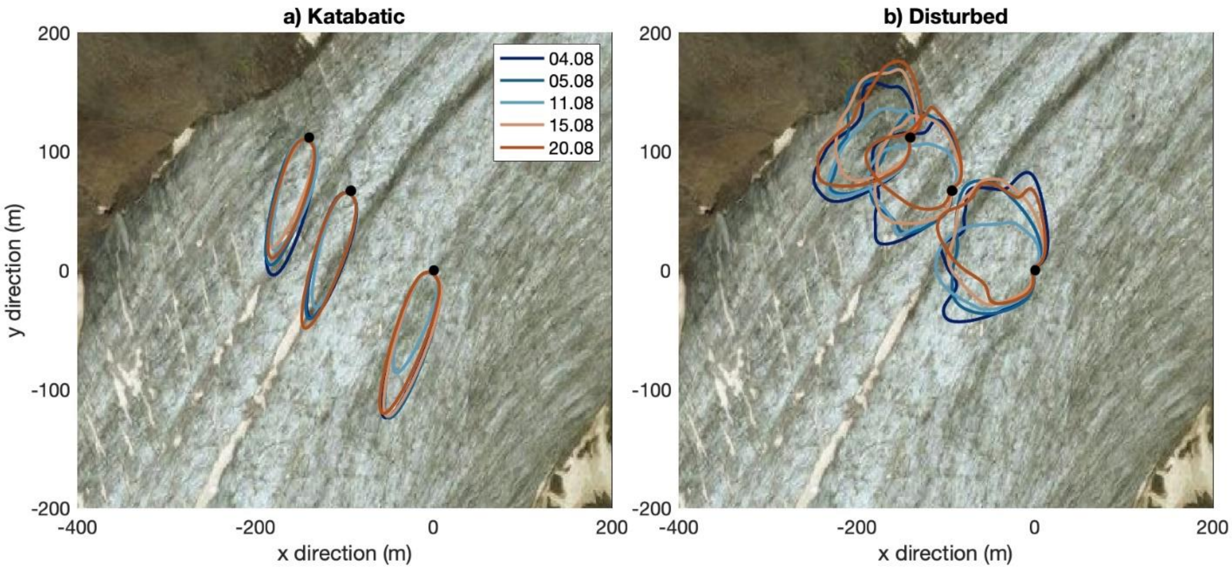


Figure 3: Climatological flux footprints for transect stations TT1-TT3 and for a) katabatic and b) disturbed conditions. Background images © Microsoft BingTM Maps Platform Arial screen shot(s) reprinted with permission from Microsoft Corporation.

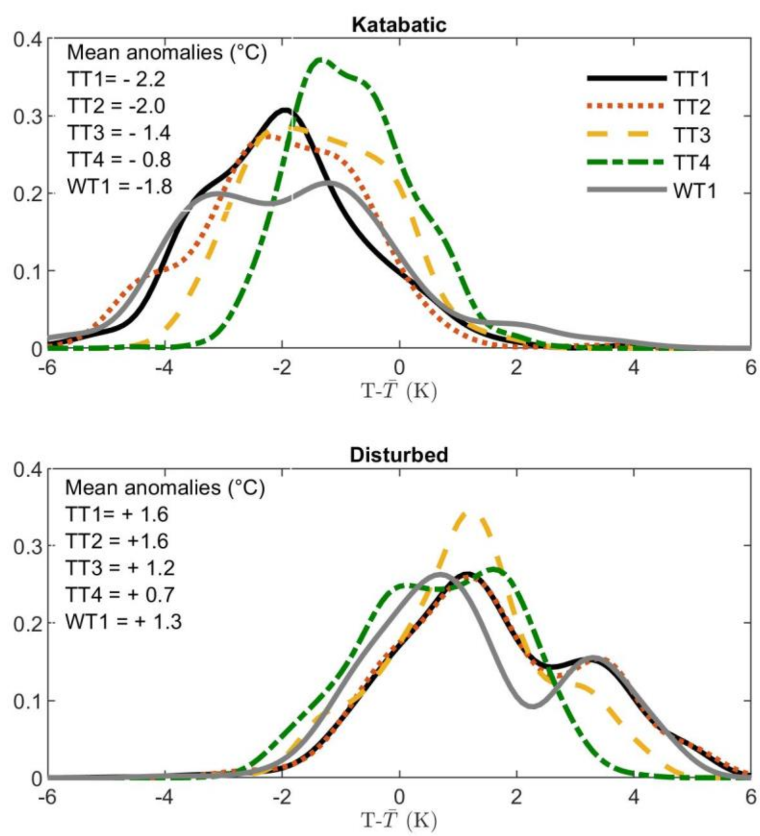


Figure 6: Anomalies of air temperatures from mean daytime air temperature at the respective stations TT1, TT2, TT3, TT4 and WT1 are shown for katabatic and disturbed conditions.

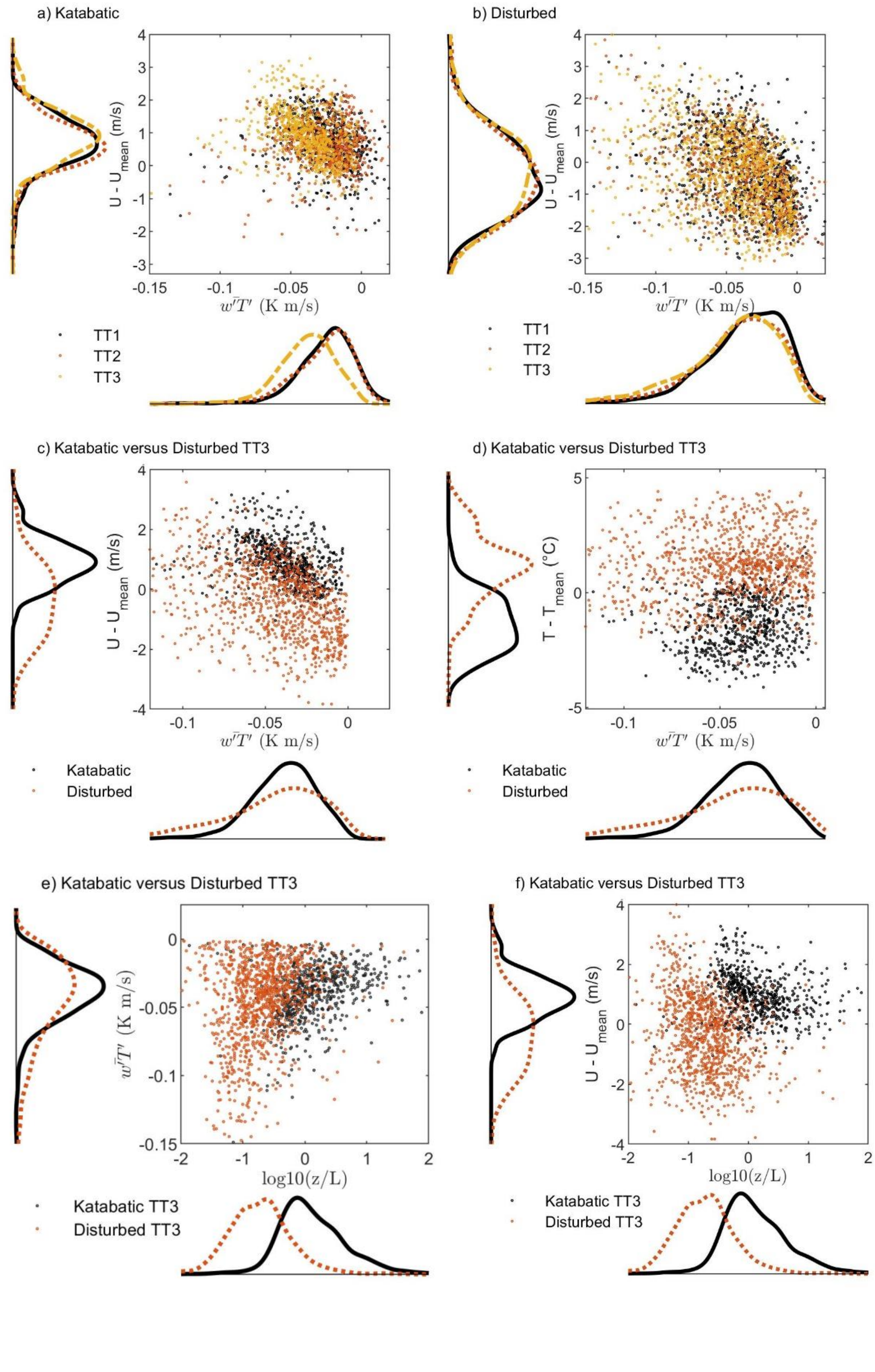


Figure 7: Vertical heat flux plotted against anomalies of wind speed from mean daytime wind speed shown for stations TT1 –TT3 for katabatic conditions *a) and disturbed* conditions *(b). Vertical turbulent heat flux plotted against anomalies of wind speed from mean daytime wind speed (c) and against anomalies of air temperature from mean daytime air temperature (d) shown for station TT3 for katabatic and disturbed* conditions*. Logarithm of Stability parameter z/L plotted against Vertical turbulent heat flux (e) and normalized wind speed (f) measured at TT3 during katabatic and disturbed flows.*

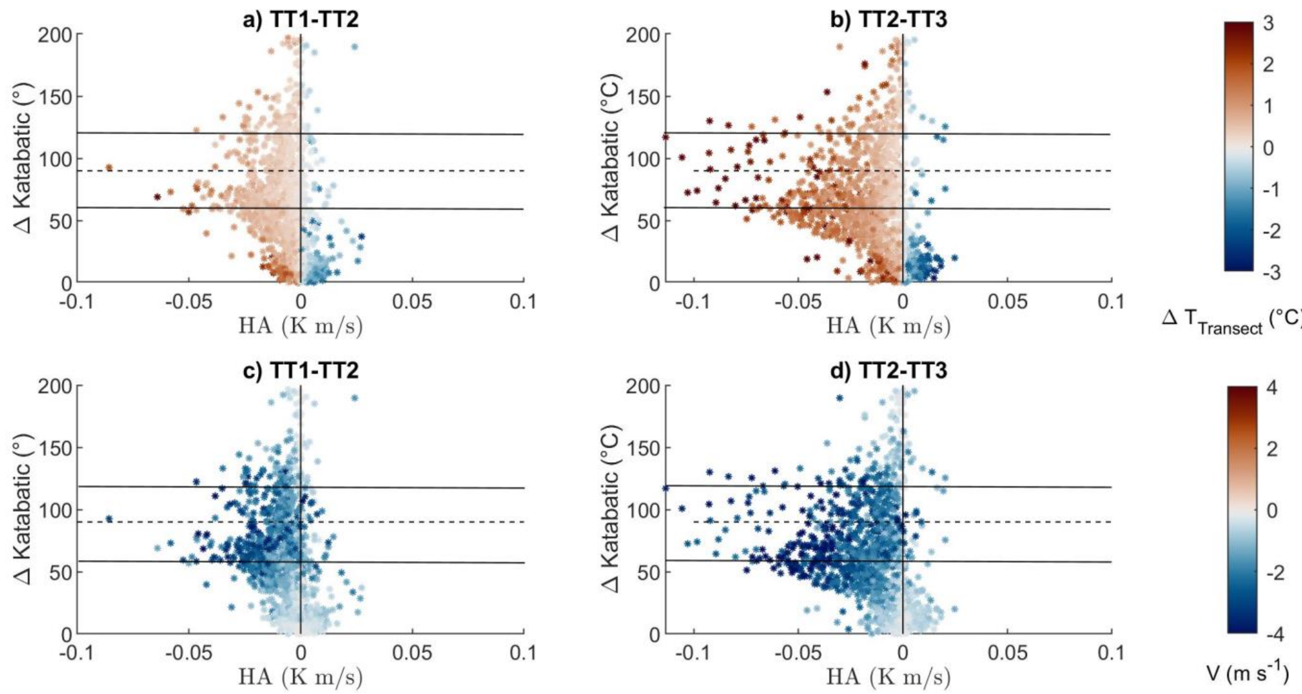


Figure 8: *Horizontal advection of heat (HA) calculated between stations TT1 and TT2 (a) and TT2 and TT3 (b) from the first level above ground are plotted against deviation from katabatic wind direction for 5 selected days with periods of clear deviation from the dominant katabatic flow direction. Colour 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 heat advection analysis for disturbed conditions is based on.*

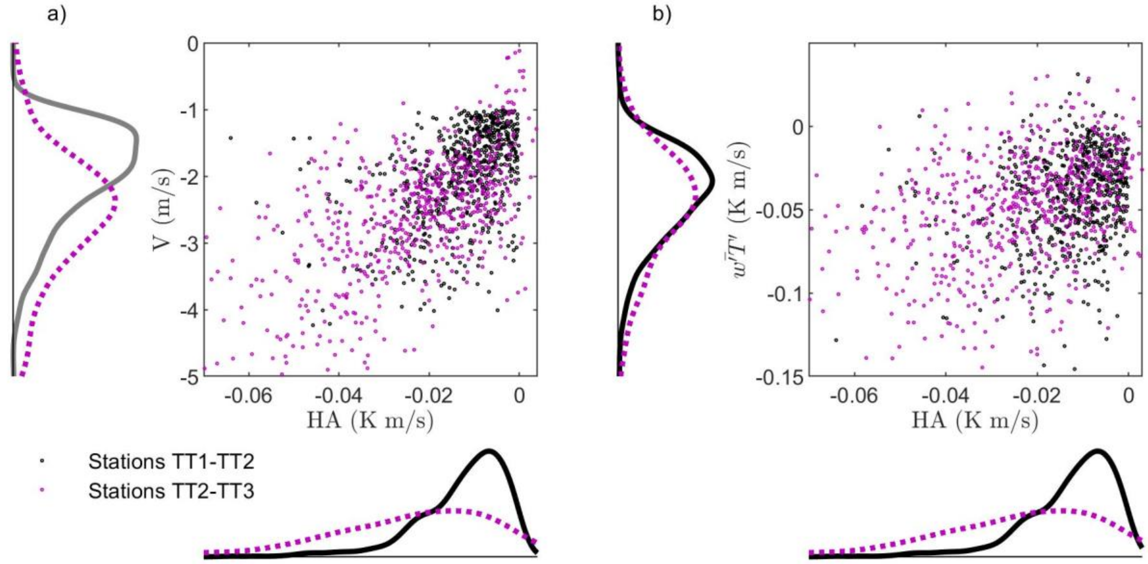
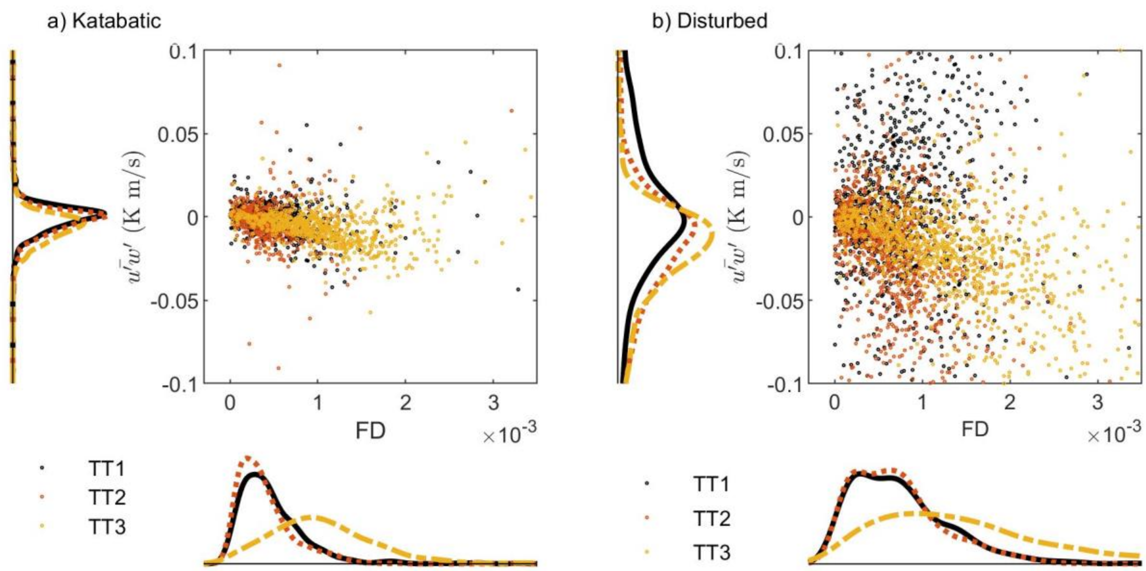


Figure 9: *Horizontal advection of heat (HA) between stations TT1 and TT2 and TT2 and TT3 plotted against measured wind speed component along the transect V (a) and turbulent vertical heat flux (b). Note that for this analysis we considered only data with evidence of horizontal heat advection along the transect (U-component along the transect larger than 1 m/s and positive air temperature differences).*



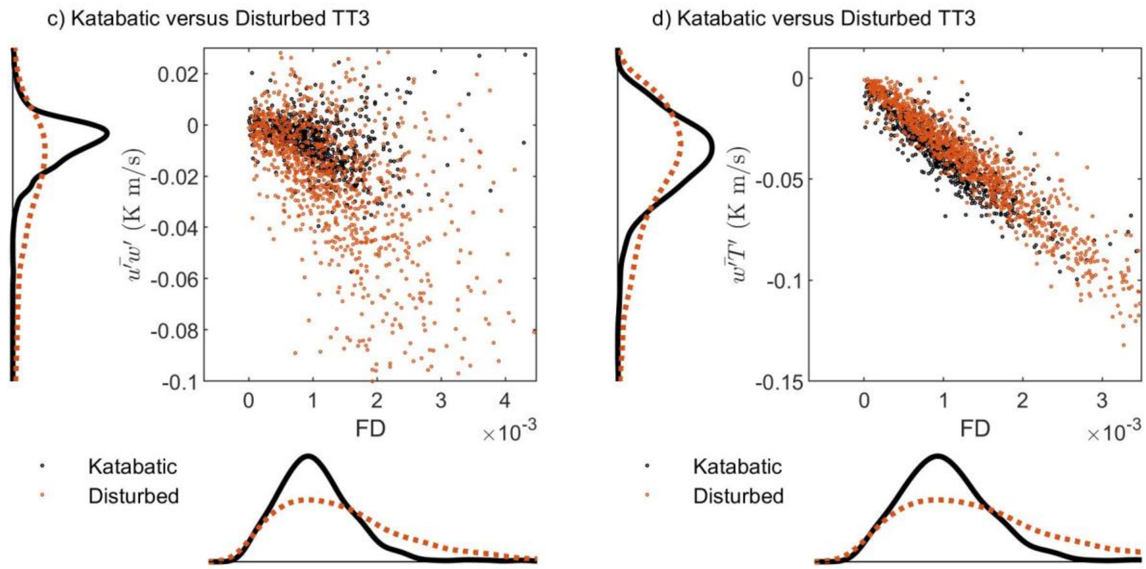


Figure 10 (new Figure 11): *Vertical flux divergence plotted against vertical momentum flux for stations TT1, TT2, TT3 are shown for katabatic (a) and disturbed situations (b). To allow a better comparison of fluxes during different flow conditions the vertical flux divergence is plotted against vertical momentum flux (c) and against vertical turbulent heat flux (d) for station TT3 for katabatic and disturbed flow.*

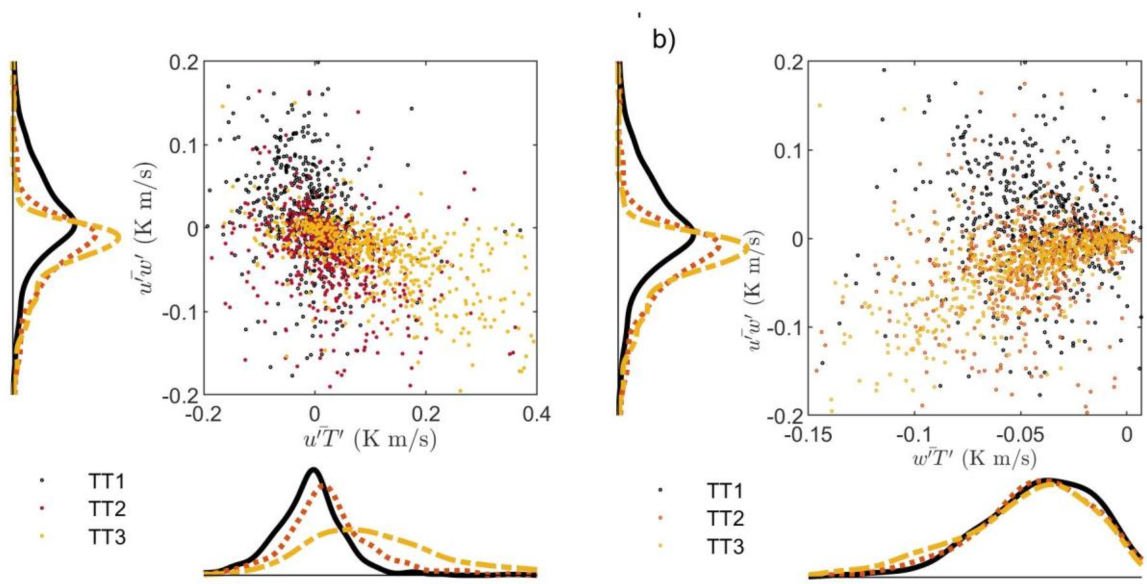


Figure 12: Streamwise horizontal turbulent heat flux plotted against streamwise momentum flux for stations TT1, TT2 and TT3 (a). Vertical turbulent heat flux plotted against streamwise momentum flux for stations TT1, TT2 and TT3 (b). Data are only shown for disturbed conditions and the 60°wind sector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

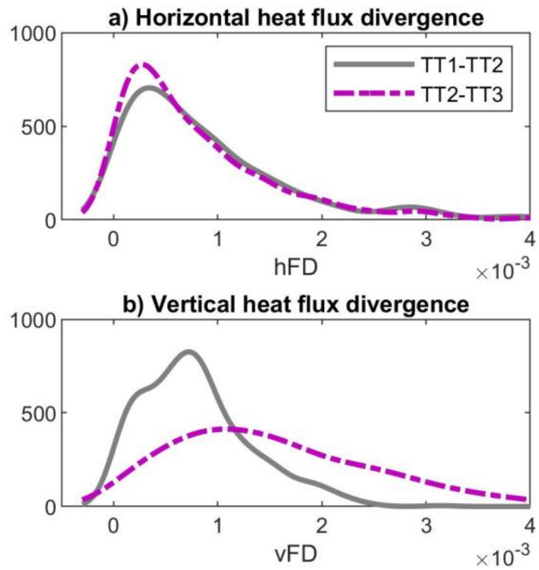


Figure 13: Kernel distribution of horizontal (hDF) and vertical (vDF) heat flux divergence shown only for disturbed situations and the wind sector 240° to 300°.