We very much thank the two reviewer for their thorough analysis of our article and for their valuable comments, annotations and suggested improvements. They had been carefully considered and most of them are accounted for in the revised manuscript. Answers and explanations to all detailed questions and annotations raised by the reviewers are provided in the following.
(RC: Reviewer comments; AC: Author comments)

RC 1: Due to the computationally intensive nature of the LES, it is understandable that a small timeframe is most suitable to demonstrate the expected variation of sensible heat fluxes over the glaciers. However, I think the paper would benefit from having more detail on the conditions of the hour for which statistics are presented. The authors describe a blue sky condition which is known to be favourable for the development of a katabatic boundary layer, however the strength of the boundary layer can also be affected by the ambient air temperature (data from the off-glacier sites seen in Figure 1 could aid this). Furthermore, could the LES be compared with a cooler/cloudier hour? Though adding some extra work, I think this would benefit the scientific community and be informative for when (under which conditions) sensible heat fluxes are most likely to be inadequately modelled.

> ***AC:*** *Measures characterizing the atmospheric condition (ambient conditions), such as lapse rates or heating rates, depend on the locations where the measurements are taken. At the slopes there is a well-mixed layer (~10-50 m) with nearly constant potential temperature (~10℃) and a thermally driven slope wind develops. The synoptic flow enhances or retards the slope winds and alters the temperature distribution. To test this, we have calculated the lapse rate on an east slope for each experiment (different large-scale forcing). When the large-scale flow aligns with the slope winds (easterly flow) the lapse rate is lower (0.0067 K/m or even lower) than for the other cases (~0.0078 K/m or even higher). We have attached two figures to this review to illustrate the advection of warm air over a ridge and how it impacts the lapse rates (ridge_east.pdf and ridge_west.pdf). The same argument holds for the heating rates of the near-surface layer. Therefore, it might be the best to provide a vertical atmospheric profile at the location Z2 on the Zufallferner. A new figure has been added showing the vertical temperature profile up to 10000 m. Above the Cevedale Peak the lapse rate is approximately -0.006 K/m, which corresponds to the profile given by the ERA-Interim data. Together with the temperature deficit (between the 2 m temperature and the free atmosphere, see Table 1) this provides a valuable information on the ambient air temperature in the valley.*
>
> *We also like to note, that the atmospheric background state for temperature and pressure from the ERA-Interim data was from the 17th August 2014 and not 12th August 2013 as given previously in the text (p6 L25/26).*
>
> *We agree with the reviewer that the scientific community would benefit from a greater variety of cases and more general conclusions on the sensible heat fluxes. In order to draw a general conclusion, however, a large number of experiments is needed to cover the wide spectrum of topographic and atmospheric constellations. Unfortunately, we have already reached our computational capacities and try to solve this in an upcoming project. Each LES run of 9 hours' simulation time requires a computational time of 5-7 days on a High-Performance Computer with 400 cores. This is the first time that high-resolution LES have been performed over alpine glaciers and it shows that this approach has potential to study small scale processes.*

RC 2: As the work details, the LES is not required to be an observed real-world case, as the realistic simulation of processes and their spatial variation is key. However, the authors indicate several weather stations in Figure 1 (which are not used). It would be interesting to present what the actual lapse rate on glacier would be and also compare the calculation of sensible heat fluxes using this measured data. If no AWS measurements are to be utilised in this study, please remove them from the figure.

> ***AC****: In an idealized setup, the surrogate atmosphere can only be compared with well-known characteristics of stable boundary layer and dynamical atmospheric features obtained from in-situ*

measurements on alpine glacier. These characteristics include the vertical (wind and temperature), sensible heat flux and turbulent structure of the boundary layer and should be of the same order of magnitude as the measurements (Section 3.1 and 3.2).

During the week of the 17th August 2014 we had temporarily installed two weather stations, one closed to Z1 on Zufallferner and another further down the valley. The glacier station measured between 13 and 14 h a mean wind velocity of 4.6 m/s at 2 m height above the surface. Even though this is closed to the simulated value (4.5-6 m/s, westerly flow), the two values are not comparable at all. The prescribed surface heating rate (1.2 K/h) of the surroundings is lower than the measured heating rate (4.1 K/hr) at that particular day. Furthermore, the idealized simulations do not account for differential heating by radiation which is important during the first two hours and leads to asymmetric cross-valley winds. Without doubt, the homogenous heating assumption is a major drawback of the code. Although the chosen heating rate is significantly lower and shadowing effects are absent the typical low level jet and the heat advection from the lateral boundaries are present. As indicated in the conclusion, due to conservative chosen boundary conditions the simulated advection effects might be weaker than the one observed in a real atmosphere.

To avoid confusion, we follow the recommendation of the reviewer and removed the stations from Figure 1.

RC 3: The authors also outline several sub-regions and 'virtual' sites of interest on Zufallferner though with no clear justification for why. I think it is important to demonstrate the spatial variation of wind fields along a glacier centreline and focus on specific sites (i.e. Z1-Z4), particularly when attempting to simulate and understand interactions of the glacier boundary layer with synoptic scale winds. Furthermore, the selection of temperature extrapolation locations is important although often somewhat arbitrary in many studies. However, the presentation of several different sites between figures (Figures 7,8,9 for example) and their naming conventions (Z3 changes to Za then to Zc) is misleading. The authors should add some additional reasoning to their choices of virtual sites. The authors should also guide the reader to aspects of figure subplots by labelling them (i.e. a-d). Misleading information for Figure 3 is particularly noteworthy.

***AC:** We thought, virtual sites make it easier for the reader to follow the discussion. Each region shows a different flow pattern: (R1) ridge region with flow separation, (R2) a steep ice fall, (R3) katabatic wind region, and (R4) divergence of katabatic winds. We have removed the sub-regions in Figure 4, 6 and 7, while we kept the regions in Figure 2 for discussion. The justification for the regions is now given in the first paragraph of Section 3.1.*

"For the discussion we introduce four specific regions: (R1) ridge region, (R2) a steep ice fall, (R3) katabatic wind region, and (R4) divergence zone of katabatic wind. Local characteristics are discussed at four virtual sites on the glacier (Z1-4)."

We agree, that the focus of the discussion should be on the winds along the glacier centerline (Z1-Z4), and we think that has been done since most of the discussion of Section 3.1 is related to the wind fields on Zufallferner. However, the discussion on the dynamic and cross-slope winds (second paragraph of Section 3.1) helps to better understand the processes (interaction with the synoptic and thermal winds) that cause the spatial variation along the centerline.

Yes, the naming convention is misleading. We have changed labels of the locations used for interpolations to (S1-S5) and also labelled the subplots to guide the reader. From the text it is indeed not obvious how we have chosen the sites. The idea was to select sites with distinct flow and advection patterns: (Z0) at the tongue with almost pure katabatic wind (used as reference station), (Za) in the higher region which is influenced by strong advection, (Zb) at the lateral boundary of the glacier which is influenced by the cross-valley circulation, (Zc) very closed to Za but not affected by strong *heat advection, and (Zd) a second station on the glacier with dominantly katabatic wind. We now give the reason to our choice in the second paragraph of Section 4.2.*

"To explore how the choice of observation sites influences the spatial variation of the surface heat flux estimates, we define a set of virtual observation on Zufallferner with distinct flow and advection patterns: (S1) located at the glacier tongue with almost pure katabatic wind (used as reference station), (S2) in the higher region which is influenced by strong heat advection, (S3) at the lateral boundary of the glacier which is influenced by the cross-valley circulation, (S4) closed to S2 but less affected by strong heat advection, and (S5) a second station on the glacier with dominantly katabatic wind. For each combination of S1 and S2-S5 the heat fluxes are estimated according to Eq. 16."

RC 4: Finally, while it is clear from section 1 what the problems of the literature are (and it is very well written), I think it is important to stress in a little more detail what the aim of the paper is and add some more discussion regarding the applicability of an LES approach at the end.

***AC:** In the last two paragraphs of the introduction we now stress in more detail the aim of the paper.*

"To overcome this difficulty, we make use of high resolution Large-Eddy Simulations (LES). The LES are considered as pseudo-reality - a testbed to identify the shortcomings in the local surface heat flux estimates when the lack of observations restrict our micrometeorological knowledge to a few sites. The plausibility of the temperature interpolation algorithms and the derived surface heat fluxes can be more strictly tested in a surrogate world of atmospheric simulations, which offer a realization of atmospheric states in which all target variables are known. The pseudo-reality atmosphere is not required to be an observed real world case, but needs to be plausible realization of the atmosphere in the sense that relevant processes are realistically simulated. The advantage of such studies is that the surrogate atmosphere provides a perfect pseudo-observation of all the variables required to establish the skill of an interpolation method and hence the surface heat flux calculations. While surrogate atmospheres have been widely used in downscaling studies it's still a new approach in glaciological studies (Frias et al., 2006; Vrac et al., 2007; Maraun, 2012)."

Frías, M. D., E. Zorita, J. Fernández, and C. Rodríguez-Puebla (2006), Testing statistical downscaling methods in simulated climates, Geophys. Res. Lett., 33, L19807, doi:10.1029/2006GL027453.

Vrac, M., M. L. Stein, K. Hayhoe, and X.-Z. Liang (2007), A general method for validating statistical downscaling methods under future climate change, Geophys. Res. Lett., 34, L18701.

Maraun, D. (2012), Nonstationarities of regional climate model biases in European seasonal mean temperature and precipitation sums, Geophys. Res. Lett., 39, L06706, doi:10.1029/2012GL051210.

Specific comments

RC: 1 7: Add the temporal scale for which of the flux over- and under-estimates are found (i.e. 1 hour of statistics).

***AC:** Changed to: "The glacier-wide hourly averaged surface heat fluxes are both over- and underestimated by up to 16 Wm^{-2} when using extrapolated temperature and wind fields."*

RC: 1 18: Re-word "loss of information".

AC: *Changed to: "The reduced spatial and temporal variability …"*

RC: 2 10: I think it is important to stress that this "over 50%" contribution from turbulent heat fluxes is typical for overcast conditions or for maritime glaciers (as is given by the studies you cite –e.g. Cullen and Conway, 2015) as otherwise the dominance is typically, from shortwave radiation. For your study you assess a clear sky condition and a continental glacier.

***AC:** We have re-written that sentence: "The energy surplus can be critical for the ablation, considering that the turbulent heat flux can represent 50% of the total energy during pronounced melt events on maritime mid-latitude mountain glaciers in summer, and even up to 30% on continental glaciers (e.g. Cullen and Conway, 2015; Gillett and Cullen, 2011; Van den Broeke, 1997; Hock, 2005; Klok and Oerlemans, 2002; Oerlemans and Klok, 2002; Giessen et al., 2008; Moore and Owens, 1984)."*

RC: 2 13: Replace "peculiar" with "particular".

***AC:** Done.*

RC: 2 25-26: Though I agree that there is still much to be understood about the impact of these assumptions on glacier melt rates, citing some of the work which has made attempts to use distributed temperature for this purpose would be suitable here. For example, Immerzeel et al. (2014) investigate this for a catchment/valley scale and Shaw et al. (2016) investigate this for a debris-covered glacier.

***AC:** Done.*

RC: 3 19: I assume here that you refer to the surface boundary layer for "SBL"? Write out in full before using the acronym.

***AC:** Yes, SBL refers to stable boundary layer. Done.*

RC: 3 20: What does SGS refer to? Write out in full as well.

***AC:** SGS refers to subgrid-scale. Done.*

RC: 4 4: A minor point, but you are missing an equation number for eddy viscosity (this should be eqn 7).

***AC:** We have added the missing equation number.*

RC: 4 9-11: This sentence needs re-writing. It is unclear what it is trying to say and the sentence has syntax errors.

> ***AC:*** *The sentence has changed to: "While, energy is transferred from the large to small scales according to the Kolmogorov energy cascade, it has been observed that locally there can be a significant transfer of energy from the residual motions to the resolved scales (backscatter)."*

RC: 5 2: Changes in temperature and phase from radiative forcing would be relevant if the LES approach was adopted over a longer time-frame. This may be worth adding to the discussion?

> ***AC:*** *In the last paragraph of Section 3.4 we now indicate the how insolation on slopes affect the circulation pattern.*
>
> *"We like to note, that the current version of the solver ignores differential surface heating by radiation and is therefore only suitable for idealized simulations. Differences in insolation on slopes due to exposure, aspect or shadow cause upslope flows to be inhomogeneous. The different onsets of the slope winds then lead to more asymmetric cross-valley circulations."*

RC: 5 16-17: How is the topography representative of many in the European Alps? Can you also add the mean slope of the glacier to this section?

> ***AC:*** *We have added more topographic information to this section:*
>
> *"The surface area of the glaciers is about 6.62 km² (2013) with an altitudinal extent from about 3750 m a.s.l near the summit of Hintere Zufallspitze, down to 2595 m a.s.l. at the lowest point of Zufallferner. The model domain includes a wide variety of topographic features such as steep slopes up to 50°, glaciated and unglaciated (summit-) ridges of various aspects, as well as larger glacier sections with smooth terrain and low slope angles. The mean slope angle of the glacierized terrain is 17°. The topography can be regarded as (i) typical for many glaciers in the European Alps and (ii) highly suitable for investigating the complex interaction of large-scale (synoptic) forcing and small scale topographic features."*

RC: 5 21: What grid size do you use for the ERA-Interim reanalysis data? Is this re-sampled from the 6 hourly temporal scale of ERA-Interim? Additional detail would be useful here.

> ***AC:*** *The ERA-Interim reanalysis data is available on a 0.75x075 degree grid. The ERA grid cell data above the investigation is mapped onto the LES grid. We have initialized the LES model with the vertical profile from 06UTC. It now reads:*
>
> *"The atmospheric background state for temperature and pressure is derived from ERA-Interim reanalysis data from 06 UTC. The vertical data is uniformly mapped onto the unstructured LES grid."*

RC: 5 28: Specify if the 100 m temperature is that from the ERA-Interim.

> ***AC:*** *Yes, the 100 m temperature is that from the ERA-Interim data. We have included now this information: "The pre-factor, C, is the temperature perturbation at the glacier surface, which in our case is the difference between surface temperature (273.16 K) and the ERA-Interim*

temperature at 100 m above the surface."

RC: 6 2: Why 8 m/s-1? Is this the mean value from the given six hour period of the reanalysis data?

> ***AC:*** *Yes, this is the mean wind velocity from the ERA-Interim data at 5500 m. We have added the following sentence at the end of the paragraph: "This corresponds to the mean wind velocity of the ERA-Interim data at 5500 m."*

RC: 6 8: It is unclear what you mean by this - "some sort of model". Please re-word this sentence.

> ***AC:*** *We have re-worded this phrase: "The filter and grid resolution are too coarse to resolve the near-wall motions, including in the viscous wall region, so that their influence closed to the wall are modelled by a shear stress model."*

RC: 6 23: How did you derive these values of z0? While your z0 fits within the range of published values (as you discuss later in section 3.4), a reference here would be useful. Do you have different values for snow and ice or is the spatial variation for all on-glacier surfaces constant? It would be interesting to plot the snowline for this day on to Figure 1 if it is known. Are the effects of different on-glacier surfaces (snow/ice) important here, considering a constant 273.16K surface temperature?

> ***AC:*** *The values have been taken from literature. We have included some references.*
>
> *The roughness length for snow and ice are the same. We have added the following sentence: "The aerodynamic roughness height, z0, is set to 0.1 m for the land surfaces (e.g. Stull, 2012) and to 0.001 m for the glacier and snow surface (e.g. Braithwaite, 1995; Giessen et al., 2008; Brock et al., 2000; Hock, 2005; Greuell and Smeets, 2001), respectively. We assume similar roughness height for snow and ice since large parts of the glaciers were covered by a thin layer of fresh snow."*
>
> *This assumption is also discussed in Section 3.4:*
> *"A crucial assumption is the surface roughness length. To obtain more general results, uniform values of z0 for snow and ice with 0.001 m are used, which is in the range of commonly used values (e.g. Braithwaite, 1995; Giessen et al., 2008; Brock et al., 2000; Hock, 2005; Greuell and Smeets, 2001). The 'uniform' assumption ignores temporal and spatial roughness length variations. However, potentially such variations can have a strong influence on the magnitude of the surface energy fluxes (Brock et al., 2000; Giessen et al., 2008). We argue that this assumption is acceptable since large parts of the glaciers were covered by a thin layer of fresh snow."*
>
> *I think you refer to the effects of the surface characteristic on the atmosphere. Different roughness height would certainly impact the momentum flux and heat exchange at the surface. However, we think that it is more important (at least in the summer season) to account for non-uniform roughness changes, e.g. seracs, ice falls or the sudden change in roughness at the glacier boundary. While elements such as seracs are not resolved the model accounts for the sudden roughness changes at the glacier boundary. On large glaciers (e.g. Kronebreen and Kongsvegen) the sudden roughness change at the tongue due to huge seracs has severe effects on the flow. The Zufallferner is rather small and the influence from the surrounding may*

overwhelm the errors made by this assumption.

RC: 6 28: What is the hour of the 12th August that is being reported in this paper? I think this may be relevant for the time of day on the glacier and the expected temperature
outside the glacier boundary layer and possible shading effects etc.

AC: *The model has been initialized with the ERA-Interim profile from 06 UTC (see comment above) and a uniform surface temperature of 273.16 K (Section 2.3). On p6L28 we refer to the last simulation hour. We have now added this information.*

As mentioned in the second comment, the idealized simulations do not account for differential heating by radiation (shading effect). The surface temperature of the surrounding is given by the prescribed surface heating rate (1.2 K/h). At the end of the simulation the surface temperature is 10.8 K.

RC: 7 8-9: Has the size of computational domain been altered to test the resultant differences
in turbulent energy generation?

AC: *Yes, we have tested various simulation setting. One concern was the development of gravity waves which would impact the boundary layer characteristics. However, we could not find significant differences between a domain size of ~15 km and ~10 km (and 12.5 m horizontal resolution). The simulations are more sensitive to the choice of the grid size. Only 60-70% of the kinetic energy was resolved when using a horizontal resolution of 25 m. Additionally, decreasing the horizontal resolution lead to greater aspect ratios of the prismatic layers, which required even shorter integration time steps (0.01 s). Decreasing the prismatic layers was not an option since this would affect the shear stress and momentum calculations closed to the surface. The choice of ~12 m was a good tradeoff between computational costs and model quality. Besides the computational domain setup, the choice of the subgrid-scale model is essential for the results. The Smagorinsky SGS model was to dissipative in the stable boundary layer which led to numerical instabilities.*

We have added the following text to Section 3.4: "When decreasing the horizontal grid resolution to 25 m the resolved kinetic energy was only 60-70%. Additionally, a coarser grid leads to greater aspect ratios of the prismatic layers, which requires very short integration time steps (0.01 s) to guarantee stability. Increasing the prismatic layer heights is problematic since this affects the shear stress and momentum calculations closed to the surface. The choice of ~12.5 m is a good tradeoff between computational costs and resolved scales."

"We have also tested the dynamic Smagorinsky model, but the simulations are found to be unstable due to large fluctuations of C_s."

Additionally, we have added a new paragraph at the end of Section 3.4 which should highlight the limitation of the LES solver: "We like to note, that the current version of the solver ignores differential surface heating by radiation and is therefore only suitable for idealized simulations. Differences in insolation on slopes due to exposure, aspect or shadow cause upslope flows to be inhomogeneous. The different onsets of the slope winds then lead to more asymmetric cross-valley circulations."

RC: 7 9: What is meant by opposite DEM boundaries? I think that a new figure providing
a schematic of the layers/grids used for the LES would be very useful, albeit selective

of the key things to include. The description of the LES model is detailed well, though considering it comprises a large proportion of the paper, the addition of a figure could be beneficial to aid the reader.

> ***AC:*** *In order to guarantee a fully turbulent atmosphere the boundaries are specified as period. Such boundaries require that faces on the opposite boundary (faces of grid cells) are equal within a certain tolerance. To do so the mesh grid points on opposite boundaries have been slowly displaced to match each other. The inner grid points are relaxed to get a smooth transition from the boundaries towards the inner domain. We have added a new figure showing a sketch of the relaxation procedure.*

RC: 7 15: Remove "very"

> ***AC:*** *Done.*

RC: 7 18: Remove "it turns out that" and add a supporting reference for M-O application.

> ***AC:*** *Done.*

RC: 8 14: Why these sites? Please add some brief justification/description.

> ***AC:*** *We've added a justification for that choice (see comment above).*

RC: 8 15-16: Remove "Apparently" – Spelling mistake "luv" – Assumed to be "lee"?

> ***AC:*** *Done.*

RC: 8 25: Replace with "Generally, katabatic winds: : :."

> ***AC:*** *Done.*

RC: 9 7: "for mountain glaciers during CLEAR sky conditions".

> ***AC:*** *Done.*

RC: 9 12: "Similarly, : : :."

> ***AC:*** *Done.*

RC: 9 12-14: The downslope winds at Z4 would also be weaker due to a minimal fetch of the boundary layer too.

> ***AC:*** *Yes, this is an important aspect which we have included now: "Similarly, a reduced fetch and, in particular, a strong shear associated with a rapid veering of the winds with height can drastically reduce the wind velocity."*

RC: 9 16: Please add the wind direction cases to Figure 3 as they are currently just interpreted from the same positioning as Figure 2. Also, it would be beneficial to add letters a-d to all subplots to more easily direct the reader to the appropriate information from the text.

> ***AC:*** *Done (see comment above).*

RC: 9 16-17: This doesn't appear to be the case for the bottom left figure, which I assume to be the Northerly wind case. Are the authors only referring to the westerly (upper left) case here?

> ***AC:*** *We have added a comment to which Figure and subplots we are referring to.*
>
> *"The intensity and height of the wind maximum decreases down-slope for most cases (see Fig. 5a, b, d), …"*

RC: 9 15-20: I think this paragraph could do with greater clarification about which cases are being described. Again, some detail about conditions during the considered time period would be interesting. Does the free-air meteorology represent the typical cycle of the region?

> ***AC:*** *We now refer to the specific cases and have given more details on the ambient conditions (see comment 1). The free-air meteorology indeed represents a typical stratification for the region (see Figure 4).*

RC: 10 2: Change "shapening" to " ‚shaping".

> ***AC:*** *Done.*

RC: 10 15: Rewrite as "More importantly, the distortion: : :.."

> ***AC:*** *Done.*

RC: 11 1: Rewrite as "On the one hand, distributed mass: : :."

> ***AC:*** *Done.*

RC: 11 5-6: spelling correction “of course”.

AC: Done.

RC: 11 18: I think adding Brock et al. (2006) here would be suitable.

AC: Yes, this reference absolutely suits here and has been added.

RC: 11 31: remove “used”.

AC: Done.

RC: 13 1: Again, I think some justification for these two ‘virtual’ points is needed.

AC: To test the influence of the flow direction on the lapse rates and derived surface heat fluxes the location were chosen in a way to have a preferable large vertical altitude difference between the stations. We have given this justification in text: “To illustrate how the flux estimates depend on the local flow conditions, we defined two virtual observation points at Zufallferner, with preferable great vertical altitude differences between the sites (S1 and S2, see Fig. 10).”

RC: 13 2: Change the acronyms here and elsewhere in the manuscript as Z0 and z0 (roughness) are too similar.

AC: We have changed Z0 to S1.

RC: 13 20: It is not clear where in Table 2 that 7 Wm -2 is derived from. Please clarify. Is this underestimated relative to the LES for just the west case, 6.9 Wm-2?

AC: We have rewritten this paragraph:

“On a glacier-scale, the bulk approach underestimates the average heat flux between 5.2 (-16.6%) and 6.9 Wm^{-2} (-20.3%) for the westerly, easterly and northerly flow (see Tab. 2). The local differences for the southerly case, however, almost cancel each other (0.8 Wm^{-2}, 2.2%) .”

RC: 13 26-28: To my understanding, Figure 9 shows the differences in sensible heat fluxes between the LES and bulk method when data are extrapolated using lapse rates (Table 3) between different site combinations. It is not clear however whether a particular wind case (of the LES) is presented in the figure. As mentioned earlier, the naming convention and the way in which it changes between subsections of the paper is confusing and needs changing. Furthermore, although the test of lateral sites is interesting and an important aspect of glacier micro-meteorology to consider, why was site Zb selected in its current position? Was this randomised?

AC: Yes, Fig. 9 shows the differences in sensible heat fluxes between LES and bulk method using the westerly flow case. The site (Zb, now called S3) is located at the boundary of the glacier which is influenced by the cross-valley circulation. We have now given a justification of the choice (see comment above):

"To explore how the choice of observation sites influences the spatial variation of the surface heat flux estimates, we define a set of virtual observation on Zufallferner with distinct flow and advection patterns: (S1) located at the glacier tongue with almost pure katabatic wind (used as reference station), (S2) in the higher region which is influenced by strong heat advection, (S3) at the lateral boundary of the glacier which is influenced by the cross-valley circulation, (S4) closed to S2 but less affected by strong heat advection, and (S5) a second station on the glacier with dominantly katabatic wind. For each combination of S1 and S2-S5 the heat fluxes are estimated according to Eq. 16."

RC: 13 29-30: Re-word "lack to reflect"

AC: We have changed the sentence to: "Evidently, the bulk approach in concert with interpolated temperature fields underestimates the spatial surface heat flux variability."

RC: 13 30: You mention variability in time. However, this paper is only demonstrating statistics for one hour (p6, l27-28). Although it is likely that the bulk approach would poorly represent this temporal variability, Figure 9 does not show it.

AC: That's correct. We have removed the comment on the temporal variability (see comment above).

RC: 13 32: Refer to Table 3 here.

AC: Done.

RC: 14 1: "Similarly, : : :."

AC: Changed.

RC: 14 1: I think it is better to refer to a "shallow" temperature gradient/lapse rate rather than "small", however, the scientific community does not always agree on this and it is a minor point.

AC: We have followed your recommendation and used the expression 'shallow'.

RC: 14 4-5: This is a crucial point, though it could perhaps be supported with measured data as well, which will still represent relative temperature differences at two on-glacier locations (through use of lapse rates) even if the LES isn't designed here to represent the observed absolute values.

AC: Please refer to RC 2, where we have discussed this issue.

RC: 14 7: replace “what generates” with “that generates”.

AC: *Changed.*

RC: 14 12: Perhaps re-word this as we are talking about a much small period of time than just a summer.

AC: *We have re-written the sentence as follows: “The idealized LES experiments demonstrate that heat advection associated with the wind systems shape the thermal conditions on the glaciers during the course of a summer day with clear sky conditions.”*

RC: 14 16: Check the consistency of spelling using British/American English – here referring to “Parametrised” - (http://www.thecryosphere.net/for_authors/manuscript_preparation.html). (See p11, l15 / p12 l9 etc)

AC: *We have checked the consistency of spelling.*

RC: 14 24-25: The difference in lapse rate between Z0-Za and Z0-Zc is strong, presumably due to the heat advection from the south west ridge of Zufallferner (Box R1). I think it would be useful to refer explicitly to this potentially large difference over a small (200 m?) distance on the glacier.

AC: *We have taken up this idea and added the following sentences: “Generally, the sensitivity of the calculated lapse rates to the choice of the observation sites is related to the steep gradients between the advected warm air masses and the ambient cold air masses on the glacier. Shifting stations by even small distances (<= 200 m) can potentially lead to remarkable differences in the calculated lapse rates of ±0.005 Km^{-1}.”*

We very much thank the two reviewer for their thorough analysis of our article and for their valuable comments, annotations and suggested improvements. They had been carefully considered and most of them are accounted for in the revised manuscript. Answers and explanations to all detailed questions and annotations raised by the reviewers are provided in the following.
(RC: Reviewer comments; AC: Author comments)

Comment 1) A still-open key scientific question is highlighted, i.e. how the assumptions generally made for extrapolating meteorological forcing field from sparse point observations impact the estimated local and glacier-wide melting rates. In particular, the focus is on calculation errors of the sensible heat flux distribution. However, the authors quantify this impact only comparing sensible heat flux calculations, whereas it should be assessed in comparison with the overall energy and mass balance (or melt rates).

***AC:** The study focuses on the effect of local advection on the spatial sensible heat flux variation on glaciers and to test the skill of commonly used approaches to estimate the surface heat fluxes at a given point on the glacier. While, without doubt, the impact of the heat flux variation on the glacier mass balance is of major interest, we have focused on the sensible heat flux for the following reasons:*

(i) Many scientific studies have revealed that especially for mid latitude mountain glaciers, the sensible heat flux, after the net radiation budget, constitutes the main energy source and consequently explains a large part of observed glacier ablation (e.g. Braithwaite, 1995; Smeets et al., 1998; Oerlemans, 2010; Gillett and Cullen, 2011; Senese et al., 2012; Conway and Cullen, 2013; Cullen and Conway, 2015). The emphasis of most studies is placed on the averaged turbulence conditions at a given point over glaciers and their impact on the surface energy balance. These studies achieved significant progress by generalizing results with respect to the inherent physical processes or mechanisms at a point scale. The spatial variability of the turbulent quantities, however, has received much less attention than the time averaged quantities.

(ii) As mentioned in the introduction, the complex interaction of glaciers, atmosphere and topography constitutes a fundamental challenge to environmental research. Non-local topographic effects control the micrometeorological conditions on glaciers, but the process itself is challenging to study. In order to reduce the degree of freedom, we exclude all quantities in the idealized simulations which are not directly affected by the flow, but are known to be important for the surface energy balance e.g. radiation divergence, conservation of moisture.

(iii) To study the impacts of the sensible heat flux on the overall energy and mass balance require a direct coupling (online) of the LES with a mass balance module, which we are currently implementing in the LES solver. However, this module introduces additional initial/boundary conditions and requires rather long spin-up times. Without well-posed boundary and initial conditions (e.g. soil properties or moisture), the problem gains complexity and adds additional degrees of freedom.

(iv) The research goal was already very ambitious. There very few studies dealing with LES in (very) complex terrain and in particular over glaciers. However, this study illustrates that there is a potential in studying the surface energy and mass balance on mountain glacier. If LES are useful for real case studies is yet to be answered.

Comment 2) In addition, due to computational restrictions, they only perform calculations for one hour on a clear-sky day in summer 2013. I suggest evaluating the impact of sensible heat flux calculations vs. the surface energy balance, in different meteorological conditions. Moreover, I'm wondering if the mass balance measurements on Langenferner (http://acinn.uibk.ac.at/research/ice-and-climate/projects/langenferner) could be used for estimating the impact on local and glacier-wide melt rates.

***AC:** We agree that the contribution of the sensible heat flux to the surface energy balance is important to understand the impacts on the mass-balance. However, the focus of this study is the* *effect of local advection on the spatial sensible heat flux variation on glaciers and to test the skill of commonly used approaches to estimate the surface heat fluxes at a given point on the glacier (see also Comment 1). In order to understand the impact, the LES (including radiation) must be coupled directly with a distributed mass balance model and integrated over longer time periods. We have re-written the introduction to emphasize our research goals (see Comment 3).*

In order to draw a general conclusion (not only for clear-sky), however, a large number of experiments is needed to cover the wide spectrum of topographic and atmospheric constellations. Unfortunately, we have already reached our computational capacities and try to solve this in an upcoming project. Each LES run of 9 hours' simulation time requires a computational time of 5-7 days on a High-Performance Computer with 400 cores. For that reason, we have focused on a clear-sky case of which we have expected pronounced thermal wind phenomena and heat advection. The latter one is an important process to understand the thermal conditions on glaciers.

The timescale of our simulations is a few hours, while the scale of mass balance measurements and stake readings is several weeks to months. Consequently, the direct measurements cannot be used for any impact assessments. Our study is motivated by the findings of many previous studies which prove the general importance of the sensible heat flux for mid latitude glacier melt (e.g. Klok and Oerlemans, 2002; Oerlemans, 2010; Gillett and Cullen, 2011; Senese et al., 2012; Conway and Cullen, 2013; Cullen and Conway, 2015).

Comment 3) The authors claim that 'the pseudo-reality atmosphere is not required to be an observed real world case, but needs to be plausible in the sense that relevant processes are realistically simulated'. It is unclear what is meant with relevant processes. In section 4 the authors say that sections 3.1, 3.2 and 3.3 demonstrate that LES capture these relevant processes, but in these sections there is only a description of model results (some of them are obvious) and complete absence of comparison with real-world observations. In my understanding, the plausibility and realism of LES is only assessed based on the authors' personal knowledge of the atmospheric circulation over mountainous terrain, but I'm not sure that it is sufficient. On the other hand, Figure 1 shows several weather stations in the study area. Why not using these data for checking the realism of calculations? How can it be assessed that LES is superior to the bulk approach, without any comparison with real-world observations?

***AC:** In an idealized setup, the surrogate atmosphere can only be compared with well-known characteristics of boundary layers and dynamical atmospheric features obtained from in-situ measurements on alpine glacier. These characteristics include the vertical (wind and temperature), sensible heat flux and turbulent structure of the boundary layer and should be of the same order of magnitude as the measurements. In Section 3.1 and 3.2 we compare the wind magnitude, LLJ, intermittency and turbulence scales with observation made by other studies. For example:*

i) *The wind magnitudes are characteristic for mountain glacier during clear sky conditions (e.g. Van den Broeke, 1997; Söderberg and Parmhed, 2006).*

ii) *Several studies observed intermittent turbulent mixing events in the SBL above glaciers and analyzed their impact on the surface energy balance (e.g. Cullen et al., 2007; Oerlemans and Grisogono, 2002; Söderberg and Parmhed, 2006; van den Broeke, 1997; Smeets et al., 1998; Munro and Davies, 1978; Hoinkes, 1954; Kuhn, 1978; Munro and Scott, 1989).*

Additional comment: Modelling the intermittency in stable boundary layers is very challenging and most numerical modelling studies, which are usually RANS model, do not capture these events. Our studies prove that LES are able to simulate such events, if the horizontal and vertical model resolution is sufficiently small to resolve most of the kinetic energy.

iii) *The scales are in the same order of magnitude as those found by other studies (e.g. Litt et al., 2015; Söderberg and Parmhed, 2006).*

Additional comment: Stable boundary layers show characteristic turbulence scales for the horizontal and vertical components. The simulation results show similar scales to those measured by other studies, which supports the choice of the grid resolution (that most TKE is resolved by the model) and the reliability of the subgrid-scale model (see later comment).

The comparison of the idealized LES simulations with the real-world observation is not possible. During the week of the 17th August 2014 we had temporarily installed two weather stations, one closed to Z1 on Zufallferner and another further down the valley. The glacier station measured between 13 and 14 h a mean wind velocity of 4.6 m/s at 2 m height above the surface. Even though this is closed to the simulated value (4.5-6 m/s, westerly flow), the two values are not comparable at all. The prescribed surface heating rate (1.2 K/h) of the surroundings is lower than the measured heating rate (4.1 K/hr) at that particular day. Furthermore, the idealized simulations do not account for differential heating by radiation which is important during the first two hours and leads to asymmetric cross-valley winds. Without doubt, the homogenous heating assumption is a major drawback of the code. Although the chosen heating rate is significantly lower and shadowing effects are absent the typical low level jet and the heat advection from the lateral boundaries are present. As indicated in the conclusion, due to conservative chosen boundary conditions the simulated advection effects might be weaker than the one observed in a real atmosphere.

We think there is a confusion why we use a surrogate atmosphere and what is the overall goal of this study. Therefore, we have updated the penultimate paragraph in the introduction as follows:

"To overcome this difficulty, we make use of high resolution Large-Eddy Simulations (LES). The LES are considered as pseudo-reality - a testbed to identify the shortcomings in the local surface heat flux estimates when the lack of observations restrict our micrometeorological knowledge to a few sites. The plausibility of the temperature interpolation algorithms and the derived surface heat fluxes can be more strictly tested in a surrogate world of atmospheric simulations, which offers a realization of atmospheric states in which all target variables are known. The pseudo-reality atmosphere is not required to be an observed real world case, but needs to be plausible realization of the atmosphere in the sense that relevant processes are realistically simulated. The advantage of such studies is that the surrogate atmosphere provides a perfect pseudo-observation of all the variables required to establish the skill of an interpolation method and hence the surface heat flux calculations. While surrogate atmospheres have been widely used in downscaling studies it's still a new approach in glaciological studies (Frias et al., 2006; Vrac et al., 2007; Maraun, 2012)."

We hope this emphasizes our overall goal to test the plausibility of interpolation algorithms and its consequences on the surface heat flux estimates. We neither make a statement that LES is superior to the bulk approach nor we claim it is a real case. It is simply a surrogate world of atmospheric states.

Comment 4) There is confusion between point-site process understanding and interpolated/extrapolated input meteorological fields from sparse meteorological observation coming from on-glacier sites. If it's true and obvious that process understanding at individual sites is not sufficient to fully characterise the micrometeorological conditions over glacier surfaces, the practical or operational need to achieve such full characterization remain questionable (and in any case is not quantified in this paper).

AC: *In fact, most scientific studies on glacier wide energy and mass balance are based on simple extrapolations of meteorological variables. Many of them use approaches based on linear gradients to create micrometeorological fields, while at the same time they report significant limitations in reproducing the spatial and temporal variability of glacier mass balance (e.g. MacDougall and Flowers, 2011; Gurgiser et al., 2013a; Prinz et al., 2016). This deficiency is also related to* *shortcomings in the representation of sensible heat flux, since the sensible heat flux has proven to explain a great part of the melt energy and its variability at many glaciers (e.g. Braithwaite, 1995; Klok and Oerlemans, 2002; Gillett and Cullen, 2011; Conway and Cullen, 2013; Cullen and Conway, 2015). Based on the explanations presented above and the findings of the cited works, we think that there is no doubt about the scientific need of better and more realistic characterization of the micrometeorological conditions over glacier surfaces.*

Comment 5) Interpolation/extrapolation of meteorological data from on-glacier sites has limited practical usefulness. In operational model applications, there are almost no input data coming from inside the glaciers. In particular, I refer to applications aimed at exploring the climate sensitivity of glaciers, which is mentioned by the authors. Because the climatic sensitivity can be defined as 'the ratio of changes in the 2 m temperature above a glacier to changes in the temperature outside the thermal regime of that glacier (Greuell and Böhm, 1998), there is little usefulness in testing the errors coming from interpolation/extrapolation of pseudo-observed (or better, calculated) wind and temperature coming from points located inside the glaciers.

AC: *It is unclear what the referee means by "practical" and "operational". We however, try to address a well-defined research problem, namely the extrapolation of point observations of governing (micro-) meteorological parameters (temperature and wind) to a larger spatial scale.*

There is a large number of studies focusing on glacier wide energy and mass balance modelling based on point observations. Some of them use on-glacier data (e.g. Hock and Holmgren, 2005; Sicart et al.,2005; Mölg et al., 2008, Reijmer and Hock, 2008; Mölg et al., 2009; MacDougall and Flowers, 2011; Sicart et al., 2011; Huintjes et al., 2015; Prinz et al. 2016), while others make recourse of off-glacier observations (e.g. Arnold et al., 1996; Klok and Oerlemans, 2002; Klok and Oerlemans, 2004; Gurgiser et al., 2013a; Gurgiser et al., 2013b)

The definition of "climatic sensitivity" as used by the referee and presented by Greuell and Böhm (1998), is not directly applicable to our research topic since we use the term "climate sensitivity" as an expression of a glaciers change in mass balance (rate) in response to a defined change in the ambient climate conditions (e.g. Oerlemans and Grisogono, 2002; Klok and Oerlemans, 2004; Mölg et al., 2008 and many more). The turbulent sensible heat flux plays a key role in process based analyses of climate change impacts to glaciers as it largely governs (together with longwave radiation) the sensitivity of a glacier to changes in air temperature (e.g. Braithwaite, 2009 and references presented above).

We agree that when the reaction of a glacier to changes in climate is examined, data from outside the (also changing) glacier boundary layer should be used (e.g. Klok and Oerlemans 2002). Nevertheless, this does not influence our conclusions since the main uncertainty potential in the calculation of micrometeorological fields highlighted by the current study is less determined by the origin of the observation data (on- or off-glacier), than by the applied extrapolation method. Consequently, our findings are not only valid for micrometeorological fields calculated from on-glacier stations, but for any kind of studies using linear gradients of temperature and wind to up-scale respective data.

However, our intention is to point out that the variations of the sensible heat flux in space and time cannot be sufficiently captured by simplified approaches. This may be negligible for glacier wide calculations of mass balance or melt during shorter time spans. But since especially mountain glaciers all over the world are currently undergoing rapid changes in shape/areal extent, the applied gradients might be not constant over longer time periods as changes in glacier extent influence the local microclimates. The same problem may appear under extraordinary conditions, such as for instance abnormal snow cover in the vicinity of the glacier, or years with changed mean synoptic flow, or other circumstances not reflected in the reference data set which was used to calculate the *gradients. It is hence obvious that more sophisticated methods are urgently needed to foster the understanding of the physical processes behind glacier changes.*

Comment 6) It could be more useful to test calculation schemes recently proposed in the literature (cited by the authors) starting from off-glacier weather stations.

AC: *We think the reviewer makes a good point and we have followed its recommendation and tested the Shea and Moore (2010) and the Greuell and Böhm (1998) temperature model. The Shea-model estimates the near-surface temperature on the glacier from the ambient temperatures using a piecewise linear regression approach. The model consists of our regression coefficients (T1, T_*, k1, k2), which need to be estimated for each station. The estimated coefficients are then related to morphometric measures, such as flow path length (FLP) and elevation. The estimation of the FLP is not trivial for unstructured grids and we had to develop our own code/algorithm to derive this measure. The code is based on a backtracking line search algorithm driven by local gradients. The attached Figure 1 shows the FLP estimates of the investigation area.*
However, the lack of observations (only one observation at each station) makes it impossible to estimate the coefficients T1, T, k1 and k2 of the Shea-Model. We made some efforts using coefficient proposed by Shea and Moore (2010) and Carturan et al. (2015), but the model is very sensitive to the parameter choice. Additionally, relating these coefficients to the morphometric measures would introduce further seven coefficients. In our specific case, the problem is not well-posed at all and its impossible to calibrate the model.*
Besides the Shea-model we also applied the temperature model proposed by Greuell and Böhm (1998). Basically, the model solves the change of heat within an air parcel travelling down an infinite slope. The approach requires the height of the katabatic wind H, the bulk transfer coefficient for heat C_h, FPL, a characteristic length, a location x_0 where the katabatic layer influences the air parcel, the mean slope, and the temperature T0 of the air parcel at x0. Most parameters can be calculated, except for x_0 which has to be determined. In literature different values for x_0 are given, ranging from 542 m. (Ayala et al. (2015)) to 1440 m (Carturan et al. (2015)). We have assumed a value of 1000 m for the analysis. The model was fitted to the observations by optimizing C_h. The model has been calibrated for each experiment using the same observations (S1 and S2) used for the linear interpolation. The estimated surface heat fluxes are 35.5 Wm-2 (westerly flow), 26.4 Wm-2 (easterly flow), 31.5 (northerly flow), and 28.8 Wm-2 (southerly flow).

We have updated Section 4.1 accordingly.

Specific comments

RC: Page 1 line 5 and 7: please add the percentage in under-overestimations, and also the percent error in mass balance calculations. Small-scale heat flux, glacier heat fluxes... please be consistent throughout the paper and try to use always the same wording (i.e. sensible heat flux)

AC: *The focus of this study is the effect of local advection on the spatial sensible heat flux variation on glaciers and to test the skill of commonly used approaches to estimate the surface heat fluxes at a given point on the glacier and not the glacier mass balance. To do so the LES (including radiation) must be coupled directly with a distributed mass balance model and integrated over longer time periods. We are currently working on the coupling of the LES with a mass balance model.*

We follow the recommendation of the reviewer and use the term sensible heat flux throughout the text.

RC: Page 1 line 8 and 9: it is unclear if site selection and flow direction refer to data measurements, extrapolations, or validations

AC: *We have re-worded the sentence to clarify that the site selection refers to the extrapolated data: "The sign and magnitude of the differences depend on the site selection which are used for extrapolation as well as on the large-scale flow direction.".*

RC: Page 1 line 9-11: this is not adequately quantified in the paper. The magnitude of sensible heat flux calculation errors and their impact on the surface energy balance and on the derived climate sensitivities should be calculated and several numbers should be added also here in the abstract.

AC: *As discussed in the Comments 2,5 and the first specific comment, we do not quantify the impact of the errors in the sensible heat flux on the surface energy balance. We have decided to remove the last sentence from the abstract to avoid misunderstanding.*

RC: Page 2 line 10: consider replacing 'can make over' with 'can represent'

AC: *Done.*

RC: Page 2 line 13: consider removing 'peculiar'. In this period it is partly unclear to which mass balance studies dealing with small scale variations of melt rates the authors are referring to

AC: *The word 'peculiar' has been replaced by 'particular'.*

The sentence has been re-phrased as follows: "Therefore, a profound knowledge of the advection processes and the micrometeorological characteristics is required to accurately calculate melt rates and their variations in space and time."

RC: Page 2 line 16: what is meant exactly with 'the deficiency of monitoring activities'?

AC: *With 'deficiency' we refer to a falling short of a desirable number of observations. We think this is an unambiguous expression.*

RC: Page 2 line 26: an open scientific question

AC: *Done.*

RC: Page 2 line 27: be fully answered

AC: *Done.*

RC: Page 2 line 28: I suggest to state more clearly the aim(s) of the study

AC: *In the last two paragraphs of the introduction we now stress in more detail the aim of the paper (see also comment above):*

"To overcome this difficulty, we make use of high resolution Large-Eddy Simulations (LES). The LES are considered as pseudo-reality - a testbed to identify the shortcomings in the local surface heat flux estimates when the lack of observations restrict our micrometeorological knowledge to a few sites. The plausibility of the temperature interpolation algorithms and the derived surface heat fluxes can be more strictly tested in a surrogate world of atmospheric simulations, which offer a realization of atmospheric states in which all target variables are known. The pseudo-reality atmosphere is not required to be an observed real world case, but needs to be plausible realization of the atmosphere in the sense that relevant processes are realistically simulated. The advantage of such studies is that the surrogate atmosphere provides a perfect pseudo-observation of all the variables required to establish the skill of an interpolation method and hence the surface heat flux calculations. While surrogate atmospheres have been widely used in downscaling studies it's still a new approach in glaciological studies (Frias et al., 2006; Vrac et al., 2007; Maraun, 2012)."

RC: Page 3 line 19-20: SBL, SGS, please define acronyms

AC: *Done. SGS refers to subgrid-scale and SBL to stable boundary layer.*

RC: Page 4 line 9-10: it has been recognized

AC: *Changed.*

RC: Page 4 line 13-14: the negligibility of assumptions should be demonstrated and/or possible errors coming from assumptions should be quantified

AC: *We have added the following explanation to justify our assumption:*

"Quantifying possible errors coming from this assumption or the model performance is challenging. The model can be tested either by a priori or a posteriori testing. The a priori test uses experimental or Direct Numerical Simulations (DNS) data to relate directly the residual-stress tensor given by the closure model. In an a posteriori test the accuracy of calculated statistics, such as mean wind or momentum flux, are compared with experimental data. Most LES approaches use a posteriori test to prove its applicability. Churchfield et al. (2014) has tested the Smagorinsky and bounded dynamic Langrangian model with the GABLS inter-comparison project (Global Energy and Water Cycle Experiment Atmospheric Boundary Layer Study, Beare et al., 2006) using a 6 m grid resolution. They found that both models are in line with the mean vertical profiles of wind speed, direction, potential temperature and variances. We therefore assume, that the backscatter of energy from the SGS model towards the resolved scales is negligible, if the LES resolves most of the turbulent kinetic energy (see Section 3.4)."

We have also added the following text to Section 3.4: "When decreasing the horizontal grid resolution to 25 m the resolved kinetic energy was only 60-70%. Additionally, a coarser grid leads to greater aspect ratios of the prismatic layers, which requires very short integration time steps (0.01 s) to guarantee stability. Increasing the prismatic layer heights is problematic since this affects the shear stress and momentum calculations closed to the surface. The choice of ~12.5 m is a good *tradeoff between computational costs and resolved scales."*

And in Section 3.4:

"We have also tested the dynamic Smagorinsky model, but the simulations are found to be unstable due to large fluctuations of C_s."

RC: Page 4 line 19-22 and page 6 line 14-16: please see the previous comment on assumptions

AC: *It has been shown that the Lagrangian dynamic model, which averages C_s over some volume backward in time along fluid particle paths, is appropriate for inhomogeneous flows (e.g. Pope, 2000; Anderson and Meneveau, 1999; Sarghini et al., 1999). It has been also successfully applied to the GABLS experiment (Churchfield, 2014), and complex terrain (Bou-Zeid et al., 2005). The references have been given in the text.*

RC: Page 6 line 23: I suggest adding some references for aerodynamic roughness heights

AC: *Done.*

RC: Page 6 line 25: ERA-Interim reanalysis data (also p5 l21)

AC: *Done.*

RC: Page 6 line 27-28: from which hour to which hour of the day?

AC: *The model has been initialized with the ERA-Interim profile from 06 UTC and a uniform surface temperature of 273.16 K (Section 2.3). Starting with the initial condition the model is integrated over a period of 9 hours. On p6L28 we refer to the last simulation hour. We have now added this information.*

Please note that the idealized simulations do not account for differential heating by radiation (shading effect). The surface temperature of the surrounding is given by the prescribed surface heating rate (1.2 K/h). At the end of the simulation the surface temperature is 10.8 K.

RC: Page 7 line 9-12: this part is somewhat unclear and it looks like the authors adjust the DEM (the only real-world component in this work) to the requirements of the numerical model. Is it correct? Please see comment to Page 4 line 13-14

AC: *Yes, we have relaxed the DEM to make use of period boundary conditions. Such boundaries require that faces on the opposite boundary (faces of grid cells) are equal within a certain tolerance. This is only possible, if the DEM grid points are equal on opposite boundaries. To do so the DEM grid points on opposite boundaries have been slowly displaced to match each other. The inner grid points are relaxed to get a smooth transition from the boundaries towards the inner domain. We have added a new figure showing a sketch of the relaxation procedure.*

RC: Page 9 line 4: please reword 'the intensity of the cross-valley circulation' to improve clarity

AC: We have re-worded this part by: "the intensity of the slope winds".

RC: Page 9 line 23-24: consider replacing 'do not jointly appear with high wind velocities' with something like 'do not appear in the areas with high wind velocities'

AC: Done.

RC: Page 10 line 34: can you quantify (or estimate) the percent contribution of the sensible heat flux to the total energy balance in your case study? This would be important for understanding the impact of calculated sensible heat flux on local-scale and area-averaged energy and mass balance

AC: We agree that the contribution of the sensible heat flux to the total energy balance is important to understand the impacts on the mass-balance. However, the focus of this study is the effect of local advection on the spatial sensible heat flux variation on glaciers and to test the skill of commonly used approaches to estimate the surface heat fluxes at a given point on the glacier. In order to understand the impact, the LES (including radiation) must be coupled directly with a distributed mass balance model and integrated over longer time periods.

RC: Page 11 line 10-11: can you provide some numbers in support to this statement?

AC: The intermittency is a local and non-stationary process. The standard deviation of the vertical velocity fluctuations, $\sigma_{w,}$ are low on the glacier (see Fig. 4) but are heavily right-skewed which indicates occasional mixing events. The power spectrum of the temperature signal shows that there are variations in the frequency of occurrence and amplitude of the mixing events. The scale-average time series show that there are average variances of up to 4.0 C^2. These burst events supply temporarily heat to the surface layer and the surface heat flux increases. This signal is neither present in the mean surface heat flux (Fig. 6) nor in the mean potential temperature (Fig. 7). We have now included references to the corresponding figures and chapters.

RC: Section 3.4: in Figure 1 two weather stations are shown on the glaciers. Why data coming from these weather stations were not used for checking the reliability of LES experiments?

AC: Please check back on comment 2, where we give an explanation why we can't compare the idealized LES with weather station data.

RC: Page 11 line 19-23: with the authors, I recognize that this is a strong assumption, in particular over glaciers with such high range of elevation (2595-3750 m), quite different from the end-of-summer situation reported for Arolla by Brock et al., (2000). It should be possible to map the snow cover for the selected day, or to use another day with available snow cover data (e.g. from Landsat imagery). Alternatively, the authors should at least quantify the possible errors stemming from this assumption.

__AC:__ We know from the fields measurement during this period that there was a thin layer of fresh snow on the glacier. However, from that particular day there is no Landsat imagery available. Again, we like to remember these are idealized simulations and not real cases. Nevertheless, we have re-written the sentence as follows: "We assume similar roughness height for snow and ice since large parts of the glaciers were covered by a thin layer of fresh snow.".

RC: Page 12 line 2-3: on which bases the authors say that the SGS model 'seems to work well' in their study?

__AC:__ In LES, the dynamics of the larger-scales are computed explicitly, while the smaller scales (residual stress tensor) are represented by the SGS model. Generally, the SGS model removes energy from the resolved scales to the residuals. In an a posteriori test we can test the accuracy of calculated statistics, such as mean wind or momentum flux, are compared with well know data from field experiments. We have shown that the calculated statistics, such as the integral turbulence scales, skewness and vertical velocity variance, are in the same order of magnitude as those obtained from observations. If the SGS model is too dissipative, the calculated measures would significantly differ from observations. In this pseudo-reality setup, it is difficult to prove the correctness of the SGS model. We have also tested the dynamic Smagorinsky model, but the simulations are found to be unstable due to large fluctuations of C_s.

We have added a new paragraph at the end of Section 3.4 to justify our conclusion:

"We have shown that the calculated statistics, such as the integral turbulence scales, skewness and vertical velocity variance, are in the same order of magnitude as those obtained from observations (e.g. Litt et al., 2015; Söderberg and Parmhed, 2006). If the SGS model is too dissipative, the calculated measures would be significantly lower than the observations. Which SGS model works best for stable boundary layers is not easy to tell, but the Lagrangian-averaged SGS model seems to work well in our study. We have also tested the dynamic Smagorinsky model, but the simulations are found to be unstable due to large fluctuations of Cs."

RC: Page 12 line 4: maybe reword the title as 'Estimation of the sensible heat using the Bulk-Approach'

__AC:__ Done.

RC: Page 12 line 20: replace 'given that' with 'in case' (I guess that it is meant where there is a weather station measuring the required variables)

__AC:__ Done.

RC: Page 12 line 20-27: please consider moving this part in the following section

__AC:__ We followed the recommendation and moved this part in the following section.

RC: Page 12 line 26-27: this is a strong statement, because there is complete absence of comparison between modelled and observed (relevant) processes. What are relevant processes? How can the authors assess that LES captures observations, without reporting observations or without citing literature on this topic?

AC: *Again we emphasize that the surrogate atmosphere can only be compared with well-known characteristics of stable boundary layers and dynamical atmospheric features obtained from in-situ measurements on alpine glacier (see comment 2). These characteristics include the vertical profiles (wind and temperature), sensible heat flux and turbulent structure of the boundary layer and should be of the same order of magnitude as the measurements. In Section 3.1, 3.2 and 3.3 we compare the wind magnitude, LLJ, intermittency and turbulence scales with observation made by other studies. We have shown that the calculated statistics, such as the integral turbulence scales, skewness and vertical velocity variance, are in the same order of magnitude as those obtained from observations (e.g. Litt et al., 2015; Söderberg and Parmhed, 2006).*

We have re-written this sentence as follows:

"As demonstrated in Sec. 3.1, 3.2 and 3.3, the LES provide plausible vertical wind and temperature profiles, surface heat fluxes and turbulent structures of the boundary layer."

RC: Page 13 line 3: please replace 'pseudo-observed' with 'calculated'. I guess these are temperature and wind speed data calculated using LES, is it right? Please specify

AC: *The sentence now reads as:*

"The simulated (LES) wind velocities and temperatures at the two sites were linearly extrapolated across the glacier (e.g. Paul and Kotlarski, 2010; Machguth et al., 2009; Huintjes et al., 2015; Weidemann et al., 2013; Jarosch et al., 2012)."

RC: Page 13 line 5: surface heat flux, surface sensible flux, or surface sensible heat flux? Please be consistent

AC: *We have check the manuscript for consistency.*

RC: Page 13 line 7-9: please explain why there are differences at the two Za and Z0 sites, given that (in my understanding) wind speed and temperature at these sites are the same using the bulk method and the LES (i.e. they differ in the rest of the analysed area, but not at Za and Z0).

AC: *This is correct. The differences at the locations should be zero, but there are small differences of about 1-3 Wm^{-2}. The sensible heat flux from the LES is calculated online at each time step. The fluctuating L_s and U can significantly increase the calculated sensible heat flux over a short time period. For the bulk approach we used the mean L_s and U calculated over the last hour, which could cause small differences in the calculations. If there is only a small difference from zero the station is attributed to one of the contour classes and it might seem that there is a large difference between the LES and the bulk method at the two sites.*

RC: Page 13 line 20: the average sensible heat flux (please, add % error in the text). How big is the impact on glacier-wide total energy balance calculations?

AC: *The sentence now reads as:*

"On a glacier-scale, the bulk approach underestimates the average heat flux between 5.2 (-16.6%) and 6.9 W m−2 (-20.3%) for the westerly, easterly and northerly flow (see Tab. 2). The local differences for the southerly case, however, almost cancel each other out (0.8 W m−2, 2.2%)."

We have not computed the glacier-wide total energy balance and therefore cannot estimate the impact of the differences on the energy balance (see comment above).

RC: Page 13 line 27: for which wind direction?
RC: Page 13 line 28: using linear extrapolations across the glaciers?

***AC:** We now explicitly mention the wind direction:*

"In the following, we estimate the sensible heat flux according to Eq. 17 for each combination of S1 and S2-S5 using the linearly extrapolated temperature and mean wind velocity (the mean value of the two sites) from the westerly flow case."

RC: Page 13 line 29: in my opinion there is an equivocal use of the term 'bulk method', which is a method for calculating turbulent exchanges, referred to the calculations using linear extrapolations across the glaciers. I would suggest clarify/avoid ambiguities

***AC:** Yes, we agree that the term 'bulk estimate' is not used correctly. We have re-worded the sentence as follows:*

"Fig. 11 shows the differences between the sensible heat fluxes calculated by the bulk approach and the surrogate atmospheres."

RC: Page 13 line 33 and in the following: please check or clarify, if gradients are too large (in absolute value) underestimations of temperature and sensible heat flux should occur in the upper parts of the glaciers. Moreover, in absence of model validation, why the LES model has to be the right one and the Bulk has to be the wrong one, a priori?

***AC:** Yes, this statement is wrong. The correct statement is:*

"In the case that stations are located in a region of strong temperature advection (e.g. case S1-S2 and S1-S3) the derived temperature gradient is too shallow, and the bulk approach overestimates the sensible heat fluxes in most regions of the glacier. Similarly, temperature gradients are too steep when stations are protected from warm air transport, and on average fluxes are underestimated (e.g case S1-S4 and S1-S5)."

As initially mentioned (comment 3), we neither make a statement that LES is superior to the bulk approach nor we claim it is a real case. It is simply a surrogate world of atmospheric states. The advantage of such studies is that the surrogate atmosphere provides a perfect pseudo-observation of all the variables required to establish the skill of an interpolation method and hence the surface heat flux calculations.

RC: Page 14 line 3: also in this case I suggest to calculate the relative importance of these errors in the overall energy balance of the glacier

AC: Please see our response to the first specific comment.

RC: Page 14 line 5-8: this part is methodological and should be moved at the beginning of Sect. 4.2. It also deserves rephrasing to improve clarity

AC: The part has been re-written and moved to the beginning of Sec. 4.2

"This approach has two major implications: i) the temperature field is completely decoupled from the flow and therefore disregards local flow features (e.g. gap flows and bluff bodies), and ii) the wind velocities are too low over large areas on the glacier."

RC: Page 14 line 12: it is unclear why the authors selected only a clear-sky case study

AC: In order to draw a general conclusion, however, a large number of experiments is needed to cover the wide spectrum of topographic and atmospheric constellations. Unfortunately, we have already reached our computational capacities and try to solve this in an upcoming project. Each LES run of 9 hours' simulation time requires a computational time of 5-7 days on a High-Performance Computer with 400 cores. For that reason, we have focused on a clear-sky case of which we have expected pronounced thermal wind phenomena and heat advection.

RC: Page 14 line 17-22: I have several points, which could/should be at least partly addressed or discussed in the manuscript. In particular they concern: i) the practical or operational need to fully characterise the micrometeorological conditions over glacier surfaces; ii) the linear extrapolation of forcing fields from sites placed over glaciers (again, almost never available in practical model applications); iii) related to the previous point, the climate sensitivity has to be assessed with respect to climatic conditions
observed outside the microclimatic influence of the glaciers.

i) This issue has been addressed in Comment 4
ii) This issue has been addressed in Comment 5
iii) This issue has been addressed in Comment 5

RC: Page 14 line 20: here and elsewhere, I suggest speaking about differences and not errors, because the comparison is between calculations and not between calculations and observations

AC: Yes, we agree and have changed the wording.

RC: Page 14 line 30: percent error of what?

AC: The number gives the mean error by which the bulk approach differs from the actual LES values. We have added this information to the number.

RC: Page 15 line 1-2: when small-scale variations of surface energy balance are required? Please add this in the introduction and recall it here and/or in the abstract

AC: The phrase now reads as: "We can conclude that a profound knowledge of the heat advection process is needed when small-scale variations of surface energy balance are required for distributed mass balance studies."
The need for small-scale variation of the sensible heat flux for accurate melt rates and their variation in space and time has been made more clear in the introduction.

RC: Page 14 line 6: using off-glacier stations for what?

***AC:** We have removed this part of the sentence.*

Comments on the figures and tables:

RC: Figure 1: this image lacks east-north coordinates or inset displaying wider geographical setting of the study area. Four weather stations are reported, whose data are not used in this paper

***AC:** Done.*

RC: Figure 2 (and following maps): I suggest adding some contour line (or hillshaded DTM, like in Fig. 1), which is needed for a better understanding of the local topography and of its effects on the calculated variables

***AC:** Actually, the figures do have a hillshading, but the glacier surface is very smooth so that it is not particularly eye-catching. We have made an attempt to add some contour lines to the figures, but the figures appear overloaded due to its small size. We would prefer to keep the figures as they are and think that Figure 1 gives all the essential information.*

RC: Figure 9: in the caption just begin with 'differences in the surface....' and correct pseudo-observations coherently with the text

***AC:** Done.*

RC: Table 3: I suggest adding LES estimates and % differences (not error, please correct also in Table 2) as in Table 2.

***AC:** The bulk estimates are always compared to the same LES case (westerly flow, 33.8 Wm^{-2}). Therefore, we think it is not necessary to include the LES estimate in Table 3. However, the % differences have been added to Table 3.*

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Effects of local advection on the spatial sensible heat flux variation on a mountain glacier

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Abstract.

Distributed mass balance models, which translate micrometeorological conditions into local melt rates, have proven deficient to reflect the energy flux variability on mountain glaciers. This deficiency is predominantly related to shortcomings in the representation of local processes in the forcing data. We found by means of idealized Large-Eddy Simulations that heat advection, associated with local wind systems, cause small-scale sensible heat flux variations by up to 100 $\mathrm{Wm^{-2}}$ during clear sky conditions. Here we show that process understanding at a few ~~on-glacier~~ observation sites is insufficient to infer on the wind and temperature distributions across the glacier. ~~On average, glacier~~ The glacier-wide hourly averaged sensible heat fluxes are both over- and underestimated by up to 16 $\mathrm{Wm^{-2}}$ when using extrapolated temperature and wind fields. The sign and magnitude of the ~~errors~~ differences depend on the site selection which are used for extrapolation as well as on the large-scale flow direction. Our results demonstrate how the shortcomings in the local sensible heat flux estimates are related to topographic effects and the insufficient ~~characterisation~~ characterization of the temperature advection process. ~~The magnitudes of the surface heat flux errors are strong enough to significantly affect the surface energy balance and derived climate sensitivities of mountain glaciers.~~

1 Introduction

The complex interaction of glaciers, atmosphere and topography constitutes a fundamental challenge in glaciological research. Countless studies aim to identify the climatic drivers behind observed glacier changes by using distributed mass and energy balance models (e.g. Arnold et al., 1996; Hock and Holmgren, 2005; Klok and Oerlemans, 2002; Mölg et al., 2009). While these kind of models summarize our understanding of the governing physical processes at a point scale, they have proven deficient to reflect the variability of the energy and mass fluxes on mountain glaciers (e.g. Gurgiser et al., 2013; MacDougall and Flowers, 2011; Prinz et al., 2016). The ~~loss of information in space and time~~ reduced spatial and temporal variability predominantly results from shortcomings in the forcing data, which in turn expresses the need for better representation of the local processes.

While large-scale weather shapes the environmental conditions in which mountain glaciers exist, the mass and energy exchange on individual glaciers is controlled by the micrometeorological conditions. Given the complex topography around mountain glaciers with its contrasting surface characteristics, it is not trivial to bridge the scale gap between the large-scale conditions and the local characteristics. The micrometeorological condition of the surface layer is directly influenced by the presence of the earth's surface and quickly responds to changes in the surface energy budget. The radiative and turbulent heat fluxes cool and heat the near-surface air layer and determine the temperature distribution across the topography. Local temperature excess and deficit create buoyancy forces that drive the thermal wind systems, including the valley circulations, slope and glacier winds (e.g. Munro and Scott, 1989; Oerlemans and Grisogono, 2002; Sicart et al., 2014; Smeets et al., 2000; van den Broeke, 1997). The thermal wind phenomena are often superimposed and partly overwhelmed by the dynamically-driven winds, which in turn are ~~characterised~~ characterized by topographic effects. Heat advection associated with the mean flow and intermittent turbulent mixing events alter the thermal conditions and, finally, link it to the large-scale weather.

The fluctuations of the thermal conditions are of practical interest for distributed glacier mass balance studies. For example, winds may advect warm air from the surroundings towards the glacier which locally increase the downward directed sensible heat flux (Ayala et al., 2015; Shea and Moore, 2010; Hannah et al., 2000; Moore and Owens, 1984; Strasser et al., 2004). The energy surplus can be critical for the ablation, considering that the turbulent heat flux can ~~make over~~ represent 50% of the total energy during ~~large~~ pronounced melt events on maritime mid-latitude mountain glaciers in summer, and even up to 30% on continental glaciers (e.g. Cullen and Conway, 2015; Gillett and Cullen, 2011; Van den Broeke, 1997; Hock, 2005; Klok and Oerlemans, 2002; Oerlemans and Klok, 2002; Giessen et al., 2008; Moore and Owens, 1984). Therefore, ~~whenever small scale variations of the melt rates are of peculiar interest,~~ a profound knowledge of the advection processes and the micrometeorological characteristics is ~~needed~~required to accurately calculate melt rates and their variations in space and time.

A fundamental obstacle in studying small-scale boundary layer characteristics is, that even on well-studied mountain glaciers, the deficiency of monitoring activities restricts the process understanding, required for detailed research, to a few sites and limited time periods (e.g. Wagnon et al., 1999; Mölg and Hardy, 2004; Obleitner and Lehning, 2004; Reijmer and Hock, 2008; Nicholson et al., 2013). The phenomenological knowledge that is valid for the specific location and weather situation does not have greater significance beyond the case (e.g. Machguth et al., 2006; Gardner et al., 2013; Zemp et al., 2013). This constraint makes it challenging to infer on micrometeorological conditions from a limited number of observations. Glaciological modelling studies typically circumvent this obstacle by constructing meteorological forcing fields, e.g. for temperature and wind, from scattered observations using fixed or variable lapse rates (e.g. Greuell and Böhm, 1998; Carturan et al., 2015; Ayala et al., 2015; Petersen et al., 2013; Huintjes et al., 2015; Weidemann et al., 2013; Jarosch et al., 2012). The interpolated fields then serve for the estimation of turbulent fluxes at any given point on the glacier. As a result of the simplified assumptions, the modelled sensible heat flux distribution is unlikely to truly reflect the full variability in time and space. It is still an open scientific ~~issue~~ question how these assumptions impact the estimated local and glacier-wide melting rates (e.g. Immerzeel et al., 2014; Shaw et al., 2016). However, this question cannot be fully answered by means of a few individual observations.

To overcome this difficulty, we make use of high resolution Large-Eddy Simulations (LES). The LES are considered as pseudo-reality - a testbed to identify the shortcomings in the local ~~surface~~ sensible heat flux estimates when the lack of observations restrict our micrometeorological knowledge to a few sites. The plausibility of the temperature interpolation algorithms and the derived sensible heat fluxes can be more strictly tested in a surrogate world of atmospheric simulations, which offer a realization of atmospheric states in which all target variables are known. The pseudo-reality atmosphere is not required to be an observed real world case, but needs to be ~~plausible~~ a plausible realization of the atmosphere in the sense that relevant processes are realistically simulated. The advantage of such studies is that the surrogate atmosphere provides a perfect pseudo-observation of all the variables required to establish the skill of an interpolation method and hence the sensible heat flux calculations. While surrogate atmospheres have been widely used in downscaling studies, this approach is still novel in glaciological studies (e.g. Maraun, 2012; Vrac et al., 2007; Frias et al., 2006).

After a brief description of the LES model (Section 2), we show that the pseudo-reality realistically describes the relevant atmospheric processes observed in a glaciated mountainous region (Section 3). We begin by exploring the mean flow fields, the turbulence characteristics and then address the spatial variations of the surface sensible heat flux. In Section 4, we use the bulk approach in concert with linearly interpolated fields based on virtual sites and ~~analyse~~ analyze the impacts on the variability of the surface sensible heat flux. The last section provides a summary of the main findings.

2 Methodology

2.1 Large-Eddy Simulation solver

The pseudo-reality atmosphere is simulated by an OpenFOAM-based incompressible LES solver (Churchfield et al., 2014). The solver is based on the incompressible filtered Navier-Stokes equations, using the Boussinesq approximation for buoyancy, along with the continuity equation

$$\frac{\partial \overline{\boldsymbol{U}}_i}{\partial \boldsymbol{x}_i} = 0. \tag{1}$$

The filtered momentum equation is given as

$$\frac{\partial \overline{\boldsymbol{U}}_j}{\partial t} + \frac{\partial \overline{\boldsymbol{U}}_i \overline{\boldsymbol{U}}_j}{\partial \boldsymbol{x}_i} = -2\epsilon_{i3k}\Omega\overline{\boldsymbol{U}}_k - \frac{\partial \overline{p}}{\partial \boldsymbol{x}_j} - \frac{\boldsymbol{\tau_{ij}}^r}{\partial \boldsymbol{x}_i} - \rho_b \boldsymbol{g}_j, \tag{2}$$

with the overline denoting the LES filtering operation, $\overline{\boldsymbol{U}}_i$ the component of the resolved-scale velocity vector in the direction $\boldsymbol{x}_i$, ϵ_{ijk} the alternating unit tensor, Ω the planetary rotation rate vector, $\overline{p}$ the pressure, and $\boldsymbol{g}_i$ the gravitation vector. The strength and the sign of the buoyancy force ρ_b is given by

$$\rho_b = 1 - \left(\frac{\overline{\theta} - \theta_0}{\theta_0}\right), \tag{3}$$

where $\overline{\theta}$ is the resolved-scale potential temperature and θ_0 is a reference temperature. In practise the isotropic part (residual kinetic energy, $\boldsymbol{k}_r \equiv 0.5\, \boldsymbol{\tau}_{ij}^R$) of the residual-stress tensor $\boldsymbol{\tau}_{ij}^R = \overline{\boldsymbol{U}_i \boldsymbol{U}_j} - \overline{\boldsymbol{U}}_i\, \overline{\boldsymbol{U}}_j$ is absorbed into the filtered pressure term, and only the anisotropic residual-stress tensor

$$\boldsymbol{\tau_{ij}}^r \equiv \boldsymbol{\tau_{ij}}^R - \frac{2}{3}\boldsymbol{k}_r \delta_{ij}, \tag{4}$$

need to be modelled (also called subgrid-scale stress tensor). As the vast majority of LES studies for ~~SBL~~stable boundary layers (SBL), we use a dynamic Smagorinsky ~~SGS~~ subgrid-scale (SGS) model which relies on the eddy-viscosity assumption to close Equation 2. The model relates the residual stresses to the resolved large-scale velocity deformation

$$\boldsymbol{\tau_{ij}}^r = -2\nu_t \overline{\boldsymbol{S}}_{ij}, \tag{5}$$

where ν_t is the eddy-viscosity of the residual motions, and

$$\overline{\boldsymbol{S}}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{\boldsymbol{U}}_i}{\partial \boldsymbol{x}_j} + \frac{\partial \overline{\boldsymbol{U}}_j}{\partial \boldsymbol{x}_i}\right) \tag{6}$$

the resolved-scale strain rate tensor. The eddy-viscosity

$$\nu_t = {\ell_s}^2 \overline{\mathcal{S}} = \left(C_s \overline{\Delta}\right)^2 \overline{\mathcal{S}} \tag{7}$$

is taken to be proportional to the Smagorinsky lengthscale ,ℓ_s, and the characteristic filtered rate of strain $\overline{\mathcal{S}} = (2\overline{\boldsymbol{S}}_{ij}\overline{\boldsymbol{S}}_{ij})^{1/2}$. The lengthscale is usually modelled by a fixed constant C_s and the filter width $\overline{\Delta}$. At high Reynolds-number turbulence, with $\overline{\Delta}$ in the inertial subrange, the resolved scales account for nearly all of the kinetic energy (Pope, 2000). According to the model, the energy transfer from the resolved-scale eddies to the residual motions is entirely balanced by the dissipation of kinetic energy (Churchfield et al., 2014). While, in the mean, energy is transferred from the large to small scales, ~~is~~ it has been recognized that locally there can be significant backscatter of energy from the residual motions on the resolved scales (Pope, 2000). Furthermore, Equation 5 is only valid for isotropic turbulence and is therefore not strictly applicable to complex terrain. The importance of the effects of backscatter and anisotropy for SBL has been shown by Kosovic and Curry (2000). Nevertheless, we assume that the details of the model are of minor importance and the effect of anisotropy becomes negligible when the grid-scale is small compared to the energy containing turbulent scales. Quantifying possible errors coming from this assumption or the model performance is challenging. The model can be tested either by a priori or a posteriori testing. The a priori test uses experimental or Direct Numerical Simulations (DNS) data to relate directly the residual-stress tensor given by the closure model. In an a posteriori test the accuracy of calculated statistics, such as mean wind or momentum flux, are compared with experimental data. Most LES approaches use a posteriori test to prove its applicability. Churchfield et al. (2014) has tested the Smagorinsky and bounded dynamic Langrangian model with the GABLS inter-comparison project (Global Energy and Water

Cycle Experiment Atmospheric Boundary Layer Study, Beare et al. (2006)) using a 6 m grid resolution. They found that both models are in line with the mean vertical profiles of wind speed, direction, potential temperature and variances. We therefore assume that the backscatter of energy from the SGS model towards the resolved scales is negligible, if the LES resolves most of the turbulent kinetic energy (see Section 3.4).

In the original formulation the value of the constant $C_s = 0.17$ is derived from the Kolmogorov spectrum assuming that the transfer of energy to the residual motions is balanced by the dissipation. This constant, however, is not ideal for all locations of the flow (Churchfield et al., 2014), i.e. in regions where the buoyancy flux extinguishes the turbulence the residual shear stresses should be zero. In general, the value of C_s should become zero in the limit of laminar flow and any non-zero value of the coefficient would incorrectly lead to residual shear stresses. To overcome this issue Meneveau et al. (1996) proposed a Lagrangian-averaged dynamic Smagorinsky model that allows the coefficient to vary in time and space based on the flow (Anderson and Meneveau, 1999; Sarghini et al., 1999; Bou-Zeid et al., 2005). This type of closure is appropriate for flow over complex terrain and is therefore used in this study (Bou-Zeid et al., 2005).

Proceeding from the instantaneous internal energy equation the conservation of potential temperature can be derived, and becomes

$$\frac{\partial \overline{\theta}}{\partial t} + \frac{\partial \overline{\boldsymbol{U}}_i \overline{\theta}}{\partial \boldsymbol{x}_i} = -\frac{\boldsymbol{\tau}_{\theta i}}{\partial \boldsymbol{x}_j}, \tag{8}$$

where $\boldsymbol{\tau}_{\theta i}$ is the SGS temperature flux given by

$$\boldsymbol{\tau}_{\theta i} = -\frac{\nu_t}{Pr_t} \frac{\partial \overline{\theta}}{\partial x_i}, \tag{9}$$

where Pr_t is the turbulent Prandtl number. Changes in temperature by radiative forcing and phase change of water are neglected in this study.

The filtered momentum equation is solved using the PIMPLE algorithm, and a preconditioned bi-conjugate gradient solver for asymmetric matrices. To reduce numerical dissipation the convective terms are solved using a second-order central differencing scheme with a multi-dimensional limiter. The time derivative is discretized by a second-order implicit scheme with adaptive time stepping.

2.2 Study Area

Even though the LES is designed as pseudo-reality, the lower boundary condition is provided by a real topography. The designated study area is located at the head of Martell Valley in the central Ortler-Cevedale Group, Autonomous Province of Bozen, Northern Italy (46.28° N, 10.60° E; see Figure 1). The model domain comprises a major part of the contiguous glaciated area covering the northern section of the Cevedale Massif, the summit of which is the highest point of the study area (3769 m a.s.l.). Three glaciers connected to each other are in the focus of the study: Fürkele Ferner, Zufallferner, and Langenferner. The surface area of the glaciers is about 6.62 km^2 (2013) with an altitudinal extent from about 3750 m a.s.l near the summit of Hintere Zufallspitze, down to 2595 m a.s.l. at the lowest point of Zufallferner. The model domain includes a wide variety of topographic features such as steep slopes up to 50°, glaciated and unglaciated (summit-) ridges of various aspects, as well as larger glacier sections with smooth terrain and low slope angles. The mean slope angle of the glacierized terrain is 17°. The topography can be regarded as (i) ~~representative~~ typical for many glaciers in the European Alps, and (ii) highly suitable for investigating the complex interaction of large-scale (synoptic) forcing and small-scale topographic features.

2.3 Initial Conditions

The surface temperature, T_s, of both the glacier surface and the surrounding topography is uniformly initialized with 273.16 K. The atmospheric background state for temperature and pressure is derived from ERA-Interim ~~data.~~ reanalysis data from the 17th August 2014 06 UTC. The vertical data is uniformly mapped onto the unstructured LES grid. To avoid temperature jumps between the free atmosphere and the underlying surface an analytical Prandtl model for thermally induced slope flows is applied as proposed by Oerlemans and Grisogono (2002):

$$\theta(z) = Ce^{\frac{-z}{\lambda}} \cos\left(\frac{z}{\lambda}\right), \tag{10}$$

where

$$\lambda = \left(\frac{4T_0 K_m K_h}{\gamma g \sin^2(\alpha)}\right)^{1/4}. \tag{11}$$

The pre-factor, C, is the temperature perturbation at the glacier surface, which in our case is the difference between surface temperature (273.16 K) and the ~~temperature of the atmosphere~~ ERA-Interim temperature at 100 m above the surface. The quantity λ is the natural length scale of the flow with $K_m = K_h = 0.1\ \mathrm{m^2 s^{-1}}$ the eddy diffusivity for momentum and heat, γ the vertical temperature lapse rate, α the terrain slope, and $T_0 = 280$ K the characteristic temperature. The temperature field in the lowest 50 m is further perturbed by random fluctuations of 0.1 K. The wind field, U, is uniformly initialized with 8 $\mathrm{ms^{-1}}$ throughout the domain. This corresponds to the mean wind velocity of the ERA-Interim data at 5500 m.

2.4 Boundary Conditions

The lateral boundaries are specified as periodic. At the top boundary a no-slip zero-stress boundary is used. The pressure gradient is set based on the boussinesq density gradient normal to the boundary, and the potential temperature gradient is specified according to the initial profile. At the surface, the same pressure boundary condition is used as at the top boundary.

The filter and grid resolution are too coarse to resolve the near-wall motions, including in the viscous wall region, so that their influence close to the wall are modelled by ~~some sort of~~ a shear stress model. A local version of Schumann's shear stress model is applied at the surface (Churchfield et al., 2014; Schumann, 1975; Wan et al., 2007). The Reynolds stress tensor is zero except for the off-diagonal components $\boldsymbol{\tau}_{13}$ and $\boldsymbol{\tau}_{23}$, with

$$\boldsymbol{\tau}_{13} = -u_*^2 \frac{\overline{\boldsymbol{U}_x}(z_1)}{|\overline{\boldsymbol{U}}(z_1)|}, \qquad \boldsymbol{\tau}_{23} = -u_*^2 \frac{\overline{\boldsymbol{U}_y}(z_1)}{|\overline{\boldsymbol{U}}(z_1)|}, \tag{12}$$

where u_* is the friction velocity, z_1 the height of the first cell ~~centre~~ center adjacent to the wall, and $||$ denotes the magnitude of the local velocity parallel to the surface. To solve for the unknown friction velocity, the Monin-Obukhov scaling law is used. The details of the optimization are discussed by Churchfield et al. (2014). Strictly speaking, the Monin-Obukhov scaling law neither applies to complex terrain nor is it formulated to apply the laws locally (Stoll and Porté-Agel, 2006; Wan et al., 2007). However, there is as yet no better solution to solve this problem.

The surface temperature flux is determined using Monin-Obukhov scaling laws for velocity and potential temperature (Basu et al., 2008). At each time step the surface temperature is updated according to the heating rate (see Section 2.5).

2.5 Numerical Experiments

Given the large computational costs, the analysis is confined to four pseudo-realistic case experiments. The simulations merely differ in the geostrophic flow direction (0°, 90°, 180° and 270°). For the simulations, a constant pressure gradient is imposed to drive the geostrophic wind velocity of 8 ms^{-1} at a height of 5500 m. The aerodynamic roughness height, z_0, is set to 0.1 m for the land surfaces (e.g. Stull, 2012) and to 0.001 m for the glacier ~~surface~~and snow surface (e.g. Braithwaite, 1995; Giessen et al., 2008; Bro respectively. We assume similar roughness height for snow and ice since large parts of the glaciers were covered by a thin layer of fresh snow. The glacier surface temperature is kept constant at the melting point during the simulation. The surrounding topography is heated with a constant heating rate of 1.2 $\mathrm{K\,hr}^{-1}$. The atmospheric background state for temperature and pressure is derived from ERA-Interim reanalysis data (Dee et al., 2011) from the ~~12th August 2013~~ 17th August 2014 (see Section 2.3 for details). The selected day had clear skies apart from some isolated orographic clouds at the ridge south of Fürkeleferner. The LES model is integrated for 8 hours. The mean quantities and statistics are calculated from the last simulation hour.

2.6 Numerical Mesh

Besides the fluid dynamical challenges, the numerical model must be able to cope with complex topography. The OpenFOAM solver allows for unstructured grids, which can be adapted more easily to steep topography than commonly used terrain following grids. The 3-dimensional unstructured mesh is generated with the OpenFOAM utility snappyhexmesh. The tool automatically generates hexahedra and split-hexahedra meshes from triangulated surface geometries, i.e. Digital Elevation Models. In this study, the mesh is generated from a high-resolution elevation model (1 m horizontal resolution) derived from airborne laser-scans conducted in September 2013 (Galos et al., 2015). The horizontal extent of the computational domain is 10 km x 10 km and is ~~centred~~ centered over the Zufallferner. The size should be sufficient to resolve the main scales that are involved in the turbulent energy generation. The domain top is set to 10 km. In order to use periodic boundary conditions opposite DEM boundaries are mirrored. This has been done by setting opposite grid points to their mean value, and slowly relaxing (exponentially) the adjacent grid points in the inner domain using a spline algorithm. The resulting relaxation zone has a width of 2 km (160 grid points), which is sufficiently smooth to avoid numerical instabilities. Starting with an initial coarse hexahedra mesh, snappyhexmesh refines the cells ~~closed~~ close to the DEM surface by cell splitting and iteratively morphing the split-hex mesh to the surface. The ~~inital~~ initial isotropic background mesh has been set up with a grid spacing of 200 m. In the lowest 300 m the final mesh has a horizontal resolution of 12.5 m. From the meteorological point of view~~the very~~, the SBL with intermittent turbulence faces some challenges. According to the Monin-Obukov similarity theory, the height above the ground z and the Obukhov length L_s are the only relevant scaling variables (Stull, 2012). The theory is only valid within the surface layer, where the vertical divergence of the fluxes ~~are~~ is negligible (variations smaller than 10% of their magnitude). However~~it turns out, that~~, the vertical gradient of the sensible heat flux above glaciers is normally greatest near the surface. Strictly speaking the Monin-Obukhov theory is not valid when the surface layer is below the observational or model level. This poses the need for a fine mesh ~~closed~~ close to the surface to allow adequate resolution of the smaller eddies. In order to better resolve the fluxes and shear stresses directly above the glacier the mesh has been further refined by prismatic inflation layers. The cell ~~centre~~ center of the first cell is located 0.6 m above the surface, and the heights of the adjacent cells increase with a constant expansion factor of 1.2. Altogether, the final prismatic layers have a total height of about 30 m.

2.7 Averaging and Intermittency

The LES resolves the large energy-containing turbulent structures, so that the output fields are fully turbulent. A given fully turbulent variable, $\widetilde{\phi}$, can be decomposed into the large-scale variation and the subgrid-scale turbulence as

$$\widetilde{\phi} = \overline{\phi} + \phi', \tag{13}$$

where the overbar is the grid cell average. The resolved turbulent contribution ϕ'' is computed by

$$\phi'' = \overline{\phi} - \langle \overline{\phi} \rangle, \tag{14}$$

where the operator $\langle \rangle$ is the averaging time scale. In this study the time scale is chosen to be 1 hour (Mahrt, 2010). The local values of the covariances are calculated as the average of the product of the fluctuations. Applying the Reynolds averaging rules finally ~~lead~~ leads to

$$\langle \overline{\widetilde{w'}\widetilde{\phi'}} \rangle = \langle \overline{w} \rangle \langle \overline{\phi} \rangle + \langle \overline{w''\phi''} \rangle + \langle \overline{w'\phi'} \rangle, \tag{15}$$

where the terms on the right hand side represent the mean advective, resolved and subgrid-scale turbulent flux. As a general measure of turbulence strength we use the standard deviation of the vertical velocity

$$\sigma_w = (\langle \overline{w'w'} \rangle + \langle \overline{w''w''} \rangle)^{\frac{1}{2}}. \tag{16}$$

Occasional bursting events tend to show a more pronounced tail, so that we use the skewness of the vertical velocity variance as a measure to ~~characterise~~ characterize turbulent mixing events (Mahrt, 2010).

3 The pseudo-reality atmosphere

3.1 Mean flow patterns and vertical profiles

The following section analyses the mean modelled flow patterns and vertical profiles. The analysis is confined to the atmospheric boundary layer near the glacier surface and the kinematic flow properties affecting it. ~~To better illustrate the characteristics we define four regions of interests (R1-4) as well as~~ For the discussion we introduce four specific regions: (R1) ridge region, (R2) a steep ice fall, (R3) katabatic wind region, and (R4) divergence zone of katabatic wind. Local characteristics are discussed at four virtual sites on the glacier (Z1-4; see Fig. 3).

Figure 3 shows the mean wind velocity, $\langle \overline{\boldsymbol{U}} \rangle$, at $2\,\mathrm{m}$ above the ground for each of the four flow experiments. ~~Apparently the~~ The flow accelerates as it passes over the summit ridges (R1), due to the strong pressure gradients between the luv side and the ridge region. After passing the ridge the higher pressure on the lee side slows down the flow again. The mean wind velocity at ridges, which are perpendicular to the synoptic flow, sometimes reaches more than 12 $\mathrm{m\,s^{-1}}$ even though the forcing wind velocity is only 8 $\mathrm{m\,s^{-1}}$ ~~.~~ (Fig. 3a). The acceleration partly leads to a flow separation behind sharp ridges (grey dashed lines in Fig. 3), resulting in a thick trailing wake or bluff body formation. In these regions, strong shears generate turbulence which is an important trigger for vertical mixing events.

On lower wider passes and gaps, the flow follows the topography and modifies the wind systems on the lee side. This is particularly evident at the long stretched glacier divide between Zufallferner and Fuerkeleferner (R1). The large-scale flow enhances the katabatic wind when both wind systems are aligned, but retards it otherwise. Since the glaciers are west-east orientated, surface wind predominantly accelerates during westerly flow (see R2 ~~). More general~~in Fig. 3a). Generally, katabatic winds in the lee of flat passes or glacier divides are strengthened by the synoptic flow.

In the central part of Zufallferner (R3), the wind velocities considerably vary with the large-scale flow directions. For example, northerly and easterly flow (Fig. 3b, c) significantly enhance the velocities at the southern boundary of Zufallferner. The local acceleration is the consequence of cross valley circulation triggered by the surrounding topography. The strong positive sensible heat fluxes at the steep slopes create buoyancy forces that drive the thermal circulations. The associated low pressure at the foot of the slopes entrains air from above. While part of the entrained air merges with the up-slope wind, the other part contributes to the glacier wind. The large-scale flow either suppresses or supports the up-slope wind, and hence the entrainment. The results suggest that the intensity of the ~~cross-valley circulation~~ slope winds largely explains the wind variations on Zufallferner.

At the glacier tongue (R4), the large-scale flow hardly affects the surface winds. The katabatic winds gently drain down the glaciers (see Table 1) with velocities ranging between 4.5 and 6.0 $\mathrm{m\,s^{-1}}$. Wind velocities are slightly higher for northerly flow ($\sim$7 $\mathrm{ms^{-1}}$). The wind magnitudes are characteristic for mountain ~~glacier during blue~~ glaciers during clear sky conditions (e.g. Van den Broeke, 1997; Söderberg and Parmhed, 2006). At Z1 and Z2 the Low Level Jet (LLJ) is consistently found below the lowest 12 m (see Fig. 5). However, the intensity and height of the LLJ vary from case to case. The previously discussed crosswind-circulation and its associated enhanced mass-flux during northerly flow significantly lifts and intensifies the LLJ (see Table 1). Strong valley winds, however, tend to retard the down-slope winds by friction which weakens and lowers the LLJ (e.g. at site Z1, ~~easterly flow). Similar,~~ see Fig. 5b). Similarly, a reduced fetch and, in particular, a strong shear associated with a rapid veering of the winds with height can drastically reduce the wind velocity. Such a situation appears within the surroundings of Z4 when the down-slope flows are superimposed by southerly large-scale flow ~~.~~ (see Fig. 5d).

The temperature deficit increases towards the glacier tongue (from Z4 to Z1) and implies a larger forcing to the glacier wind (see Table 1). However the reverse situation is observed, as illustrated in Fig. 5. The intensity and height of the wind maximum decreases down-slope ~~,~~ for most cases (see Fig. 5a, b, d), which somehow contradicts the often observed structure of katabatic flows. The reason for this is the still perceptible influence of the large-scale flow on the katabatic winds down to site Z2. This is evidenced by the fact that no wind maximum is found at the higher sites, Z3 and Z4. Nevertheless, there is a significant positive correlation (0.66) between the height and strength of the LLJ.

3.2 Turbulence characteristics and intermittency

Fig. 6 shows the standard deviation of the vertical velocity fluctuations, σ_w, at 2 m above the ground. Along the ridges turbulence is produced by shears and advected downwind with the flow. Therefore highest values of up to 2.0 $\mathrm{m\,s^{-1}}$ do not ~~jointly appear~~ appear in areas with high wind velocities, but are rather being found behind the sharp ridges.

At some distance away from the mountain ridges the boundary layer is less turbulent ($\sigma_w < 0.5\ \mathrm{m\,s^{-1}}$). However, the distributions of σ_w at the sites Z1-4 are heavily right-skewed (see Table 1), which is a good indication of occasional mixing events embedded within the turbulence. Several studies observed intermittent turbulent mixing events in the SBL above glaciers and ~~analysed~~ analyzed their impact on the surface energy balance (e.g. Cullen et al., 2007; Oerlemans and Grisogono, 2002; Söderberg and Parmhed, 2006; van den Broeke, 1997; Smeets et al., 1998; Munro and Davies, 1978; Hoinkes, 1954; Kuhn, 1978; Munro and Scott, 1989). Single mixing events may have only little impact on the time-averaged quantities, but the intermittent heat supply can be substantial for the melt energy (Oerlemans and Grisogono, 2002; Dadic et al., 2013; Mahrt, 2010; Van den Broeke, 1997). Local turbulent mixing events are driven by the characteristics of local turbulence, submeso motions, and the large-scale flow (Helgason and Pomeroy, 2012; Poulos et al., 2007; Högström et al., 2002). Non-local topographic effects, such as gap flows or bluff bodies, can ~~favour~~ favor the probability of periodic occurrence of burst events at a given point on the glacier ~~shapening~~ shaping the local mircometeorological conditions (Söderberg and Parmhed, 2006; Litt et al., 2015).

The vertical mixing of momentum and heat is a non-stationary process with changing frequency and intensity across the time (Torrence and Compo, 1998; Roesch and Schmidbauer, 2014). Therefore, it is convenient to ~~analyse~~ analyze the frequency structure of recurrent intermittency by decomposing the temperature signal into time-frequency space using wavelets. To illustrate the characteristics of intermittency we have calculated the wavelet power spectrum of the temperature signal at Z2 (southerly flow). Fig. 7 shows the normalized wavelet spectrum and the average power taken over time. The global spectrum shows that most of the power is concentrated around 90 s. There are variations in the frequency of occurrence and amplitude of the mixing events. On average episodic mixing events occur every 10 minutes and last for about 90 s. The wavelet spectrum differs at each site and flow (not shown), but characteristic events are present in all cases. The frequency structure of the recurrent mixing events implies that the surface layer is episodically affected by anisotropic large-scale eddies. Contrary to near-neutral conditions, integral turbulence scales differ significantly between the horizontal and vertical components (see Tab. 1). The scales are in the same order of magnitude as those found by other studies (e.g. Litt et al., 2015; Söderberg and Parmhed, 2006). Since the stable stratification is weak in the surface layer ($Ri_b \sim 0.04$), it is very unlikely that the downward directed sensible heat flux is strong enough to explain these large differences. More important, ~~probably, is~~ the distortion of the detached eddies (turbulence) ~~by local shear~~ in the surface layer ~~, which~~ by local shear, leads to groups of elongated sloping eddies (Högström et al., 2002).

3.3 Spatial variations of the surface sensible heat flux

According to the principle of energy conservation the local change in the potential temperature tendency of dry air at any given point is related to the advective, turbulent and the radiative heat fluxes. The latter one is not explicitly modelled in this study but indirectly given by the prescribed surface temperature. In this case, the heating and cooling of the near-surface layer is only a result of the advective and turbulent transport. Local advection is usually negligible over flat terrain and during weak wind conditions, but is considered a relevant process on mountain glaciers with consequences on the spatial variations of the surface heat flux (Moore and Owens, 1984).

Fig. 8 shows the spatial variability of the modelled mean ~~surface~~ sensible heat flux ~~over~~ on the glaciers. The fluxes vary locally between 10 $\mathrm{W\,m^{-2}}$ and 120 $\mathrm{W\,m^{-2}}$, with slightly smaller values in the higher parts of the glacier due to lower temperatures. Note that positive signs indicate downward directed fluxes. Along the glacier ~~centre lines the~~ centerlines the sensible heat fluxes are in the range of 20 $\mathrm{W\,m^{-2}}$ to 60 $\mathrm{W\,m^{-2}}$, which is in good accordance with observations made on mid-latitude glaciers during clear sky conditions (e.g. Giessen et al., 2008; Oerlemans and Klok, 2002; Greuell and Smeets, 2001; Brock et al., 2000). Enhanced sensible heat fluxes occur in the peripheral zones of glaciers and along narrow and deeply carved valleys (e.g. Langenferner, R2), where strong cross-valley circulations locally advect air towards the glacier (see Fig. 9). The glacier topography locally inhibits a far-reaching advection and ~~restrict~~ restricts the zone of influence to a narrow band along the glacier margin (e.g. R3). Accordingly, the peripheral glacier zones show the highest variability.

Between the individual experiments the spatial variability ~~show~~ shows striking differences (see Fig. 8). However, these differences are small or even negligible when taking the glacier-wide averages (see Tab. 2). These findings have important implications on glacier mass balance studies. On the one hand~~side~~, distributed mass balance estimates (models) require a fundamental understanding of the heat advection (Fig. 9), since the sensible heat flux can make over ~~50~~30% of the total energy during large melt events on continental mid-latitude mountain glaciers in summer ~~(e.g. Cullen and Conway, 2015; Gillett and Cullen, 2011; Van den Br~~ On the other hand, however, we can conclude that topographic effects are less crucial for mean glacier-wide mass change estimates although ~~off-course~~ of course the calculated amount of total ablation can depend on the spatial (altitudinal) distribution of the sensible heat flux since additional energy causes more melt in areas where the surface temperature is at the melting point. While in areas with surface temperatures lower than the melting point more energy is consumed by the ground heat flux to warm up the glacier.

While advection is essential for local estimates the question remains whether the impact of recurrent mixing events ~~are~~ is of the same order of magnitude (see Sec. ~~??~~3.2). Although the intermittent events temporarily increase the ~~surface heat flux~~temperature in the surface layer and the sensible heat flux (see Fig. 7), there is little evidence that these events impact the mean potential temperature (see Fig. 9) and the time averaged fluxes ~~.~~ (see Fig. 8). In conclusion, local thermal micrometeorological conditions are mainly shaped by warm air advection through the cross-valley circulations.

3.4 Reliability of the LES experiments

Even though the pseudo-reality atmosphere seems to describe realistically the physical processes and patterns, the simulations must be interpreted with care. The patterns depend on the model assumptions which include ~~parametrizations~~ parameterizations and idealized boundary conditions.

A crucial assumption is the surface roughness length. To obtain more general results, uniform values of z_0 for snow and ice with 0.001 m are used, which is in the range of commonly used values ~~(e.g. Braithwaite, 1995; Giessen et al., 2008; Brock et al., 2000; Hoc~~ The "uniform" assumption ignores temporal and spatial roughness length variations. However, potentially such variations can have a strong influence on the magnitude of the surface energy fluxes (Brock et al., 2000; Giessen et al., 2008). We argue that this assumption is acceptable ~~for the summer season, and in particular for the end of the ablation season. In this time of the year, the spatial variability of z_0 is usually small and almost similar values can be found for snowand ice (Brock et al., 2000)~~since large parts of the glaciers were covered by a thin layer of fresh snow.

The roughness lengths of snow and ice are relatively small compared to non-uniform roughness elements at a scale of tens of meters such as deep seracs or ice falls. The scales of these elements are approximately of the same order as the horizontal model resolution. Enhanced mixing due to the sudden roughness changes ~~is~~ are therefore not resolved by the model, and it is very likely that the model underestimates the overall variability.

In general, the model resolution is very decisive for the overall quality of the LES simulations. LES require that $\sim 80\%$ of the turbulent kinetic energy is resolved by the model itself, and only a minor part is modelled by the SGS model (Pope, 2000). In the performed experiments, on average 20-30% of the total turbulent kinetic energy is modelled by the SGS model. Slightly higher fractions, of up to 40%, are found at exposed mountain ridges. When decreasing the horizontal grid resolution to 25 m, the resolved kinetic energy was only 60-70%. Additionally, a coarser grid leads to greater aspect ratios of the prismatic layers, which requires very short integration time steps (0.01 s) to guarantee stability. Increasing the prismatic layer heights is problematic since this affects the shear stress and momentum calculations close to the surface. The choice of $\sim$ 12.5 m is a good tradeoff between computational costs and resolved scales.

The ~~used~~ Lagrangian-averaged dynamic Smagorinsky model assumes that the energy transfer from the resolved-scale eddies to the residual motions is entirely balanced by the dissipation of kinetic energy. However, dissipation is not necessarily in balance with the energy production in stably stratified boundary layers. As a consequence, the SGS model is likely to dissipate too much energy. ~~In case of the four experiments the stable stratification was weak ($Ri_b \sim 0.04$), and we can assume that the overestimated dissipation is negligible~~We have shown that the calculated statistics, such as the integral turbulence scales, skewness and vertical velocity variance, are in the same order of magnitude as those obtained from observations (e.g. Litt et al., 2015; Söderberg and Parmhed, 2006). If the SGS model is too dissipative, the calculated measures would be significantly lower than the observations. Which SGS model works best for stable boundary layers is not easy to tell, but the Lagrangian-averaged SGS model seems to work well in our study. We have also tested the dynamic Smagorinsky model, but the simulations are found to be unstable due to large fluctuations of C_s.

We like to note, that the current version of the solver ignores differential surface heating by radiation and is therefore only suitable for idealized simulations. Differences in insolation on slopes due to exposure, aspect or shadow cause upslope flows to be inhomogeneous. The different onsets of the slope winds then lead to more asymmetric cross-valley circulations.

4 Estimation of the ~~energy exchange~~ sensible heat flux using the Bulk-Approach

Physically based distributed mass balance models are often applied to translate the local-scale weather conditions into net mass gain and loss at the glacier surface. The ablation process, which removes ice and snow, is controlled by the net energy balance at the ice-atmosphere interface. Direct measurements of energy balance components exist in most cases only for radiation, while surface heat and moisture fluxes are rarely measured directly on glaciers. The simplest and most widely used method to ~~parametrize~~ parameterize the turbulent energy exchange from available meteorological observations is the bulk approach. The approach is based on the Monin-Obukhov theory and assumes constant fluxes within the surface layer. This is not necessarily true in the presence of a LLJ, but the method is found to give good results when measurements are below the wind velocity maximum (Greuell and Smeets, 2001). The ~~surface sensible~~ sensible heat flux is usually estimated by

$$Q_H = \frac{\rho c_p \kappa^2 U (T_a - T_s)}{\left[\ln\left(\frac{z}{z_0}\right) + \psi_m\left(\frac{z}{L_s}\right)\right]\left[\ln\left(\frac{z}{z_{0h}}\right) + \psi_h\left(\frac{z}{L_s}\right)\right]}, \tag{17}$$

where ρ is the air density ($\mathrm{kg\,m^{-3}}$), c_p the specific heat of air at constant pressure (1004 $\mathrm{J\,kg^{-1}\,K^{-1}}$), κ is the von Karman constant (0.4), U is the wind velocity ($\mathrm{m\,s^{-1}}$), T_a and T_s the air temperature (K) at the height z (m) and the surface. The parameters z_0 and z_{0h} (m) are the roughness lengths for momentum and heat, respectively. The characteristic length scale L_s (m) is the Obukhov-length and is proportional to the height of the dynamic sub-layer. The vertically integrated stability functions for momentum, ψ_m, and heat, ψ_h, are given as

$$\psi_m = \psi_h = \frac{4.7 \cdot z}{L_s}. \tag{18}$$

4.1 Shortcomings in the sensible heat flux estimates related to the large-scale flow direction

It is straightforward to apply Eqn. 17 to any given point on the glacier, ~~given that~~ in case all quantities are known. However, highly resolved observational data on glaciers, as required to ~~characterise~~ characterize the spatial fields, are usually scarce and need to be extrapolated. Extrapolation algorithms in turn are based on simplified distribution assumptions and are unlikely to sufficiently reconstruct the full variability of a quantity in time and space. To identify the shortcomings in the local sensible heat flux estimates due to deficiencies in the observations (extrapolation), we consider the LES as pseudo-reality. The pseudo-reality atmosphere is not required to be an observed real world case, but needs to be plausible in the sense that relevant processes are realistically simulated. As demonstrated in Sec. 3.1, ~~3.3 and ??~~3.2 and 3.3, the LES ~~model captures the relevant processes observed in mountainous terrain~~provide plausible realizations of the vertical wind and temperature profiles, sensible heat fluxes and turbulent structures of the boundary layer.

4.2 ~~Shortcomings in the sensible heat flux estimates related to the large-scale flow direction~~

To illustrate how the sensible heat flux estimates depend on the local flow conditions, we ~~defined two virtual observation points at Zufallferner(Z_0 and Z_a;~~ define two pseudo-observation sites at Zufallferner, with preferable great vertical differences between the sites (S1 and S2, see Fig. 10). The ~~pseudo-observed~~ simulated (LES) wind velocities and temperatures at the two sites ~~were~~ are linearly extrapolated across the glacier to obtain a temperature field (e.g. Paul and Kotlarski, 2010; Machguth et al., 2009; Huintjes et al., 2015; Weidemann et al., 2013; Jarosch et al., 2012). For comparison, we also estimate a second temperature field using a simple thermodynamic glacier wind model that accounts for air temperature variations along the flow line. The model details are given in Greuell and Böhm (1998), Ayala et al. (2015), Petersen et al. (2013), and Carturan et al. (2015). The model is fitted to the observations by optimizing the bulk transfer coefficient for heat and the location on the glacier from where air parcels are dominated by the katabatic wind. Assuming that the Obukhov-length, L_s, equals the observed value at ~~Z_0, the surface heat flux was~~ S1, the sensible heat flux is then calculated at all grid points (Eqn. 17).

Fig. 10 shows the differences between the ~~calculated surface heat fluxes obtained from the bulk method and the LES~~LES and the calculated sensible heat fluxes using the linearly interpolated temperature fields together with the bulk method. As T_s, z_0 and L_s are known from the LES, the discrepancies must be the result of the insufficient ~~characterisation~~ characterization of the spatial U and T_a fields. It is evident that the forcing fields lack to reflect the variability of the local processes which originate from the complex topography. Shortcomings are eminently striking in regions of warm air advection (see Sec. 3.3 and Fig. 9). ~~The bulk~~ This approach, for instance, underestimates the fluxes by up to 40 $\mathrm{W\,m^{-2}}$ in the peripheral zone of Zufallferner (steep slopes) and also in the vicinity of ~~Z_a~~S2. Local advection processes equally explain the deficits in the higher regions of Fürkele Ferner.

On contrary, the fluxes are largely overestimated along the glacier ~~centrelines~~ centerlines and tongues. In these regions the well-developed katabatic flow prevents warm air advection from the surroundings (see Sec. 3.1). For example, this is the case at the tongues of Fürkele Ferner and Zufallferner where glacier winds converge due to the topography. Here, the persistent winds are barely perturbed by the warm air advection from the surrounding terrain. Instead, the air continuously cools on the way down the glacier by a downward sensible heat flux, and is therefore potentially cooler than in other parts of the glacier. The linear temperature gradients, determined from the two locations (~~Z_0 and Z_a~~S1 and S2), do not account for this additional cooling. Hence, the extrapolated fields are too warm and the bulk approach overestimates the ~~surface~~ sensible heat fluxes by 10-30 $\mathrm{W\,m^{-2}}$.

On a glacier-scale, the bulk approach in concert with linearly interpolated temperature fields underestimates the average heat flux ~~by up to 7~~ between 5.2 (-16.6%) and 6.9 $\mathrm{W\,m^{-2}}$ (-20.3%) for the westerly, easterly and northerly flow (see Tab. 2).

The ~~only exception is~~ local differences for the southerly case~~where local differences~~ , however, almost cancel each other out ~~.~~ (0.8 $\mathrm{W\,m^{-2}}$, 2.2%). The thermodynamic glacier model accounts for the cooling of air parcels along the flow path due to the turbulent heat exchange and reproduces the cooler glacier tongue region (not shown). At the lateral glacier boundaries, the model is generally cooler than the LES, so that it slightly underestimates the glacier-wide averaged sensible heat fluxes (see Tab. 2).

4.2 Shortcomings in the sensible heat flux estimates due to the choice of observation sites

The choice and number of observation sites on glaciers is always a compromise between logistic feasibility, financial expenditure and scientific issue. These factors usually restrict the monitoring activities to a few sites along the glacier ~~centrelines~~centerlines. Even from a pure scientific perspective the choice of observation sites that meet all requirements is challenging.

To explore how the choice of observation sites influences the spatial variation of the sensible heat flux estimates, we define a set of ~~virtual observation~~ pseudo-observation on Zufallferner (~~Z_0 and Z_{a-d}~~S1-S5; see Fig. 11 and Tab. 3) ~~. For each combination of Z_0 and Z_{a-d} the heat fluxes are estimated~~ with distinct flow and advection patterns: (S1) located at the glacier tongue with almost pure katabatic wind (used as reference station), (S2) in the higher region which is influenced by strong heat advection, (S3) at the lateral boundary of the glacier which is influenced by the cross-valley circulation, (S4) close to S2 but less affected by strong heat advection, and (S5) a second station on the glacier with dominantly katabatic wind. In the following, we estimate the sensible heat flux according to Eq. 17 ~~.~~for each combination of S1 and S2-S5 using the linearly extrapolated temperature and mean wind velocity (the mean value of the two sites) from the westerly flow case. This approach has two major implications: i) the temperature field is completely decoupled from the flow and therefore disregards local flow features (e.g. gap flows and bluff bodies), and ii) the wind velocities are too low over large areas on the glacier.

Fig. 11 shows the differences between the ~~bulk estimates and pseudo-reality atmosphere~~sensible heat fluxes calculated by the bulk approach and the surrogate atmospheres. Evidently, the bulk ~~estimates lack to reflect the variability in time and space~~approach in concert with interpolated temperature fields underestimates the spatial sensible heat flux variability. Since the spatial patterns are similar for all cases, the shortcoming must be related to the insufficient ~~characterisation~~ characterization of the temperature advection process. The magnitude of the differences, however, ~~result~~ results from the derived temperature gradients, and thus on the location of the second station, ~~Z_{a-d}.~~ S2-S5 (see Tab. 3). In the case that stations are located in a region of strong temperature advection (e.g. case ~~Z_0-Z_a and Z_0-Z_b)~~S1-S2 and S1-S3), the derived temperature gradient is too ~~large~~shallow, and the bulk approach overestimates the ~~surface~~ sensible heat fluxes in most regions of the glacier. ~~Similar~~Similarly, temperature gradients are too ~~small~~ steep when stations are protected from warm air transport, and on average fluxes are underestimated (e.g case ~~Z_0-Z_c and Z_0-Z_d~~S1-S4 and S1-S5). On glacier-wide average the excess/deficit in energy varies between -14.5 and 16.6 $\mathrm{W m^{-2}}$ (see Tab. 3).

The results confirm that the phenomenological understanding at few locations and weather situation is not valid beyond the case and insufficient to infer on the micrometeorological conditions on mountain glaciers. ~~We assumed a uniform wind velocity which ignores important local flow features (e.g. gaps and bluff bodies) and drastically underestimates the wind velocities over~~

~~large areas. Like in most other mass-balance studies, the temperature fields were decoupled from the flow fields what generates a static temperature field without allowing for temperature advection.~~

5 Conclusions

We have shown how complex topography influences the micrometeorlogical conditions on three mid-latitude mountain glaciers in the Italian Ortler-Cevedale Group. The idealized LES experiments demonstrate that heat advection associated with the wind systems shape the thermal conditions on the glaciers ~~in~~ during the course of a summer day with clear sky conditions~~during summer~~. In particular, the cross-valley circulations, and bluff body formations behind sharp ridges, transport warm air from the surroundings to the peripheral zones of the glaciers and locally increase the ~~surface~~ sensible heat fluxes by 50-100 $\mathrm{W m^{-2}}$. Intermittent downburst events, however, entrain little heat from the free atmosphere towards the surface. The effective energy surplus is supposed to be even higher when the longwave radiation is ~~parametrised~~ parameterized by air temperature.

Our pseudo-reality experiments demonstrate that it is challenging to fully ~~characterise~~ characterize the micrometeorological conditions over glacier surfaces from a limited number of observations. Linearly extrapolated forcing fields fail to reflect the temperature variability that originates from insufficient ~~characterisation~~ characterization of advection. The shortcomings in the forcing fields have direct consequences on estimated ~~surface~~ sensible heat fluxes (e.g. by the bulk approach). Local ~~errors in the surface~~ differences in the sensible heat fluxes of up to 60 $\mathrm{W m^{-2}}$ are strong enough to significantly affect the ablation rate estimates, as well as the derived climate sensitivities of mountain glaciers.

The choice of observations sites, and thus the derived temperature gradients, determine the magnitude of the local sensible heat flux errors. Calculated temperature lapse rates are ~~steeper (<-0.01~~ shallower ($<-0.003\,\mathrm{K m^{-1}}$) than the environmental lapse rate ($-0.0065\,\mathrm{K m^{-1}}$)~~when one of the stations is~~ , or even change sign ($+0.006\,\mathrm{K m^{-1}}$, see Table 3), when the higher stations are influenced by warm air advection. Consequently, the overestimated air temperatures produce higher downward directed sensible heat fluxes for most parts of the glaciers. In case stations are protected from warm air transport or located in well developed katabatic flows, calculated temperature gradients are generally ~~shallower (>-0.005~~ steeper ($>-0.005\,\mathrm{K m^{-1}}$) than the environmental lapse rate. The shallow lapse rates result in very low sensible heat flux estimates in the peripheral and higher zones of the glaciers, where heat advection is an important process. Generally, the sensitivity of the calculated lapse rates to the choice of the observation sites is related to the steep gradients between the advected warm air masses and the ambient cold air masses on the glacier. Shifting stations by even small distances (≤ 200 m) can potentially lead to remarkable differences in the calculated lapse rates of $\pm 0.005\,\mathrm{K m^{-1}}$.

As a glacier-wide average, the choice of observation sites causes ~~errors~~ differences of about $\pm 16\,\mathrm{W m^{-2}}$ ($\sim 20\%$ of the actual LES value). The estimated errors are considered conservative given the weak geostrophic forcing and low surface heating rate. However, the error quantification is only valid for the specific experimental design, and the infinite topographic possibilities and variety of site combinations make it impossible to draw a general conclusion about the best sites on a glacier.

We can conclude that a profound knowledge of the heat advection process is needed when small-scale variations of surface energy balance are required for distributed mass balance studies. Current thermodynamic and statistical ~~centreline~~ centerline models describe temperature variations along the flowline of glaciers, but do not resolve the cross-glacier variability ~~(e.g. Greuell and Böhm~~ In order to account for the lateral variations, temperature and wind fields need to be coupled. We suggest that future efforts should consider more representative wind fields (e.g. simulated by mass-consistent models) in concert with simple ~~centreline modelsusing off-glacier stations~~centerline models.

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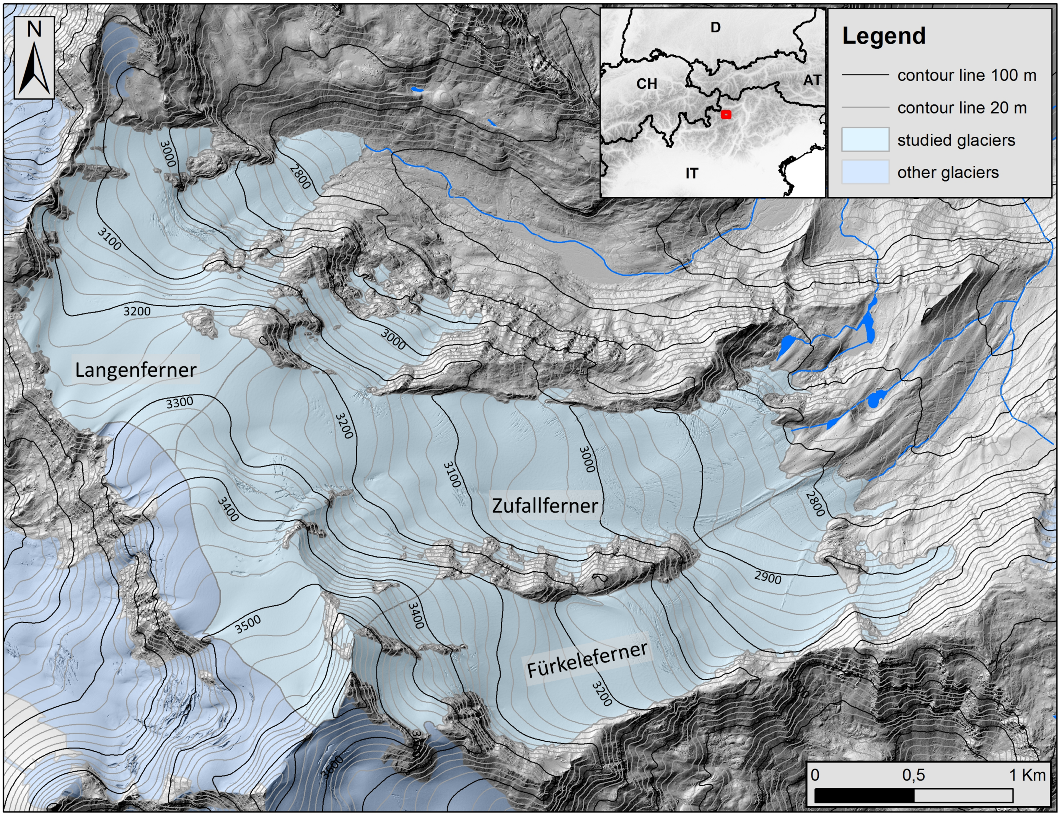

Figure 1. Map showing the surface topography of the studied glaciers and the surrounding terrain.

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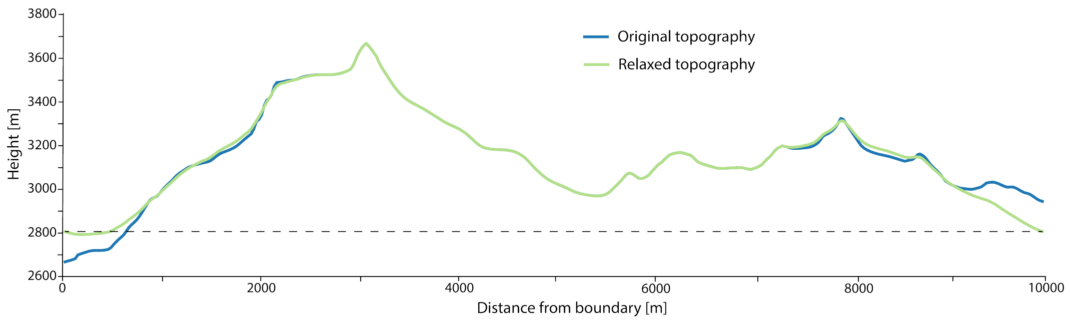

Figure 2. Adaption and relaxation of the computational domain. The blue and green lines show a east-west profile of the original and relaxed topography, repsectively. The boundary grid cells have been set to the mean value of both cells (dashed line). The adjacent grid points are slowly relaxed (exponentially) to get a smooth transition from the boundaries towards the inner domain using a spline algorithm.

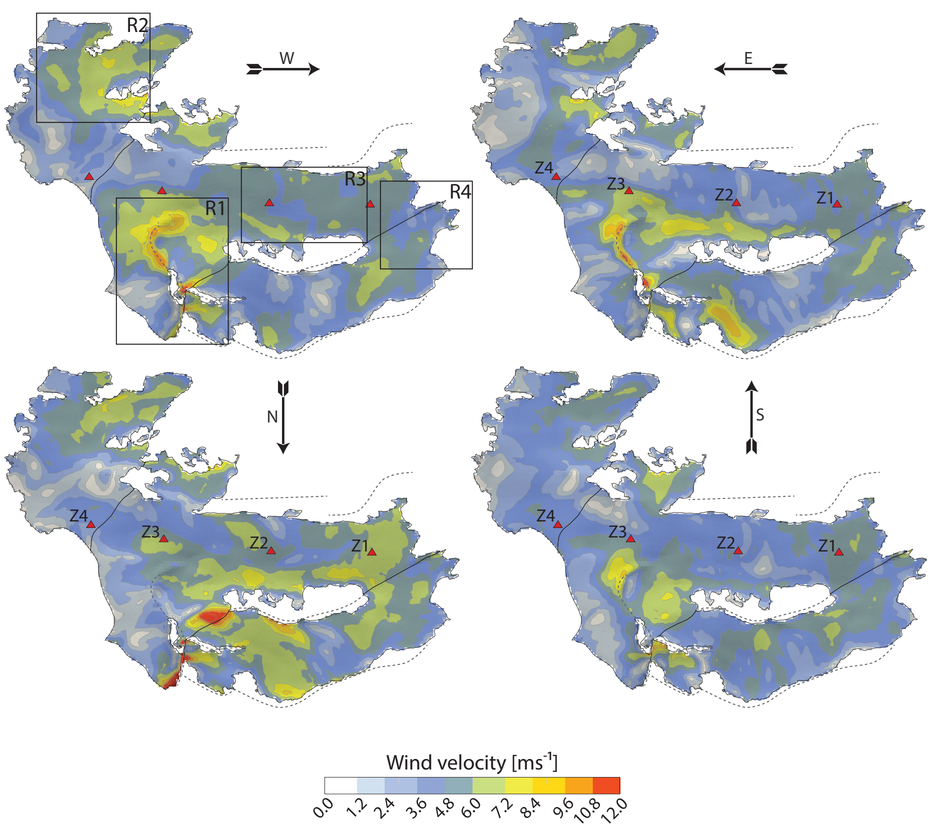

Figure 3. Mean velocity of the surface wind fields (2 m) for each of the four case experiment. The four boxes R1-4 and the sites Z1-4 define regions and locations on the glacier which are used for discussion in the results section. The grey dashed lines represent sharp ridges in the study area.

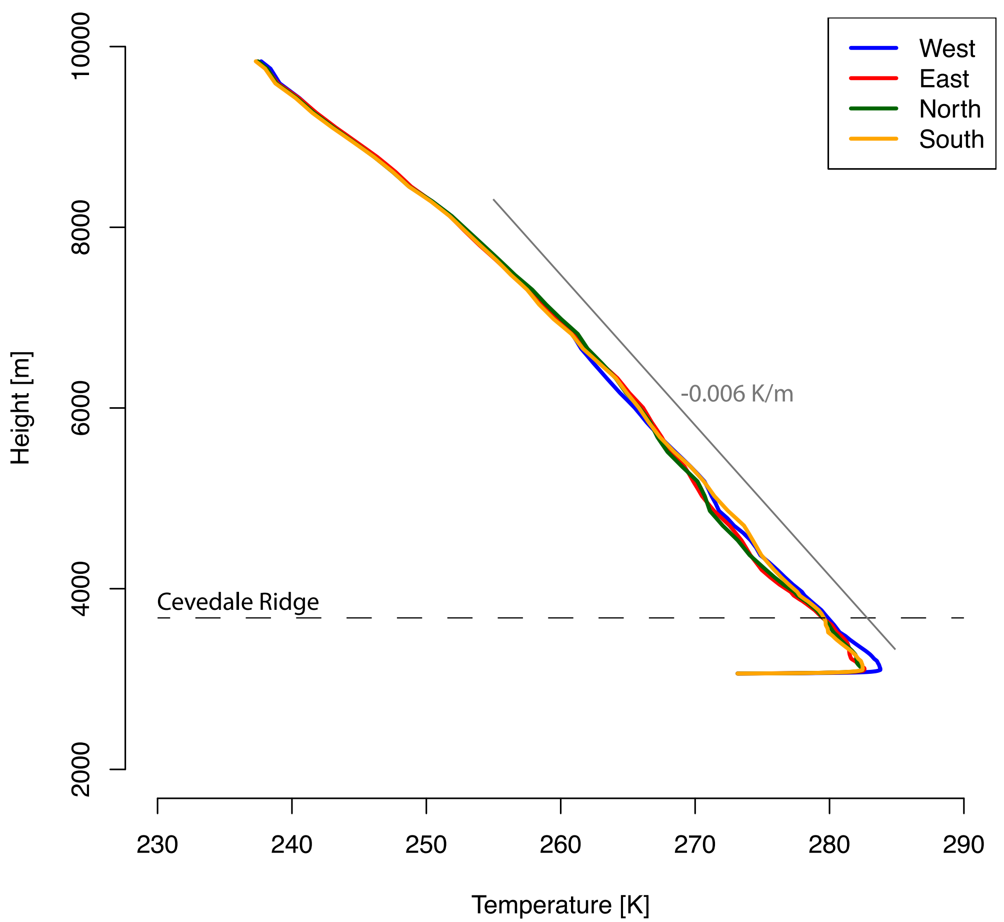

Figure 4. Vertical temperature profiles at location Z2 for each experiment. The dashed line indicates the altitude of the Cevedal ridge. The grey solid line represents a lapse rate of -0.006 $\mathrm{K/m}$.

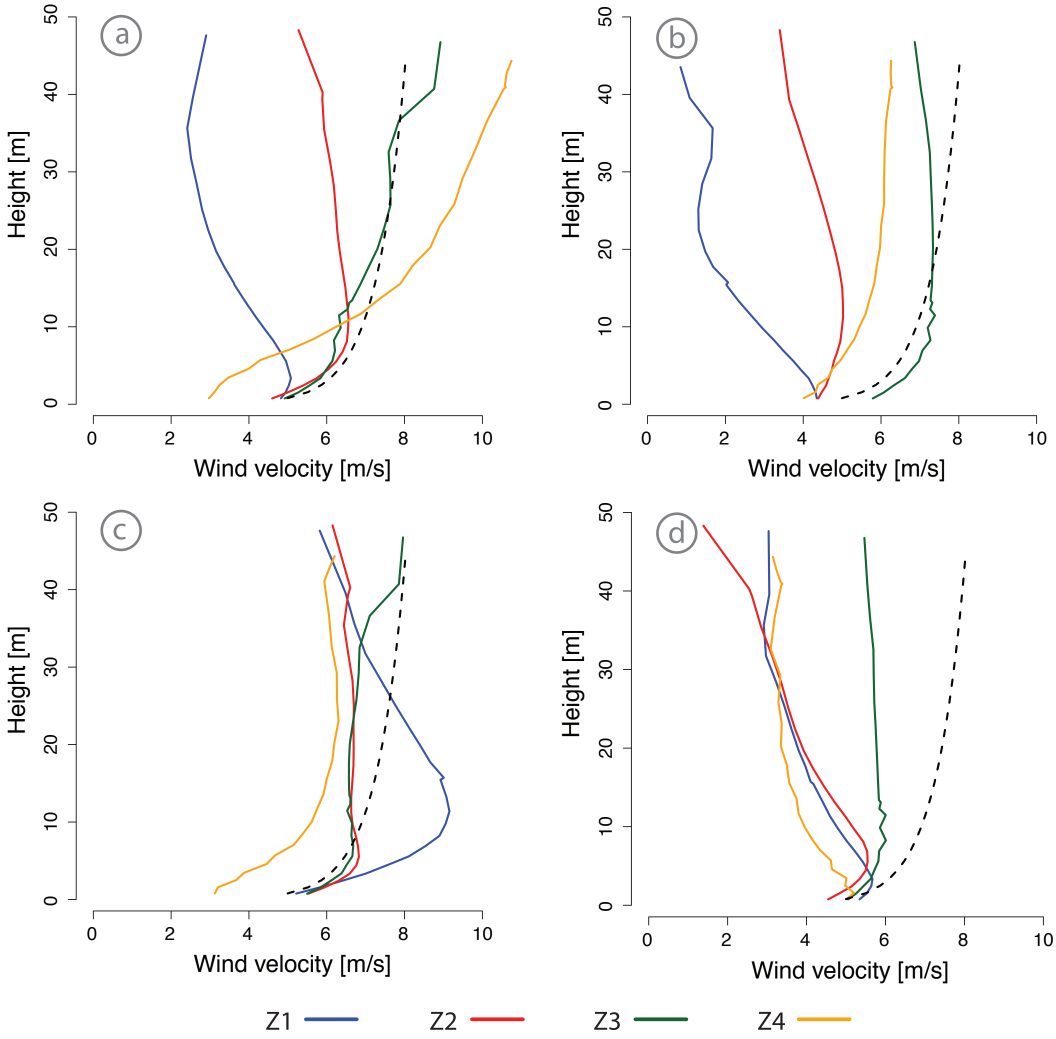

Figure 5. Vertical profiles of the mean wind velocity at the four sites (Z1, Z2, Z3 and Z4) for each case experiment. The dashed line represents a neutral logarithmic wind profile with $z_0 = 0.01$ m and $u_* = 0.3$ ms^{-1}.

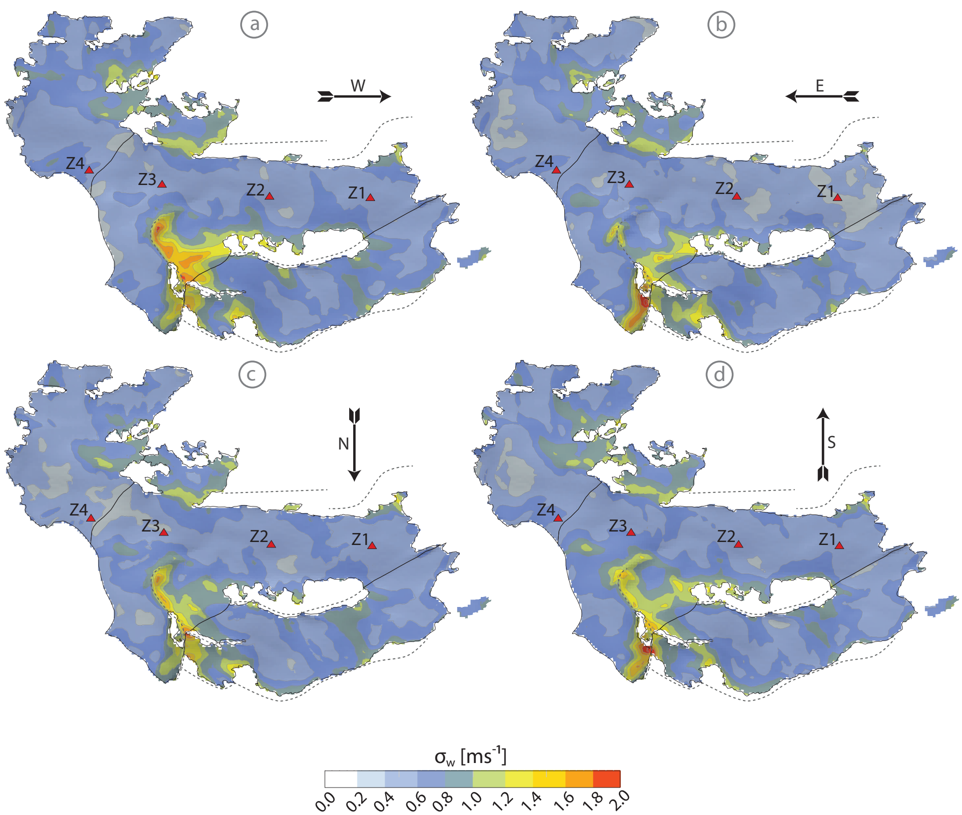

Figure 6. Standard deviation of the vertical velocity fluctuation at 2 m above ground for each of the four case experiments.

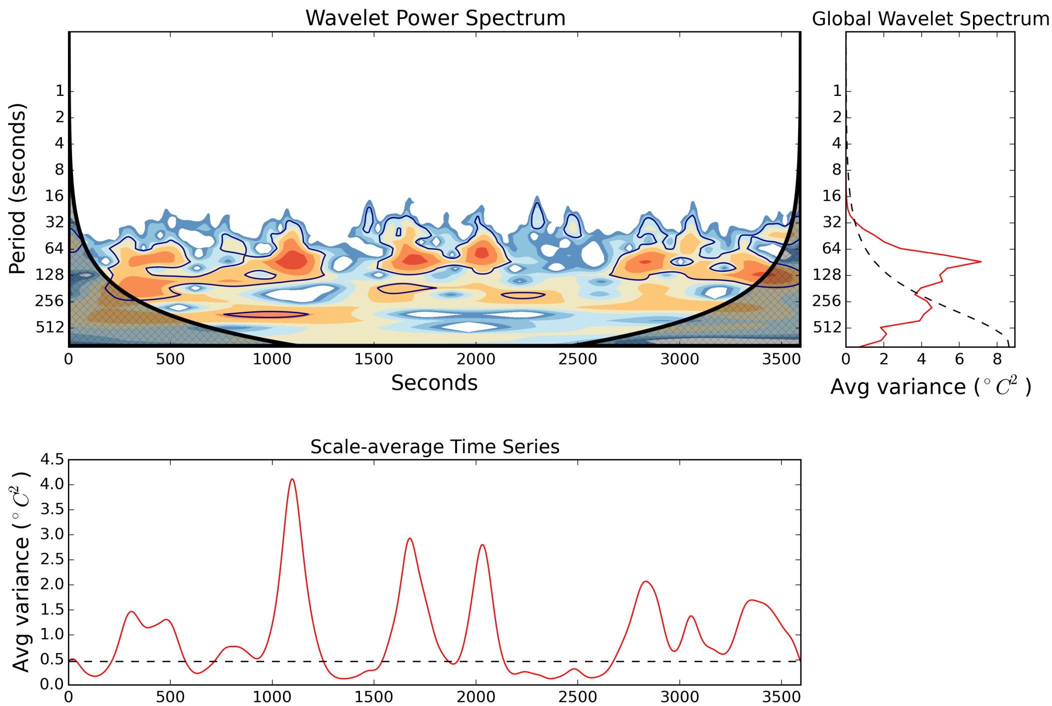

Figure 7. Example of a rectified wavelet power spectrum of the temperature signal at location Z2 for southerly flow (upper left column) , the time average-wavelet power spectra (right column), and the scaled-averaged time series (lower left column). Red and blue indicate high and low scaled powers (in base 2 logarithm), respectively. Black lines outline the wavelet spectrum at a 95% confidence level. The cross-hatched region marks the cone of influence, where edge effects become important.

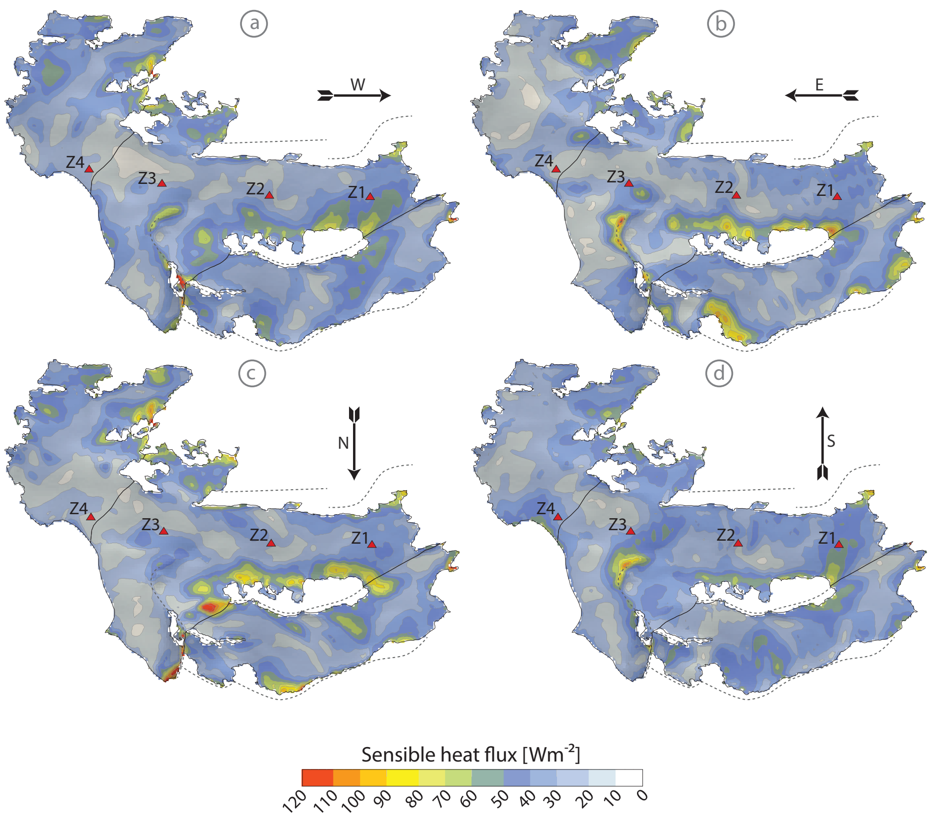

Figure 8. Mean sensible heat flux from the LES runs for each of the four case experiments.

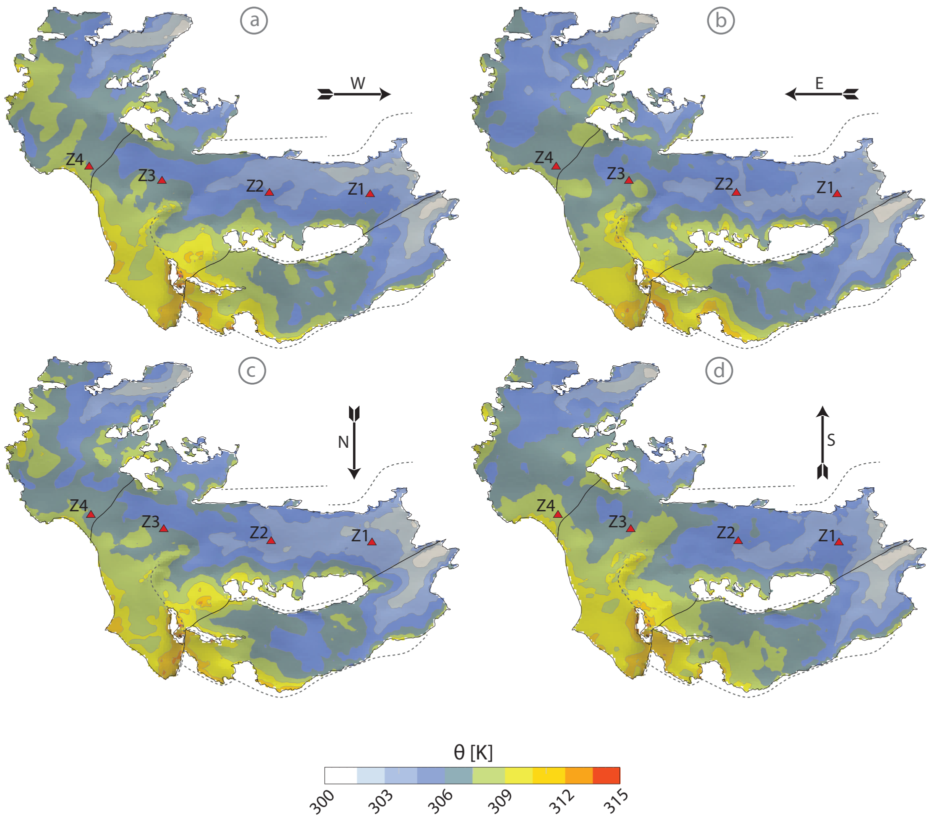

Figure 9. Potential temperature at 2 m above the surface for each of the four case experiment. The ~~four boxes R1-4 and the~~ sites Z1-4 define regions and locations on the glacier which are used for discussion in the results section. The grey dashed lines represent sharp ridges in the study area.

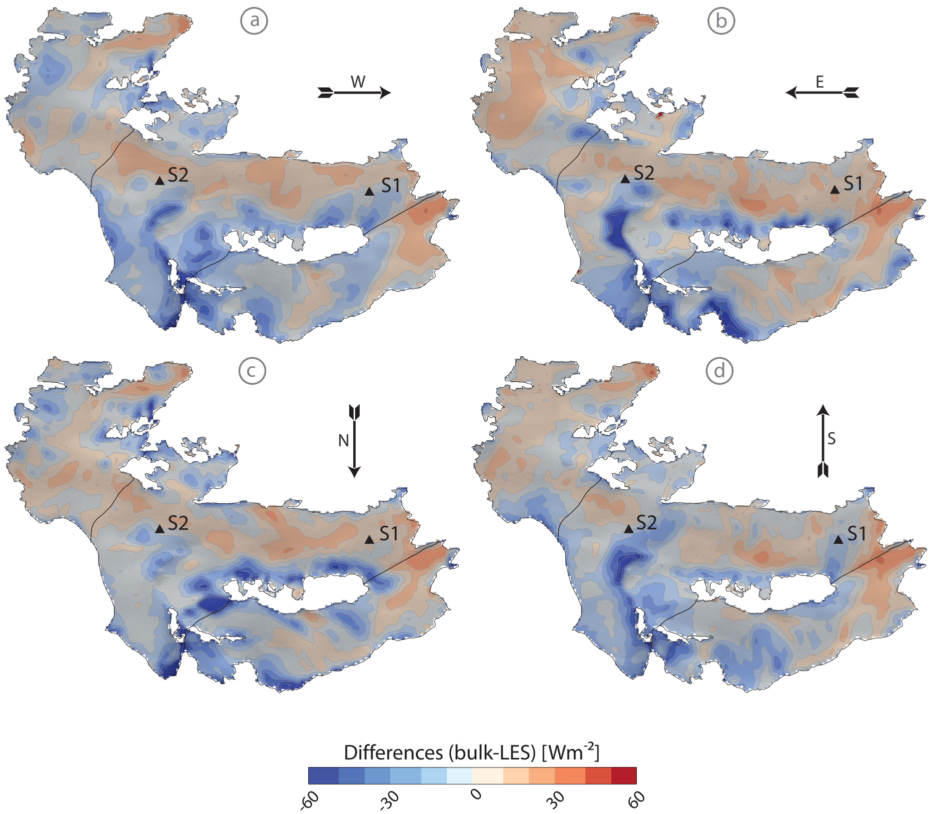

Figure 10. Differences in the mean surface sensible heat fluxes between the LES and the bulk method for different wind direction. Positive differences correspond to an overestimation of the surface heat flux by the bulk approach.

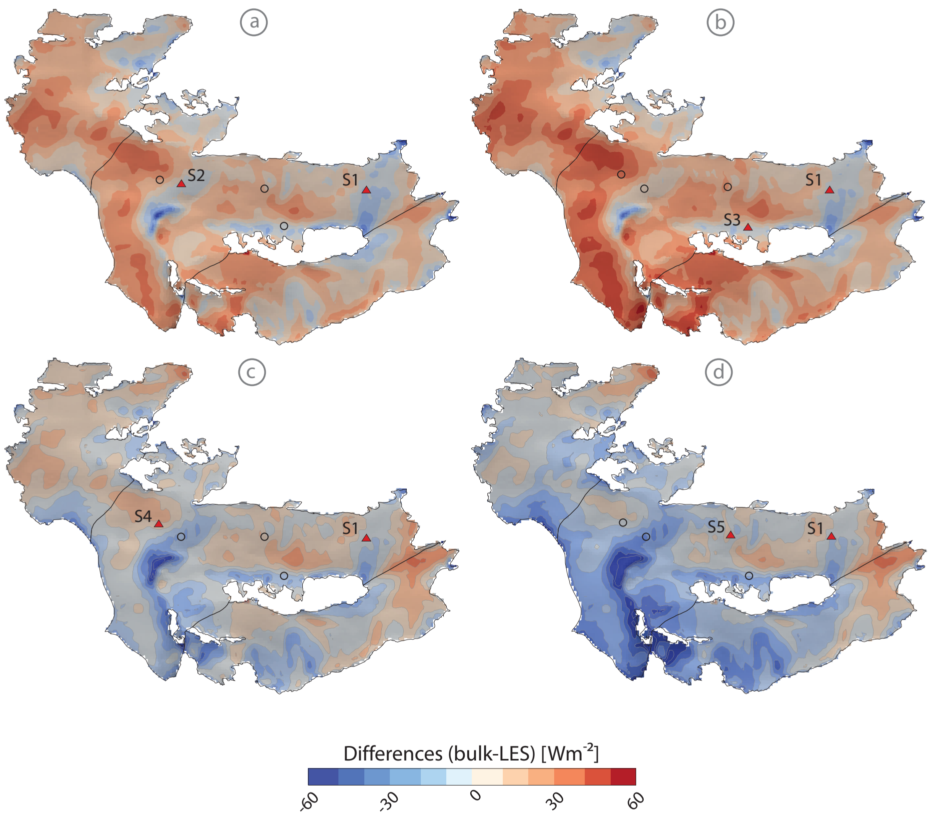

Figure 11. ~~Shown are the differences~~ Differences in the surface sensible heat fluxes between the LES and the bulk method. The cases A-D indicate different extrapolation scenarios based on the pseudo-observations ($\cancel{Z_0}$S1, $\cancel{Z_{a-d}}$S2-S5) . Positive differences correspond to regions where the fluxes have been overestimated by the bulk approach.

Table 1. Mean statistics at the sites (Z1-4) at 2 m above the surface, derived from the Large-eddy simulations. Given are the heights of the LLJ (second column), wind velocities of the LLJ (third column), wind directions (fourth column), differences between the surface temperature and the temperatures at 100 m above the ground (fifth column), skewness of the vertical velocity variances (sixth column), integral turbulence scales (seventh to ninth column), and the bulk Richardson numbers (last column).

Experiment/Location	h [m]	v [ms^{-1}]	dir [°]	$\theta_\triangle$ [K]	Skewness	$\frac{\sigma_u}{u_*}$	$\frac{\sigma_v}{u_*}$	$\frac{\sigma_w}{u_*}$	Ri_b
West / Z1	3.3	5.0	235	13.3	2.35	4.96	4.54	0.96	0.04
West / Z2	11.2	6.5	252	12.6	6.94	3.96	4.57	0.84	0.03
West / Z3	-	-	203	10.8	3.14	3.41	2.70	0.54	0.02
West / Z4	-	-	187	10.5	4.73	4.99	3.35	1.24	0.04
East / Z1	0.8	4.3	254	11.6	3.12	2.79	4.11	0.53	0.04
East / Z2	11.2	5.0	266	11.0	2.26	3.40	6.05	0.64	0.03
East / Z3	11.4	7.3	164	9.6	4.70	3.51	2.97	0.63	0.03
East / Z4	-	-	234	9.2	3.33	3.89	4.67	1.26	0.03
North / Z1	11.3	9.1	240	13.1	3.11	4.26	6.99	0.91	0.03
North / Z2	5.5	6.8	275	10.9	6.03	3.74	4.83	0.66	0.03
North / Z3	-	-	225	9.8	6.05	3.14	2.43	0.47	0.02
North / Z4	-	-	234	9.5	2.72	4.91	3.42	1.05	0.05
South / Z1	3.3	5.6	255	12.7	2.60	3.55	4.46	0.83	0.04
South / Z2	5.5	5.5	290	11.2	2.90	4.13	4.41	0.77	0.03
South / Z3	8.2	6.0	159	10.8	2.29	6.16	3.93	1.26	0.04
South / Z4	1.5	5.1	163	10.0	2.09	4.63	5.27	1.32	0.05

Table 2. Comparison of the ~~bulk approach with~~ surface heat fluxes. Shown are the glacier-wide averaged surface heat fluxes from the LES ~~for distinct flow directions~~and the estimated fluxes calculated with the bulk-approach using different temperature fields as predictor (linearly interpolated and a thermodynamic glacier wind model based on Greuell and Böhm (1998)). ~~Positive~~ The mean relative ~~errors correspond to an overestimation of~~ differences are given in the ~~fluxes by the bulk approach~~brackets.

	West	East	North	South
Large-eddy simulation [Wm^{-2}]	33.8	31.2	33.8	33.0
~~Bulk approach~~ Linear interpolation [Wm^{-2}]	26.9 (-20.3)	26.0 (-16.6)	27.4 (-19.3)	33.8 (+2.2)
~~Mean relative error~~ Greuell and Böhm (1998) [~~%~~Wm^{-2}]	~~-20.3~~ 35.5 (+5.0)	~~-16.6~~ 26.4 (-16.4)	~~-19.3~~ 31.5 (-6.8)	~~2.2~~ 28.8 (-12.7)

Table 3. ~~Shown are the mean~~ Mean glacier-wide sensible heat fluxes using the bulk approach with linearly extrapolated temperature and wind fields. The table shows extrapolation scenarios based on different pseudo-observations (~~Z_0~~S1, ~~Z_{a-d}~~S2-S5). The exact location of the pseudo-observations is given in Fig. 11. Given are ~~also~~ the mean and relative differences between the bulk estimates and LES as well as the lapse rates. Positive differences correspond to an overestimation of the fluxes by the bulk approach.

	~~Z_0-Z_a~~ S1-S2	~~Z_0-Z_b~~ S1-S3	~~Z_0-Z_c~~ S1-S4	~~Z_0-Z_d~~ S1-S5
Bulk approach $[\mathrm{Wm^{-2}}]$	42.76	49.66	28.85	18.77
Mean difference $[\mathrm{Wm^{-2}}]$	9.82	16.58	-4.04	-14.53
Mean relative difference [%]	26.5	46.9	-14.6	-44.4
Lapse rate $[\mathrm{Km^{-1}}]$	~~0.015~~ -0.003	~~0.019~~ 0.006	~~0.005~~ -0.004	~~0.004~~ -0.006