Referee #1

This paper conducted a comprehensive study of energy balance for a debris-covered glacier using turbulence-resolving numerical simulations. The paper is well organized and written, and the conclusion is supported by the results. I am generally favorable to publication. However, I feel that the following point needs to be addressed before publication.

My major concern is that the one-meter spatial resolution used in the paper is way beyond the dissipation range, so I would be very hesitated to call it a DNS. I would like to be clear that I am not questioning the validity of the numerical results and the corresponding conclusion in this paper. I agree that a one-meter resolution, constant eddy viscosity model should outperform a 10-meter resolution LES-SGS model. However, instead of calling it a DNS, I would suggest calling it a different name, e.g., a constant eddy viscosity LES, a high-resolution LES, or a quasi-DNS? The authors did show that doubling the spatial resolution (and the Reynolds number) had a small impact on the simulation results. In my opinion, this only indicates that, numerically, increasing the grid resolution has a limited impact on the simulation results. However, whether a one-meter resolution simulation can explicitly capture the right physics (small-scale turbulence behavior) in the atmosphere is still not quite clear. I suggest the authors conduct a validation that compares the quasi-DNS results with field experiments. I am also curious to see how a LES model behavior, compared with the quasi-DNS runs. Without such a comparison, it is hard to justify the one-meter resolution DNS configuration.

We thank the anonymous reviewer for their time, and their insightful and helpful suggestions to make the manuscript more accessible and accurate.

To make the differences and links between LES, DNS more clear we have now included in the introduction L97-102:

"Turbulence can be simulated by two techniques: LES (Large Eddy simulations) and DNS (Direct Numerical simulations). The difference between them is the treatment of the smallest scales in the flow; LES uses a subgrid parameterization and DNS resolves these explicitly. DNS at atmospheric viscosity is computationally unfeasible, but it is not always necessary to resolve all scales as many flow characteristics become independent of the Reynolds number at much larger values for the viscosity than that of the atmosphere. In this paper, we build on this property (see Appendix A). One could also refer to this technique as LES with a constant eddy viscosity."

In this manuscript we presented a DNS with a viscosity much higher than the atmosphere to simulate a flow with moderate Reynolds numbers. The essential quality of our simulation is that we have demonstrated that the viscosity is sufficiently large to show Reynolds number independence for the statistics that we are interested in. This allows us to do less computationally expensive simulations and obtain similar results. The terminology of the simulations we performed in our research is not trivial, since the modelling techniques we used are novel. We do not claim to provide the ultimate solution but we used this technique to get better insight into turbulence above complex terrain. Further research should show which technique performs best. We now choose the terminology DNS with constant eddy viscosity in the manuscript (L140-141), however we appreciate some guidance of the editor on what is preferred from the perspective of The Cryosphere.

We included in the old manuscript a thorough discussion about the use of DNS and LES to cover this topic (Section Suitability of DNS). In that Section we elaborated also on why we think a LES comparison does not add value, due to the inappropriate surface model under high Reynolds numbers in complex terrain. This means comparison to LES won't give more insight in turbulent flows than DNS with a constant eddy viscosity.

The reviewer would like to see a comparison with field measurements, however we already did this in the old manuscript. We have compared the DNS simulations to unique Eddy Covariance measurements on Lirung Glacier in the Results section (Figure 8). Those show for the location of the EC-tower the simulated and measured sensible and latent heat flux aggregated over 1 hour for fair comparison. As the measured spatial surface temperature is input data for the model we can not use this for validation of the simulations. The comparison with the EC-measurements show acceptable agreement with the simulations, demonstrating MicroHH captures important processes.

For the further improvements of our analysis and presentation we refer to our replies to the reviewer's specific comments below

Some minor comments:
Line 97, page 3. "using a novel DNS mode", please be more specific in terms of what novel algorithms or techniques are used in the DNS solver?

- *While the code is relatively new, the numerical methods are established finite difference methods (Morinishi et al., 1998). We will remove the qualification "novel".*

Page 8. I suggest the authors add a schematic to illustrate the boundary conditions and especially, the immersed boundary method used to represent the DEM. Also, please be more specific why did the authors use 0.2 mˆ2 sˆ-1 as the eddy viscosity, as opposed to other possible values?

In this paper we want to focus on the application and usability of turbulence resolving models rather than discuss the model technical details. We therefore give all user-specific information and model input needed to continue with this study. We included only a limited description of the model in the methods, since this information (including the immersed boundary method) can easily be found in the main paper of the MicroHH model (van Heerwaarden et al., 2017). We think the cryospheric reader would be mainly interested in the applicability of this study.

We include an explanation about the eddy viscosity term in L208: "We used a constant eddy viscosity of 0.2 $m^2 s^{-1}$. Preferably the viscosity of the atmosphere is used in the simulations, however this is computationally unfeasible in our simulations. Therefore we chose the lowest possible eddy viscosity and checked the results for convergence."

Referee #2

Overview:

This is an important study that sheds light on the small scale variations in turbulent heat fluxes across the surface of a debris covered glacier using a high-resolution computational fluid dynamics model applied to the near surface atmosphere. It uses a novel approach to provide valuable insight into the relative importance of key, typically measured meteorological variables and, I believe, will be of great interest to the debris covered glacier scientific community (particularly to distributed modelers). The author/s clearly has/ve a solid understanding of the physical processes underlying the stated observations in the simulation results. I think this strength could be highlighted more by, in a renamed Results and Discussion section, explaining the physical processes first, then how the results demonstrate them.

The authors show that variations in melt over the surface of a debris covered glacier is due not only to debris thickness but also to variations in turbulent fluxes. Perhaps this is intuitive, but this study is the first to show it by simulating spatial patterns in wind, humidity, and temperature. This paper shows that turbulent fluxes are important to understanding the development of ice cliffs, which have previously been shown to be ablation hotspots. It importantly shows that surface heterogeneities are an important driver of energy exchange.

We thank the anonymous reviewer for their time, and their insightful and helpful suggestions to make the manuscript more accessible and accurate.

We agree with the reviewer the manuscript would benefit from a renamed Results and discussion section (Section 3). We now implemented this in the new version of the manuscript. We also made some changes regarding the explanation and inserted a paragraph about the purpose of the experiments (see below at the specific comment)

For the further improvements of our analysis and presentation we refer to our replies to the reviewer's specific comments below

General comments:

The discussion of the study's focus on micro meteorological variables must be honed. Turbulent fluxes are determined by wind speed and surface roughness length, as well as by temperature (sensible) and humidity (latent). In the abstract, the manuscript reads "turbulent fluxes, wind fields, moisture and temperature..."; in the conclusion, the manuscript reads "turbulent fluxes, wind fields, surface specific humidity and temperature for a debris-covered glacier is investigated." I suggest reframing the language around the purpose of this study: specifically, not listing (and, thereby, implying) turbulent fluxes as separate from wind, humidity, and temperature.

Turbulent fluxes are indeed depending on the interplay between the wind, moisture and temperature of a specific site. We did not mean to suggest the effects are separate, however we stated the listing since we can only investigate the individual effects in our simulations.

We adjusted "turbulent fluxes, wind fields, moisture and temperature..." in the abstract (L14-16) and introduction (L137-141) to: In this study, we assess the effect of surface properties of debris on the spatial distribution of micro meteorological variables, such as wind fields, moisture and temperature by sensitivity tests. Subsequently we investigated how those drive the turbulent fluxes and eventually the conductive heat flux for a debris-covered glacier.

This manuscript needs English editing (grammar and punctuation) beyond what can be provided in my review; I made some suggestions, but the manuscript needs major editing for readability. The English hampered my comprehension of the scientific basis of the paper.

We carefully checked the grammar throughout the manuscript and made some improvements. We also incorporated the limited comments as suggested by reviewer 1. We hope the last mistakes will be noticed during proofreading and final typesetting.

I found the Introduction especially confusing to follow–partly because of wording choices (e.g. however, thus, and nonetheless in a single sentence) and partly because there is insufficient detail on key elements of an introduction but superfluous detail on non-essential inclusions (e.g. methods and wall modeling). The authors do not describe LES and DNS beyond spelling out the acronyms, and the authors do not discuss the reasoning behind a spatial resolution of ~1 m. The section needs clearer language to communicate a revised structure of problem/question –> hypothesis –> aims (generally exploring turbulent fluxes) –> objectives (specific, describing methods). I find that the statements of the problem (incomplete understanding of the drivers of heterogeneous melt patterns) and hypothesis are roundabout and unclear. In the last paragraph of the introduction, the aim and objectives are intermixed.

We are not sure which key elements the reviewer misses. We expanded our explanation about LES and DNS starting in L96, see reviewer 1. The reason we included quite some details in the method section is that people who want to continue with this study have a complete overview how to run the model MicroHH. In the Methods Section only an overview of the governing equations of MicroHH are given. We think this should give the reader enough basic information on the modelling framework. For more information we refer in the manuscript to van Heerwaarden et al. (2017).

We restructured the problem description in the introduction to:
"The drivers of heterogeneous melt patterns on debris-covered glaciers and the role turbulent fluxes play are not well understood. In this study, the impact of surface properties (roughness, surface temperature and surface moisture) of debris on the spatial distribution of small-scale meteorological variables, such as the turbulent fluxes, wind fields, moisture and temperature is investigated for the Lirung Glacier (Nepal) using a novel quasi DNS model with a spatial resolution of ~1 m. Observational data are used as boundary conditions, which include a high-resolution DEM (digital elevation map) and thermal imagery, retrieved from UAV (unmanned aerial vehicle) flights. We show the impact of heterogeneous surface conditions and we show that turbulent fluxes are an important contributor to the energy balance of ice cliffs. This is the first high-resolution study for a debris-covered glacier that investigates the effects of debris on meteorological variables using a turbulent fluxes resolving model. This study improves our process-understanding of debris-glacier melt, and eventually the understanding of the contribution of debris glacier melt to the current river discharge and how this will change in future. "

~1m resolution is indeed not directly justified in the text. We clarify this now better in L213-215 and added:
"A spatial resolution of 1 meter is the highest possible spatial resolution, given the constraints of computational power and spatial resolution of the input data. In Appendix A we show the spatial resolution of 1 meter is sufficient to capture the characteristics of the flow and that increasing the resolution will not add more information."

Simulations: I think the suite of simulations provides valuable insight into the different variables in the energy balance. However, the author needs to make a distinction between humidity moisture and surface roughness topography/DEM as well as improve the explanation for the source of the distributed temperature and humidity data. A priori, it seems that it could be useful to conduct simulations with halved temperature and humidity deviations from the means. I think that the justification and explanation for choosing the 7 simulations needs to be strengthened and clarified, as I miss the reasons for performing the specific simulations.

We are not sure what the reviewer means by "the author needs to make a distinction between humidity moisture and surface roughness topography/DEM", as we discuss all experiments separately in the manuscript. In those experiments we make a clear distinction between the effects of temperature, specific moisture and DEM effects, and in the last experiment we combine those.
We are sorry for the confusion but the experiments are listed in Table 1:

Table 1: Overview of experiments done with MicroHH. The DEM indicates the boundary condition used for the topography (0 means no DEM, ½ DEM is the original DEM halved in height, real is the spatial measured value), T_s the surface potential temperature (313.3K is a homogeneous value, real is the spatial measured value), q_s is the surface specific humidity (8.6 g kg^{-1} is a homogeneously value, the choice for the relative humidity range is described in Sect. 2.4)

Experiment	Description	DEM	T_s	q_s
HOM_{flat}	Homogeneous glacier	0	313.3 K	8.6 g kg^{-1}
$HOM_{1/2DEM}$	½ DEM	½ DEM	313.3K	8.6 g kg^{-1}
HOM_{DEM}	Roughness effects	Real	313.3 K	8.6 g kg^{-1}
HET_T	T_s effects 'normal'	Real	real	8.6 g kg^{-1}
HET_{qdry}	q_s dry	Real	313.3 K	Spatially RH=70-75%
HET_{qmoist}	q_s wet	Real	313.3 K	Spatially RH=70-85%
REAL	"Reality"	real	real	Spatially RH=70-85%

For completeness we now inserted a small paragraph in L257 to make the purpose of the experiments more clear:
"With the HOM_{flat} $HOM_{1/2DEM}$ and HOM_{DEM} experiments we quantify the sensitivity of the turbulent fluxes to the topography. The HET_T experiment will reveal the effects of a spatially variable surface temperature compared to a homogeneous surface temperature (HOM_{DEM}). The HET_{qdry} and HET_{qmoist} experiments are aimed to reveal the influence of heterogeneous surface specific humidity compared to a homogeneous value (HOM_{DEM}) and will show the effects between a relatively dry and moist debris layer. In the REAL experiment all effects are combined and will be compared to HOM_{flat} and HOM_{DEM} to understand the combined effects as well."

Also, we added in L250: "These experiments are chosen to determine the separate effects of topography, surface temperature and surface specific humidity on the surface energy balance of a debris-covered glacier."

We designed the experiments carefully to show the impact of roughness, humidity and temperature on the atmosphere. We would have liked to perform additional experiments but they are computationally very expensive. To our opinion these experiments reflect the most optimal configuration with the available resources. Nonetheless, experiments suggested by the reviewer could be very interesting for upcoming studies.

Specific comments:
- Title: suggest simplifying to "using 3D turbulence-resolving simulations to investigate the energy balance of a debris-covered glacier"

  We would like to point out in the title that we specifically look at surface properties, as there are also other variables could play an important role in turbulent-resolving simulations (temperature lapse rates, wind profiles, pressure differences etc. We therefore choose to keep the existing title of the manuscript.

- Abstract: needs to be original and not contain exact sentences from the body of the manuscript. It would be appropriate to mention that you designed a series of simulations that differed in input parameters in order to isolate and investigate the effects of varying those parameters.

  We changed the first part in the abstract to:
  "Debris-covered glaciers account for almost one fifth of the total glacier ice volume in High Mountain Asia, however their contribution to the total glacier melt remains uncertain and the drivers controlling this melt are still largely unknown. Debris influences the thermal properties (e.g. albedo, thermal conductivity, roughness) of the glacier surface and thus the surface energy balance and glacier melt. In this study, we assess the effect of surface properties of debris on the spatial distribution of micro meteorological variables, such as wind fields, moisture and temperature by sensitivity tests. Subsequently we investigated how those drive the turbulent fluxes and eventually the conductive heat flux for a debris-covered glacier.

- Line 12: remove first "total"

  We implemented this change
- Line 20: suggest replace "ascertain" with "provide insight into"

We changes this

- Line 32: explain/rephrase "non-saturated surface" or provide a reference.

We rephrased "non-saturated surface" to "unsaturated surface"

- Line 43: add a citation for gravel. Be more specific that you are talking about surface roughness lengths. Later, you use surface roughness interchangeably with topography (and DEM). Specifying length here would eliminate subsequent confusion.

The Miles et al., 2017 citation is also valid for the gravel statement.

We changed "surface roughness" in L60 to "surface roughness length". In the manuscript we refer to "surface roughness length" as z_0. And "surface roughness" as the topography roughness.

- Line 51: what does "spatial melt" mean? You don't cite any distributed energy balance model on debris covered glaciers: e.g., Reid et al (2012), Fyffe et al (2014)

Sorry for the confusion, we meant 'model melt spatially' instead of spatial melt. We didn't included the references Reid et al (2012 and Fyffe et al (2014)), since those are based on Reid 2010 (which we cite).

- Line 54: "we" or "they"?

We changed it to 'they'

- Line 55: there are many remotely-sensed observations. If excluding these, be specific. Also, missing references with data: Vincent et al (2016), Nicholson et al (2018), Nicholson Mertes (2017)

We agree there are many remotely-sensed observation studies of the surface of debris-covered glaciers, however those do not give insight in small-scale atmospheric processes. We understand the confusion and we changed "as observations on debris-covered tongues are limited" to "as atmospheric field observations on debris-covered tongues are limited"

- Line 58: this is a bold claim. Be specific for what observations are over short time spans.

We added "field" in L55 to clarify we mean field observations and not remotely sensed observations.

- Line 60: modeling would lend significant new insights, but you haven't argued it is "essential." Language implies it is the only method to shed light on the question, whereas it is only one approach.

We rephrased L77-78 from:

"Due to this large spatial variation, a high-resolution modelling approach is therefore essential to capture the coupling and interaction between the surface and the atmosphere with sufficient accuracy (Mott et al., 2014)"

to:

"Due to this large spatial variation, a high-resolution modelling approach can give important new insights into the coupling and interaction between the surface and the atmosphere with sufficient accuracy (Mott et al., 2014)"

- Line 64: "heat fluxES"

We have changed this

- Line 65: "gradientS"

We have changed this

- Line 65: Steiner et al (2018) found that bulk methods overestimate turbulent heat fluxes. . . seems relevant to mention.

We have added in L92 "As a result, Steiner et al., (2018) found for example that bulk methods overestimate turbulent heat fluxes."

- Line 66: summarize the "many assumptions" since this point is central to the problem you aim to address

We rephrased L91-92from:

"On debris-covered glaciers however, many assumptions of the bulk-method do not hold due to the high spatial heterogeneity of atmospheric variables, a general lack of atmospheric stability or inappropriate parameterizations for the complex interaction between the heating surface and the boundary layer (Steiner et al., 2018)."

"However, the bulk method assumes atmospheric stability and a constant surface roughness, which are not valid over debris-covered glacier surfaces (Steiner et al., 2018)."

- Line 70: "therefore" is for results, not for clarification. Suggest id est here. "and therefore wind, humidity and temperature fields" –> "(i.e. its wind, humidity and temperature fields)"

OK, we changed this

- Line 86: "we are converging to that range in this study": meaning unclear

We do not resolve all the scales in the atmosphere in this study, however, only a marginal part of the total variance is missed and the most relevant results are independent of the Reynolds number.

We have added in L119: "as we show that only a marginal part of the total variance is missed and the most relevant results are independent of the Reynolds number".

- Line 105: inconsistent formatting
  We changed the formatting of the header.
- Lines 107 - 108: rephrase sentence
  We changed this line from: "The Langtang catchment has an area of approximately 560 km^2 and is glacierized for 30% and 25% of all glaciers is debris-covered"
  to:
  "The Langtang catchment has an area of approximately 560 km^2 and is glacierized for 30%. One fourth of all glaciers is debris-covered."
- Figure 1 and most subsequent figures: include axis units and labels!
  We added now in all spatial figures the x and y direction and its unit (m). Changes are done in all figures, except Figure 4, 8 (only title change), 10 (added label of ice cliff), A2 and A3.
- Line 131: suggest section title "field measurements." Section as a whole needs tightening of language to be more to-the-point. It is difficult to decipher meaning.
  We changed the section title to "field measurements"
- Line 135: what is the purpose of this citation?
  The data is used before in Steiner et al., 2018. For more details you can consult that paper.
- Line 149: what is the purpose of these citations? Consider adding the words "following" or "after" if that's what you mean
  The data is used and processed in Immerzeel et al. 2014 and Kraaijenbrink et al., 2016.
- Lines 151 - 152: info in sentence "we only. . . the model" needs to be added to the previous section to explain the extent of the microHH domain
  We discuss Figure 2 in L212, and we think L217-220 do fit at current place
- Line 157: if this dash is to indicate negative, make sure it is on the same line (and page!) as the following number... and that Fig2A has the stated range included in its colorbar.
  We adjusted the topography range in the text to 0-57m, to avoid confusion. The topography showed in Figure 2A is the model input.
- Line 159: suggest rewrite "2- Line 162: suggest replace "used... LES)" with "a computational fluid dynamics model designed to simulate turbulent flows in the atmosphere through direct numerical simulation (DNS) and large eddy simulation (LES)."
  We rephrased L225 to "In total 2% of the domain is covered…"
  L162 is replaced as suggested
- Line 164: suggest replacing "what could be interpreted as" with "which effectively renders it"
  We replaced this as suggested
- Line 166: refer the reader?
  We kept the sentence as "For specific details of the model we refer to Heerwaarden et al. (2017) but we do give a brief description of the model below."
- Line 170: instead of what, which (error appears many times)
  Check all cases throughout manuscript
- Line 171: instead of therefore, thereby
  We changed this.
- Line 173: instead of are, is
  We kept are
- Lines 193 - 194: these lines need review with respect to units and consistency. (Density is not kg/kg; what is "thermal diffusivity for heat" with a value of 0.1 m^2/s? If you mean thermal diffusivity of water, give a calculation with specified T and P. Should be ~0.1 x 10^{-7} m^2/s)
  Density is in units of kg/m3, whereas the thermal diffusivity of heat in the atmosphere is chosen to be 0.1 m2/s in order to constrain the Reynolds number. In order to convert the flux to actual fluxes in the atmosphere, we take into account the actual thermal diffusivity of air (~1 e-5 m2/s).
- Line 196: "accumulated temperature" is not intuitive. Please explain.
  We added in the text "of a gridcell" and "and should be divided by the surface area of that cell to obtain the flux in W/m^2"
- Line 209: here and elsewhere, meterS when more than 1

We changed this throughout the manuscript.

- Line 210: condition is

  We changed this

- Line 232: themselves

  We changed this

- Line 233: suggest "are periodic, such that air flowing out of one side of the domain will enter on the opposite side."

  We changed this

- Line 249: the table lists seven experiments, not six

  We changed 6 → 7

- Lines 263 - 264: these sentences are superfluous

  We think this information can be relevant who wants to use this model as it gives an indication how expensive the model runs are.

- Line 265: By this point, I am missing an in-depth description of experiment design and what question each experiment was designed to answer. A reader can possibly deduce this from the results, but the purpose should be stated more explicitly.

  We inserted a small paragraph in L349:

  "With the HOM_{flat} $HOM_{1/2DEM}$ and HOM_{DEM} experiments we quantify the sensitivity of the turbulent fluxes to the topography. The HET_T experiment will reveal the effects of a spatially variable surface temperature compared to a homogeneous surface temperature (HOM_{DEM}). The HET_{qdry} and HET_{qmoist} experiments are aimed to reveal the influence of heterogeneous surface specific humidity compared to a homogeneous value (HOM_{DEM}) and will show the effects between a relatively dry and moist debris layer. In the REAL experiment all effects are combined and will be compared to HOM_{flat} and HOM_{DEM} to understand the combined effects as well."

- Table 1 caption needs proofreading (homogenous or homogenously?; should be "spatially varying")

  We changed the caption to:

  Table 1: Overview of experiments done with MicroHH. The DEM indicates the boundary condition used for the topography (0 means no topography, 1/2 DEM is the original topography halved in height, real is the spatially measured value), Ts is the surface potential temperature (313.3K is a homogeneous value, real is the spatially measured value), qs is the surface specific humidity (8.6 g kg-1 is a homogeneous value, the choice for the relative humidity range is described in Sect. 2.4).

- Line 273: 2012 (not 2013)

  We changed this

- Line 300: suggest "all fluxes are defined as positive towards the surface except for the conductive heat flux"

  We changed this

- Line 302: suggest renaming the section "results and discussion" and including more discussion rather than assuming that the reader can deduce the significance from the figures (e.g. line 308: "the effect of the surface roughness on the SHF and LHF is evident (figure 3A - F)"). This section would benefit from an overview of the fact that the authors perform seven experiments designed to very key parameters that control turbulent heat fluxes in order to investigate the relative importance of various controls. Then, the subsections and figure captions could be strengthened by statements of which tests were designed to test which variables.

  We included now the purpose of each experiment in Line 349-354 (see above) and think this is sufficient for the reader to understand the purpose of each experiment. We also renamed the section to results and discussion. We added:

  L405: "seven experiments are performed (Table 1) where key parameters are varied that control turbulent heat fluxes in order to investigate the relative importance of topography, humidity and surface temperature."

  L308 (old line number): We do not agree, since we explain what is evident from the figures in L308-L310 in lines directly following this statement: "The turbulent fluxes are intensified with increasing variability in topography, since increasing the surface roughness is directly related to the surface roughness length and the generation of turbulence."

- Line 306: introduce that for temperature you contrast HET_T with HOM_{DEM} and mention how you plan to incorporate "REAL"

See above (L349-354)

- Figure 4: this figure summarizes the results of the experiments very well. The caption could benefit from a reminder of the sign convention for fluxes.

  We added to the caption of Figure 4: " Fluxes pointed to the surface are positive."

- Section 3.1.4: it is not clear why only three of the experiments are discussed in this section. The last sentence of this section raises a very important point, which should be discussed further.

  We discuss in this section when homogeneous surface conditions are reasonable and when not. The last sentence is therefore a conclusion of the paragraph and does in our opinion not need more explanation.

- Line 351: "spatial variations in"

  We changed this

- Figures 5, 6, 7: what kind of cross sections are these? (Reference the black lines in figure 2 in the manuscript text around figures 5 - 7.)

  We added x, y and z labels in the panels of Figures 5-7, so it is now clear which cross sections are meant from Figure 2.

- Line 360: use topography rather than DEM. The two are not interchangeable

  We have changed this.

- Line 364: "ejections." What about diffusion and advection?

  We have added "mainly" to indicate there are other processes present but not leading.

- Line 377: "reduce," but can't it also increase? Suggest "alter."

  We changed this.

- Figure 7: the last column of some figures is striking because the change with height (cold to warm versus warm to cold) differs between experiments. Must discuss this and other features of the figures.

  The heterogeneous surface temperature causes negative surface temperatures on ice cliffs. We have now added in L481: "Heterogeneous surface temperatures allow negative surface temperatures at ice cliffs, resulting in reversed temperature gradients close to the surface (HET_T and REAL; Figure 7)."

- Line 372: point out specific features in figures

  We have added: " This is for example visible above the ice cliff (x=510-600m), where the wind gradient is decreasing to the bottom. "

- Lines 395 and 402: LC or LT?

  We changed this to LT

- Figure 8: dry debris and wet debris (change word order). It would be more intuitive to group the dried debris as A and B, the wet debris as C and D, etc.

  We changed the word order in the figure header. We have kept the numbering, as we want the figure to be 'horizontal'

- Lines 395 - 396: this sentence seems to negate the importance of the following figure. Needs clarification.

  We have added in L515: "This means the variability of turbulent fluxes is large, even with constant surface boundary conditions."

- Line 405: paraphrase "REAL case" for clarity

  We changed "case" to "experiment"

- Line 407: "spatial distribution of surface moisture. . ."

  We have changed this

- Line 410: good insight into physical properties. Not clear how to disentangle effects of topography from effects of debris.

  We compare the HOM_{DEM} experiment with the REAL experiment, so in both are the topography effects and do not need to get disentangled.

- Lines 411 - 413: this is an important point which is difficult to discern because of the language. Rewrite. Also, author(s) need to distinguish their contributions from physical principles. SHF more sensitive to T for dry debris is true b/c water has a higher heat capacity than air. "10 times as high" in next line is something learned through the model.

  We changed the sentence from:

  Different sensitivities of turbulent fluxes to surface temperature or moisture are thus applicable in wet and dry climates and the choice of surface boundary conditions should be chosen carefully for simulations.

  To:

  "Turbulent fluxes have different sensitivities to surface temperature and moisture indicating that the sensitivities are different in wet and dry climates. As a result surface boundary conditions should be chosen carefully for simulations."

In L535 it is stated that the LHF is 10 times as high in the experiments, so it is clear this is learned from the model and is not used as a physical explanation.

- Lines 416 - 417: If these are averages, why is there an uncertainty? And why is it greater than the average?

  It is not uncertainty but the standard deviation of spatial variability; we have now indicated this in L539:

  "Domain averaged (with its spatial standard deviation)"

- Line 421: "near-surface air is saturated" contradicted at end of paragraph

  We mean only the air above the ice cliff, at the end of the paragraph we discuss the whole domain. The relatively dry eddies generated above (dry) debris flow over a saturated ice cliff. This is therefore not a contradiction with L424-425.

- Line 429: weighted how? Approach needs an explanation.

  The AWS data are presented as a weighted average everywhere in manuscript. We stated this in L201

- Line 441: Suggest "figure 9 shows conductive flux into the debris under the seven simulations."

  We changed this.

- Line 452: can you say anything here about the physics with respect to thermal conductivity, density, and heat capacity? Conductive heat flux is determined by the temperature gradient in the debris, so this is expected. Clarify what additional insight your simulations provide.

  We define the conductive heat flux as the surplus of the surface energy balance (equation 12). To clarify this, we have added in the manuscript: "The energy reaching the ice below the debris is dependent on the thermal conductivity, density and heat capacity of the debris."

- Table 2 line 480: what is the significance of the non-normal distributions, for which standard deviations exceed the means? Consider using other statistical metrics instead/also.

  It denotes the spatial variation in the domain, we have added in L620 "…heat flux (± spatial variation)…"

- Table 2: refer to this table in the text

  This is done in L580

- Table 2: what is the breakdown of ice-cliff area vs. debris area in the domain? Mention in caption and discuss in text if you contrast in a table.

  Ice cliffs cover 2% of the domain, as stated in L225. We now repeat this in the caption for completeness.

Lines 467 - 472: relate to recently published findings on ice cliffs in HMA

  We have added: "Other studies found ice cliffs melt between 5.7 and 13.7 times faster than ice below surrounding debris debris (Brun et al., 2016; Sakai et al., 2002; Buri et al., 2016; Reid and Brock, 2014). Although those consider total melt rather than the surface energy balance, the pronounced differences between melt on ice cliffs and debris are in line with our research."

- Line 477: observationS of what value(s)?

  Observations of specific humidity, as stated at start of this line

- Lines 504 - 505: clarify with "every 10 seconds of [time interval] in the simulation"

  We have added "time" to indicate panels are shown with 10 seconds time interval

- Figure 10: label ice cliff face, give variables in headings for each row of figures (A - F, G - L, and M - R), and specify the exact time interval in the caption. Also, should be 660<x<500.

  The ice cliff is now made more clear in Figure 10. The labels are given in the individual subplots. We changed 660<x>500m to 660<x<500m. The exact time intervals are given in the caption. We added 'with 10s time interval'.

- Line 529: "and is" to "that was"

  We have changed this.

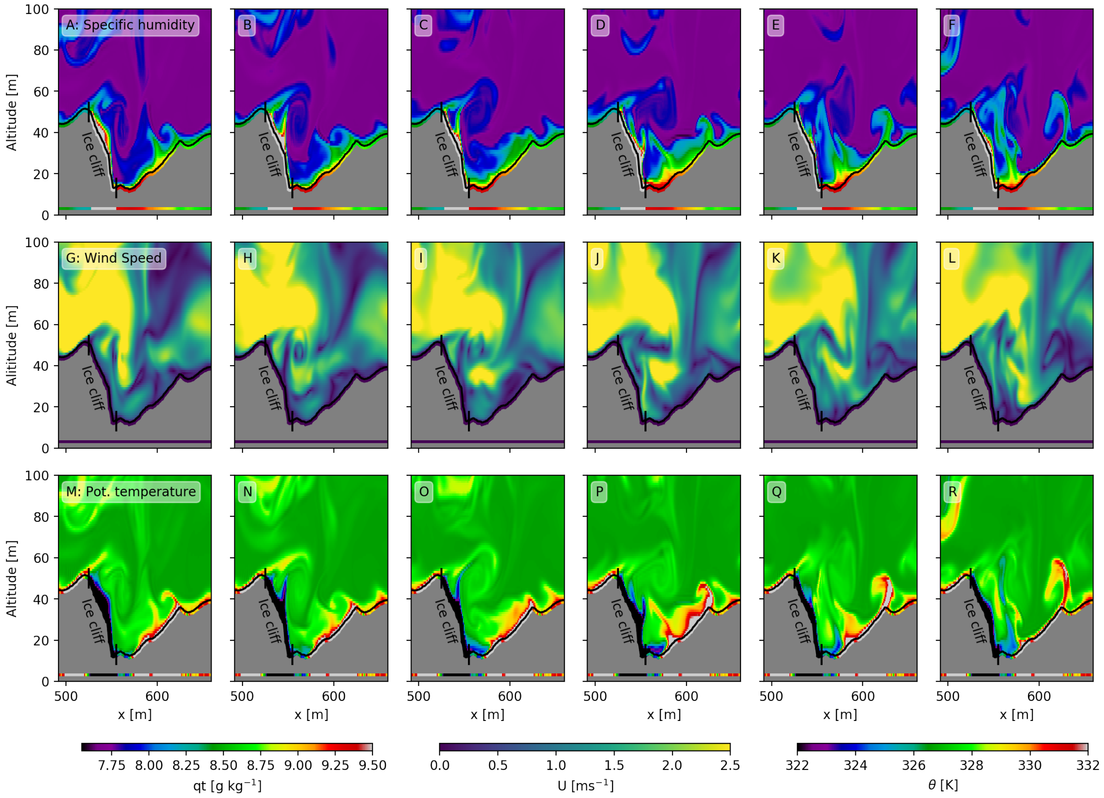
- Line 531: turbulent fluxes likely play

  We have changed this.

- Line 532: it is appropriate to refer to the figure, but the reader cannot "see" the windspeed derivative where the ice cliff changes slope. Labeling the ice cliff and circling the region of interest on the figure would help.

  We agree the reader can not see the derivative, however we focus on the vertical wind speed variations; those can be seen in Figure 5.

We label the ice cliff now in Figure 10:



- Line 535: "wind flow does flow": rewrite

    We changed this to "the main wind flow is over the depression"

- Section 4: suggest renaming as "sensitivity to Reynolds number" and start with a short description of the Reynolds number and why you chose to perform a sensitivity test on it. The first paragraph of this section states that both DNS and LES are impossible. The meaning of this paragraph is especially difficult to discern from the English that is used.

    We would like to state that neither DNS nor LES is impossible, but that each has its own set of problems that need to be overcome in order to make meaningful simulations. We renamed the Section as suggested by the reviewer. We added a paragraph about the Reynolds number in L688:

    "The Reynolds number (Re) is a measure for the flow characteristics and is the ratio between inertial and viscous forces in a fluid (Eq. 18). A low Reynolds number would indicate a laminar flow and high Reynolds numbers a turbulent flow.

    $$Re=\frac{uL}{\nu}, \qquad (18)$$

    Where u is the velocity (m/s), L is the characteristic length scale (m) and v is the kinematic viscosity (m^2/s) of the fluid. By decreasing the kinematic viscosity the fluid will become more turbulent and resolve smaller scales."

- Lines 545 - 550: what is the effect of the different resolutions on the profiles near the surface, where the difference is most apparent? You show the resolution is not too large for achieving accuracy, but could the same patterns be captured with a resolution larger than one meter? How much larger?

    We did some sensitivity tests with coarser resolutions, however those missed the details a 1m resolution simulation gives. The focus of the paper is not on the sensitivity to the spatial resolution and we decided not look in detail to this.

- Lines 561 - 563: rephrase

    We rephrased from: "The simulation at low viscosity naturally resolves smaller scales than the simulation with a higher viscosity, yet the additional variability does not relevantly add variance to the signal and are therefore irrelevant for the flow (Figure A3, wave numbers>11)"

    To: "The simulation at low viscosity naturally resolves smaller scales than the simulation with a *higher viscosity (see Equation 18). In Figure A3 we see that the additional variability does only add a small amount of variance to the signal and is therefore irrelevant for the flow (wave numbers>11)"*

- Line 556: topography, not orography

We changed orography to topography

- Section 5 "Limitations": this section especially needs proofreading by the author(s). The writing makes it difficult to discern many of the concepts, which are ones important to the paper.

We made some changes in the Section Limitations:

L722: over → for
L724: added "is unknown" end of sentence
L724: is → was
L725: gain understanding in →gain understanding of
L726: show → showed
L726: turbulence resolving → turbulence-resolving
L727: identify → identified
L729: hereafter → in the following paragraphs
L730: removed 'very'
L732-733: "Debris-covered glacier studies normally deal with this unknown by assuming the debris surface…" → "Studies normally deal with this limited information about surface moisture by assuming that"
L757: Step forward for → step forward to
L781: prescribed →included
L792: lead to: result in
L794: representative for → representative of
L794: However→ However,
L794: such → so
L795: High resolution → high-resolution

- Line 576: add that debris moisture is important to not only turbulent heat fluxes but also the conductive heat flux that ultimately melts glacier ice

We added "and therefore the conductive heat flux that ultimately melts the ice."

- In this discussion of moisture, can you add some discussion of season and any implications of your findings for the monsoon season in particular?

We added in L626: "During monsoon surface moisture will be higher than in the rest of the year, indicating the conductive heat flux at the surface will be higher during monsoon than in winter and spring"

- Line 598: here, it sounds like the AWS station you used *happened* to be in a spatially-representative place but that you got lucky because "in reality it remains very hard to locate a station such that it is representative for the whole domain." If this is not the case, please change the language. Additionally, it would be helpful if you quantified the amount of bias that could be introduced by upscaling point measurements not representative of the domain.

Our experiments made sure the homogeneous value is representative for the domain, as this is an average of the heterogeneous values. This means our homogeneous value is per definition representative of the domain. The bias of upscaling point measurements is given by comparing homogeneous surface conditions (HOM experiments) and heterogeneous surface conditions (HET experiments).

- Line 615 - 618: these lines read that you investigated the impact surface temperature and specific humidity have on surface specific humidity and temperature. Please rewrite with greater clarity.

We agree this is confusing. We changed the sentence to "In this study, the impact of surface properties of debris (surface roughness, temperature and specific humidity) on the spatial distribution of small-scale meteorological variables, such as turbulent fluxes and near-surface wind fields, specific humidity and temperature for a debris-covered glacier is investigated.

- Line 642: I would think that that the bare ice on ice cliffs has a higher albedo than debris covered surroundings; explain or cite otherwise.

Ice cliffs generally have an amount of sand/dust on the ice cliffs that lowers the albedo. This is stated in Steiner et al. (2015), and indicated in the methods Section, L377.

- Line 648: this paragraph is important to include only if you quantify and show an example of the large biases that are possible.

We showed the bias between homogeneous and heterogeneous variables in the results section and keep this paragraph.

- Line 661: add labels to axes in the .gif's (videos)

We have done this for the vertical cross sections and conductive heat flux videos. It will take a few days before this is visible on Zenodo

- References: cite publications in The Cryosphere, not The Cryosphere Discussions where possible (e.g., Rounce et al., 2015)

We update Rounce et al., (2015) to the fully published article.

Using 3D turbulence-resolving simulations to understand the impact of surface properties on the energy balance of a debris-covered glacier

Pleun NJ Bonekamp[1], Chiel C van Heerwaarden[2], Jakob F Steiner[1] and Walter W Immerzeel[1]

1. Department of Physical Geography, Utrecht University, The Netherlands

2. Meteorology and Air Quality Group, Wageningen University, The Netherlands

Correspondence to: Pleun NJ Bonekamp (p.n.j.bonekamp@uu.nl)

Abstract

Debris-covered glaciers account for almost one fifth of the total glacier ice volume in High Mountain Asia, however their contribution to the total glacier melt remains uncertain and the drivers controlling this melt are still largely unknown. Debris influences the thermal properties (e.g. albedo, thermal conductivity, roughness) of the glacier surface and thus the surface energy balance and glacier melt. In this study, we assess the effect of surface properties of debris on the spatial distribution of micro meteorological variables, such as wind fields, moisture and temperature by sensitivity tests. Subsequently we investigated how those drive the turbulent fluxes and eventually the conductive heat flux for a debris-covered glacier. We simulated a debris-covered glacier (Lirung Glacier, Nepal) at a high-resolution of 1 m with the MicroHH model with boundary conditions retrieved from an automatic weather station (temperature, wind and specific humidity) and UAV flights (digital elevation map and surface temperature), and the model is validated with eddy covariance data. Subsequently, a sensitivity analysis was performed to provide insight into how heterogeneous surface variables control the glacier micro-climate. Additionally, we show ice cliffs are local melt hot spots and that turbulent fluxes and local heat advection amplify spatial heterogeneity on the surface. The high spatial variability of small-scale meteorological variables suggests that point based station observations cannot be simply extrapolated to an entire glacier and should be considered in future studies for a better estimation of glacier melt in High Mountain Asia.

Deleted: Debris-covered glaciers account for 18% of the total glacier ice volume in High Mountain Asia, however the drivers controlling the melt of these glaciers are still largely unknown and their total contribution to the total glacier melt remains uncertain. Debris influences the surface energy balance and therefore glacier melt by influencing the thermal properties (e.g. albedo, thermal conductivity, roughness) of the glacier surface. In this study, the impact of surface properties of debris on the spatial distribution of micro meteorological variables, such as the turbulent fluxes, wind fields, moisture and temperature and eventually the conductive heat flux for a debris-covered glacier is investigated.

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1. Introduction

Glaciers in High Mountain Asia (HMA) act as a fresh water supply for millions of people living downstream, and this supply will change due to global warming (Lutz et al., 2013; Wester et al., 2019). Debris-covered glaciers account for 18% of the total glacier ice volume in High Mountain Asia, however the exact melt processes of these glaciers are still unknown and their total contribution to the total glacier melt remains uncertain (Kraaijenbrink et al., 2017).

Debris-covered glacier surfaces differ from clean ice glaciers by surface temperatures that can exceed the melting point considerably, a higher topographic variability and the possibility of an unsaturated surface. As a result debris influences the

Deleted: nonsurface energy balance and therefore glacier melt by influencing the thermal properties (e.g. albedo, thermal conductivity) of the glacier surface (Reid and Brock, 2010). Glacier ablation is generally enhanced due to the albedo effect by debris thickness smaller than a few centimetres, while it decreases exponentially with thickening debris by ice insulation (Östrem, 1959).

The energy exchange between the (debris-covered) glacier surface and atmosphere is determined by small-scale meteorological conditions, rather than large-scale weather patterns (Sauter and Galos, 2016). Heterogeneous surface conditions affect the microclimate resulting in large spatial differences in energy balance components (Reid and Brock, 2010). For example, daytime surface temperatures can range between melting point (ice and water) and 27.5 °C due to inhomogeneous surface heating and variable debris thickness (Kraaijenbrink et al., 2018; Steiner and Pellicciotti, 2016) and the surface roughness length ranges from ~0.005 m (gravel) to ~0.5 m (boulders; Miles et al., 2017). Local melt hot spots generally exist on the surface of a debris-covered glacier in the form of ice cliffs and supraglacial ponds (Buri et al., 2016; Miles et al., 2016), causing highly heterogeneous ablation rates. However, it is not entirely understood how those ice cliffs and ponds form, evolve and disappear. While cut-and-closure of englacial drainage systems are likely an important driver (Benn et al., 2017; Miles et al., 2017b) and the interaction between cliffs and ponds is an important process (Miles et al., 2017b; Steiner et al., 2019), heterogeneous meteorological forcing over the debris surface likely also plays a role (Buri and Pellicciotti, 2018). The influence of spatial variability and especially with respect to turbulent exchange in the atmosphere however has so far not been investigated.

Currently there are several methods to model melt spatially of a debris-covered glacier including a multilayer energy balance model (Reid and Brock, 2010) and a fully coupled atmosphere-glacier mass balance model (Collier et al., 2013), where only the latter includes two-way debris-atmosphere feedbacks. However these approaches remain limited in their scope since they lack insight in the spatial and temporal distribution of surface and meteorological variables, as atmospheric field observations on debris-covered tongues are limited to a few field locations in the Himalaya (Lejeune et al., 2013; Ragettli et al., 2013; Rounce et al., 2015; Steiner et al., 2018), the Karakoram (Mihalcea et al., 2008) and the Tien Shan (Yao et al., 2014), and are all of relatively short time spans in the range of days to multiple months. Extrapolating point measurements remains a challenge on debris-covered glaciers, as measurements from a single weather station are not representative for the complex, inhomogeneous terrain. Due to this large spatial variation, a high-resolution modelling approach can give important new insights into the coupling and interaction between the surface and the atmosphere with sufficient accuracy (Mott et al., 2014).

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Turbulent fluxes can play a substantial role in the surface energy balance of a debris-covered glacier (Rounce et al., 2015; Steiner et al., 2018) and are often calculated with the bulk method, where the sensible and latent heat fluxes are related to the temperature and moisture gradients between the atmosphere and surface respectively.

However, the bulk method assumes atmospheric stability and a constant surface roughness, which are not valid over debris-covered glacier surfaces (Steiner et al., 2018). As a result, (Steiner et al. (2018) found for example that bulk methods overestimate turbulent heat fluxes.

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In order to get insight in the microclimate of a debris-covered glacier (i.e. wind, humidity and temperature fields), high-resolution turbulent resolving simulations may provide the solution. Turbulence can be simulated by two techniques: LES (Large Eddy simulations) and DNS (Direct Numerical simulations). The difference between them is the treatment of the smallest scales in the flow; LES uses a subgrid parameterization and DNS resolves these explicitly. DNS at atmospheric viscosity is computationally unfeasible, but it is not always necessary to resolve all scales as many flow characteristics become independent of the Reynolds number at much larger values for the viscosity than that of the atmosphere. In this paper, we build on this property (see Appendix A). One could also refer to this technique as LES with a constant eddy viscosity.

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Large-eddy simulations (LES) studies have been conducted for clean-ice glaciers, focussing on katabatic winds and sensible heat fluxes (e.g. Axelsen & Dop 2009; Axelsen & van Dop 2009; Sauter & Peter Galos 2016). LES often imply a simplification of reality, such as a flat terrain and horizontally homogeneous meteorological conditions (Axelsen and Dop, 2009), though simulations can give insight in fundamental processes. LES ignore the smallest length scales of turbulence and can be used if the behaviour of those scales can be described as a function of the resolved structures in the simulation. In order to resolve also the smallest length scales direct numerical simulation (DNS) should be used.

Both DNS and LES have advantages and drawbacks for the simulation of atmospheric turbulent flows. Generally, it is assumed LES represents high Reynolds numbers well, while DNS is only correct if all scales in the flow are resolved. However, as shown by (Moin and Mahesh, 1998), it is in many cases unnecessary to resolve the flow up to the Kolmogorov scale, as many of the statistics of turbulent flows become independent of the Reynolds number at Reynolds numbers far less than the atmospheric one. This is proven for convective boundary layers in the atmosphere (Van Heerwaarden and Mellado, 2016), turbulent channel flow (e.g. Moser et al., 1999; Schultz and Flack, 2013), Ekman flow (Spalart, 2009), and stable atmospheric boundary layers (Ansorge and Mellado, 2016). Additionally, Dimotakis, (2000) has delivered clear guidelines on estimating whether turbulence is fully developed and we are converging to that range in this study as we show that only a marginal part of the total variance is missed and the most relevant results are independent of the Reynolds number

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Applying LES combined with wall models in complex terrain is questionable, as the Monin-Obukhov Similarity Theory (MOST) that is used to compute the interaction with the wall has been demonstrated invalid already over simple slopes (Nadeau et al., 2013). Wall modelling on the faces of non-horizontal objects is an unsolved challenge, as all assumptions of the MOST break down. Since no alternative is available MOST is often used nonetheless. This could come with side effects of which the consequences are potentially harder to estimate and interpret than those of moderate Reynolds numbers in the application of DNS.

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The drivers of heterogeneous melt patterns on debris-covered glaciers and the role turbulent fluxes play are not well understood. In this study, the impact of surface properties (roughness, surface temperature and surface moisture) of debris on the spatial distribution of small-scale meteorological variables, such as wind fields, moisture and temperature and subsequently the turbulent fluxes and conductive heat flux is investigated for the Lirung Glacier (Nepal) using a DNS model with constant eddy viscosity and a spatial resolution of ~1 m. Observational data are used as boundary conditions, which include a high-resolution DEM (digital elevation map) and thermal imagery, retrieved from UAV (unmanned aerial vehicle) flights. We show the impact of heterogeneous surface conditions and we show that turbulent fluxes are an important contributor to the energy balance of ice cliffs. This is the first high-resolution study for a debris-covered glacier that investigates the effects of debris on meteorological variables using a turbulent fluxes resolving model. This study improves our process-understanding of debris-glacier melt, and eventually the understanding of the contribution of debris glacier melt to the current river discharge and how this will change in future.

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2. Methods

2.1. Study area

Lirung Glacier is a debris-covered glacier in the Langtang catchment located 50 kilometres North of Kathmandu (Nepal; Figure 1). The Langtang catchment has an area of approximately 560 km^2 and is glacierized for 30%. One fourth of all glaciers is debris-covered. Lirung Glacier itself is 3.5 km long and on average 500 m wide (Immerzeel et al., 2014a) and ranges in elevation from 4000 m to 7132 m a.s.l.. The surface is highly heterogeneous and debris is composed of a range of textures from silt to gravel to boulders (Miles, 2017). The average gradient of the tongue is approximately 2 degrees and debris thickness ranges from 0.1 to 2.0 m (McCarthy et al., 2017). This area is influenced during the summer months by the Indian summer monsoon, which provides 70% of the annual precipitation. (Immerzeel et al., 2014b). The winters are relatively dry and precipitation generally occurs only during a few cyclonic events (Bonekamp et al., 2019; Collier and Immerzeel, 2015).

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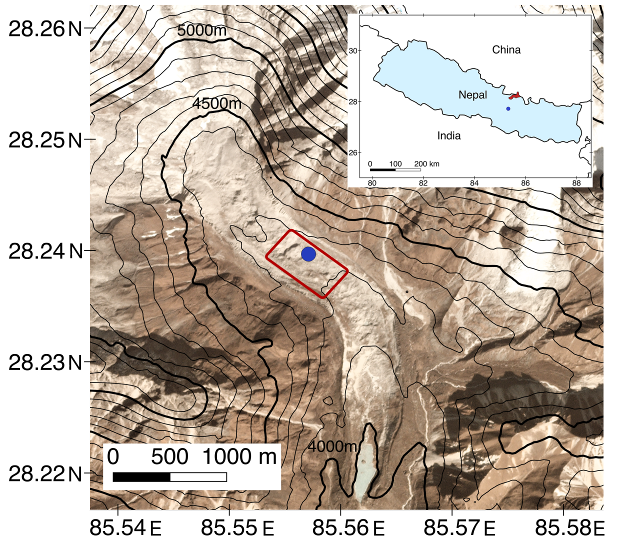

Figure 1: Lirung Glacier with the microHH domain (red contour) and the location of the AWS (blue point). The background image is a Planet image from 9 December 2018 (Planet Team, 2017). *The inset shows the Langtang catchment (red) and its location in Nepal.*

2.2 Field measurements

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Data of an AWS on the glacier (Figure 1) is used and observations are made of air temperature, wind speed, relative humidity and incoming and outgoing short- and longwave radiation. Measurements over multiple days at the location exist (see Steiner et al. (2018) for details), however for this study we use the data between 10:30 – 11:30 LT on 12 October 2016 averaged over 10-minute intervals (Steiner et al. 2018). The AWS also included an IRGASON eddy covariance (EC) system measuring high frequency (10 Hz) fluctuations in temperature, humidity and wind speed. Based on this the sensible and latent heat fluxes are calculated as 5-minute averages. The EC system its footprint depends on sensor orientation, wind speed and direction (Steiner et al., 2018), which in combination with an inhomogeneous surface complicates the direct comparison between measurements and simulation. We calculated the footprint area using the EddyPro software and determined the weighted contribution of each model pixel within the footprint area to the flux observation at the AWS site to make a succinct comparison with the measurements.

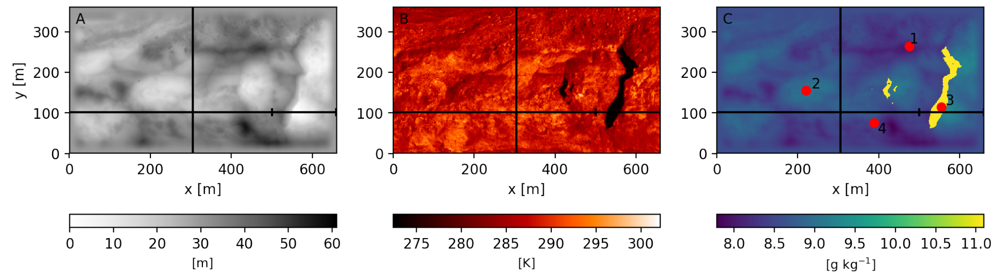

Figure 2: Boundary conditions used in MicroHH: the DEM (A), surface temperature (B) and surface specific humidity (C). Black lines (A-C) indicate the locations of the vertical cross sections used in Figure 5-7. The vertical cross section used in Figure 9 is a subset of the cross section (x=500-660, y=102) and its start and end point are indicated by small vertical lines. Red points indicate the locations used in Figure 8 (1=dry debris, 2=wet debris, 3=ice cliff and 4=AWS).

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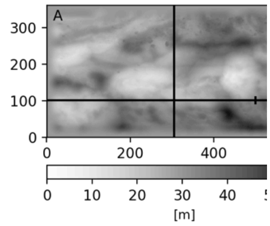

The high resolution DEM is based on the structure-from-motion workflow using optical imagery retrieved on 9 October 2016 (13:00 LT) and is resampled to 1 m resolution for further use (Figure 2A) (Immerzeel et al., 2014a; Kraaijenbrink et al., 2016). A spatial resolution of 1 meter is the highest possible spatial resolution, given the constraints of computational power and spatial resolution of the input data. In Appendix A we show the spatial resolution of 1 meter is sufficient to capture the characteristics of the flow and that increasing the resolution will not add more information. The surface temperature (12 October 2016 11:00 LT) is retrieved with the UAV thermal infrared camera and is biased corrected (Kraaijenbrink et al., 2018). We only use a subset of the UAV data in this research, since the domain is constrained by the intersect of the optical and thermal flight extent, and the domain should be rectangular in the model. The DEM of the domain is detrended, rotated to the main wind direction and smoothened at the boundaries in order to connect the outer left pixels with the outer right pixels of the domain to allow for periodic boundaries. Periodic boundary conditions presume that the fluxes exiting the domain are used as influx in the next time step. This allows us to investigate processes and feedbacks solely in the domain, as larger forcings are excluded. We only include the glacier surface in the domain and not the surrounding moraines. The final extent of the domain is 660x361 m, the final detrended topography ranges from 0 to 57 meter, and the surface temperature ranges from 273.1 K (ice cliff at melting point) to 302.2 K with an average of 282.2K (corresponding potential temperature is 331.3 K). In total 2% of the domain is covered with ice cliffs and is representative for the glacier as the ice cliff glacier average is found to be between 1.4 and 3.4% (Steiner et al., 2019).

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2.3 Model

The MicroHH model (Heerwaarden et al., 2017) is a computational fluid dynamics model designed to simulate turbulent flows in the atmosphere through direct numerical simulation (DNS) and large eddy simulation (LES). We use MicroHH as a

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DNS model with a constant eddy viscosity, which effectively renders a LES with the most primitive eddy viscosity model possible. MicroHH can be run in parallel and is made for efficient computations. This model allows heterogeneous surface boundary conditions such as topography, surface temperature and surface specific humidity. For specific details of the model we refer to Heerwaarden et al. (2017) but we do give a brief description of the model below.

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MicroHH solves the conservation equations of mass, momentum and energy under the Boussinesq approximation and assumes constant density with altitude which simplifies the governing equations substantially. The conservation of mass is thereby reduced to the conservation of volume in Einstein summation:

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$$\frac{\partial u_i}{\partial x_i} = 0, \qquad (1)$$

u_i are components of the velocity vector (υ, v, w) and x_i the position of the vector (x, y, z). The thermodynamics are a relation between fluctuations of virtual potential temperature (ϑ_v') and density (ρ') under the Boussinesq approximation by:

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$$\frac{\vartheta_v'}{\vartheta_{v0}} = -\frac{\rho'}{\rho_0}, \qquad (2)$$

With ϑ_{v0} the reference virtual potential temperature and ρ_0 the reference density. The conservation of momentum is formulated as:

$$\frac{\partial u_i}{\partial t} = -\frac{\partial u_i u_j}{\partial x_j} - \frac{1}{\rho_0}\frac{\partial p'}{\partial x_i} + \delta_{i3} g \frac{\theta_v'}{\theta_{v0}} + \nu \frac{\partial^2 u_i}{\partial x_j^2} + F_i, \qquad (3)$$

Where δ is the Kronecker delta, ν the kinematic viscosity, g the gravity constant (9.81 ms^{-2}) and F_i the external forces originating from for example large scale forcings. We used moist dynamics in our simulations and this implies the liquid water potential temperature θ_l is the conserved variable in the energy conservation equation.

$$\theta_l \approx \theta - \frac{L_v}{c_p \Pi}, \qquad (4)$$

with L_v the latent heat of vaporization (2.5 10^6 kJ kg^{-1}), c_p the specific heat of dry air (1002 kJ kg^{-1}) and Π the Exner function:

$$\Pi = \left(\frac{p}{p_{00}}\right)^{R_d/c_p}, \qquad (5)$$

with p the actual pressure, p_{00} the reference pressure (1000 hPa) and R_d the gas constant for dry air (287.058 $Jkg^{-1}K^{-1}$).

The conservation of energy is defined by:

$$\frac{\partial \theta_l}{\partial t} = -\frac{1}{\rho_0}\frac{\partial \rho_{0 u_j} \theta_l}{\partial x_j} + \kappa_\theta \frac{\partial^2 \theta_l}{\partial x_j^2} + \frac{\theta_{l0}}{\rho_0 c_p T_0} Q \, . \quad (6)$$

The density of dry air (ρ_0) is measured by the eddy covariance system and is set to 0.75 kg m^{-3}. κ_θ is the thermal diffusivity for heat (0.1 m^2s^{-1}) and Q the external heat source or sink. T_0 is the reference temperature profile.

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MicroHH gives output of the 3D variables (total specific moisture, liquid potential temperature and the u and v components of the wind) at desired cross sections parallel along the axes x,y,z. The accumulated temperature (thl_{flux}) and moisture fluxes (qt_{flux}) are given at the surface of a grid cell and should be divided by the surface area of that cell to obtain the flux in Wm^{-2}. Therefore the fluxes are converted to a sensible (SHF) and latent heat flux (LHF) by:

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$$SHF = \rho \cdot thl_{flux} \cdot c_p \, , \quad (7)$$

and

$$LHF = \rho \cdot qt_{flux} \cdot L_v \, , \quad (8)$$

where thl_{flux} and qt_{flux} are the diffusive fluxes perpendicular to the surface and are directly dependent on the temperature and moisture gradient between the surface and atmosphere.

2.4 Boundary conditions

The bottom boundary condition for the velocity components is set to a Dirichlet no-slip condition (zero velocity at this interface) and the top boundary condition is a Neumann free slip condition (velocity gradient). Random noise is added to the flow in order to add turbulence and is applied to the wind vectors *u* and *v* with an amplitude of 0.1 ms^{-1}. We used a constant eddy viscosity of 0.2 m^2s^{-1}. We used a constant eddy viscosity of 0.2 m^2s^{-1}. Preferably the viscosity of the atmosphere is used in the simulations, however this is computationally unfeasible in our simulations. Therefore we chose the lowest possible eddy viscosity and checked the results for convergence. A second order spatial discretization scheme is used. A buffer zone of the upper hundred meters is used for numerical stability and the state values decrease exponentially to the top boundary. The boundary conditions is at the DEM surface a Dirichlet boundary condition and can be prescribed spatially for specific

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humidity and surface temperature. In our experiments the surface temperature will be set to measured values by the UAV. The specific humidity is not measured spatially by the UAV, although the spatial variability of the relative humidity (RH) is made dependent on the topography to indicate dry higher elevated parts and wetter depressions by:

$$RH = RH_0 - 0.26 \cdot \mathrm{DEM}, \qquad (9)$$

with RH_0=85% at the lowest point and RH 70% at the highest point of the DEM, with an average of q=8.6 gkg^{-1}. This approximation follows the reasoning that melt water entrained in the debris accumulates in depressions. Additionally, finer grained debris equally tends to be found in depressions from wash outs, resulting in a higher retention capacity of the surface. At the location of the AWS the relative humidity (measured at 3.1m) is 66% and with this relationship we assume the surface is everywhere moister than the atmosphere. The relative humidity during this morning varied from 54% to 100% in time at the AWS location, which is also a typical range during general diurnal variability (Steiner et al., 2018). We assume a spatially constant saturation vapor pressure in the domain based on the air temperature measured by the AWS by Tetens' Formula:

$$e_s = 0.61078 \cdot e^{\frac{17.27 \cdot T}{(T+237.3)}}, \qquad (10)$$

and calculate the spatial variable specific humidity by:

$$q = \frac{\mathrm{RH}}{100\%} \cdot 0.622 \frac{\mathrm{e_s}}{\mathrm{p}}. \qquad (11)$$

In order to implement the DEM in MicroHH, ghost cells below the surface are included for interpolation at the surface following the immersed boundary technique as described by (Tseng and Ferziger, 2003). This method allows for fast computation and senses the presence of the boundary condition by the extrapolated values below the complex surface. The ghost cells themselves are excluded from all analysis and are only needed for model performance. The lateral boundary conditions are periodic, such that air flowing out of one side of the domain will enter on the opposite side and act as a lateral boundary condition. The domain can therefore be interpreted as an infinite iteration of the prescribed domain.

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2.5 Vertical profile

MicroHH is initialized with vertical profiles of liquid potential temperature $\left(\frac{\mathrm{d}\theta_l}{\mathrm{dz}}\right)$, specific humidity $\left(\frac{\mathrm{dq}}{\mathrm{dz}}\right)$ and wind $\left(\frac{du}{\mathrm{dz}}\right)$. The large-scale pressure force is prescribed by the geostrophic flow components U_g and V_g. Profiles of the wind vectors are taken from ERA-INTERIM data at 12:00 UTC, since this profile matched best with the observations and are interpolated in the lowest 100 meters to surface values measured by the AWS. The profiles of the liquid potential temperature and specific humidity are taken constant with height with the value measured at the AWS, since MicroHH was highly sensitive to those initial vertical profiles and varying them did not lead to improvement of the simulation of the latent and sensible heat flux. The ERA-INTERIM profiles contain a temperature and moisture bias at the surface compared to the AWS and in order to get realistic profiles, we interpolated the lower part of the atmosphere to the AWS value. However, this would imply a strong contrast between low air and air at several hundreds of meters and after mixing of the atmosphere, strong gradients and biases appeared in the simulations. We therefore assumed constant profiles for temperature and specific humidity rather than adjusted ERA-INTERIM profiles and that the spin up time (1 hour) is sufficient to acquire temperature and specific humidity profiles that represent the prescribed surface properties.

2.6 Experiments

In total 7 experiments are designed to investigate the effects of surface roughness, surface temperature and surface moisture on turbulent fluxes, wind and temperature fields on a debris-covered glacier. These experiments are chosen to determine the separate effects of topography, surface temperature and surface specific humidity on the surface energy balance of a debris-covered glacier. The experiments are listed in Table 1. The first two columns indicate the name and the description of the experiments respectively, and the last three columns define which surface boundary conditions are used. If a number is given, this means the surface is homogeneously forced with that value. For the DEM and surface temperature spatially variable measured values are available and this is indicated with *real* in Table 1. A DEM of 0 indicates no topography input is used and the surface is flat and homogeneous. In the last experiment (*REAL*) all variables are prescribed spatially. A specific humidity of 8.6 g kg $^{-1}$ and surface potential temperature of 313.3K are the averages of the measured spatial fields.

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With the HOM_{flat} $HOM_{1/2DEM}$ and HOM_{DEM} experiments we quantify the sensitivity of the turbulent fluxes to the topography. The HET_{T} experiment will reveal the effects of a spatially variable surface temperature compared to a homogeneous surface temperature (HOM_{DEM}). The HET_{qdry} and HET_{qmoist} experiments are aimed to reveal the influence of heterogeneous surface specific humidity compared to a homogeneous value (HOM_{DEM}) and will show the effects between a relatively dry and moist debris layer. In the REAL experiment all effects are combined and will be compared to HOM_{flat} and HOM_{DEM} to understand the combined effects as well.

Our experiments are representative for the meteorological conditions on 12 October 2016, at 11:00 LT, assuming this is a static state. For each experiment we have output for one hour (without considering spin up) and we consider these results as the range of possible outcomes at 11:00 LT.

The domain extent is 660x331x500 (x,y,z) meters, and 672x384x480 gridpoints are used, so the spatial resolution is approximately 1 meter. The number of grid points is determined by the amount of nodes used on the Cartesius cluster (www.surfsara.nl). One run typically takes 10.5 hours to complete and runs on 1024 processors.

Table 1: Overview of experiments done with MicroHH. The DEM indicates the boundary condition used for the topography (0 means no DEM, ½ DEM is the original DEM halved in height, real is the spatially measured value), T_s is the surface potential temperature (313.3K is a homogeneous value, real is the spatially measured value), q_s is the surface specific humidity (8.6 g kg^{-1} is a homogeneous value, the choice for the relative humidity range is described in Sect. 2.4)

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Experiment	Description	DEM	T_s	q_s
HOM_{flat}	Homogeneous glacier	0	313.3 K	8.6 g kg^{-1}
$HOM_{1/2DEM}$	½ DEM	½ DEM	313.3K	8.6 g kg^{-1}
HOM_{DEM}	Roughness effects	Real	313.3 K	8.6 g kg^{-1}
HET_T	T_s effects ‘normal’	Real	real	8.6 g kg^{-1}
HET_{qdry}	q_s dry	Real	313.3 K	Spatially RH=70-75%
HET_{qmoist}	q_s wet	Real	313.3 K	Spatially RH=70-85%
REAL	“Reality”	real	real	Spatially RH=70-85%

2.7 Conductive flux

The surface energy balance determines how much energy is left at the surface and can be used to heat up the debris or melt ice. The conductive flux (Q_c) is the energy flux into the debris (Nicholson and Benn, 2006, 2012), and can be quantified by:

$$Q_c = Q_{SW}+Q_{LW}+Q_L + Q_H \,, \quad (12)$$

where Q_{sw} and Q_{LW} are the net shortwave and long wave radiation, Q_L and Q_H the latent and sensible heat flux respectively. Q_{SW} is the sum of the direct incoming (I_s), diffuse radiation (D_s) and reflected shortwave radiation from surrounding terrain (D_t) multiplied by (1-albedo). The surface albedo is taken constant as 0.18 for both the debris as the ice cliffs, as this is measured by the AWS and is in the range of possible albedo for ice cliffs on Lirung Glacier (Steiner et al., 2015). D_s is calculated as:

$$D_s=V_s k_d I_0, \quad (13)$$

with V_s is the sky-view factor, k_d the diffuse fraction and I_0 the shortwave radiation measured by the AWS. The reflected shortwave radiation by surrounding terrain is calculated with the albedo (α) as:

$$D_t=\alpha I_0(1-V_s). \quad (14)$$

Q_{LW} is calculated as:

$$Q_{LW} = V_l LW_{in} + LW_d - LW_{out} \tag{15}$$

where V_l is the sky-view factor for longwave radiation, LW_{in} the incoming longwave radiation, LW_d The longwave radiation emitted by surrounding debris and LW_{out} the outgoing longwave radiation related to the surface temperature T_s:

$$LW_{out} = \varepsilon_d \sigma T_s^4 \, , \tag{16}$$

with an emissivity (ε_d) of 0.95 and σ the Stefan Boltzmann constant. LW_{in} is taken homogeneous as measured by the AWS (hourly average) and the longwave radiation emitted by surrounding debris is calculated spatially as:

$$LW_d = V_d \varepsilon_d \, \sigma T_s^4 \, , \tag{17}$$

where V_d is the debris-view factor (see Steiner et al. (2015) for details).

The latent and sensible heat flux are calculated as stated in Sect. 2.3. This method assumes the debris is in steady state and no heating or cooling of the debris is happening during that period. All fluxes are defined as positive towards the surface except for the conductive heat flux. All averages and standard deviations discussed in this paper are spatial averages, unless specified otherwise.

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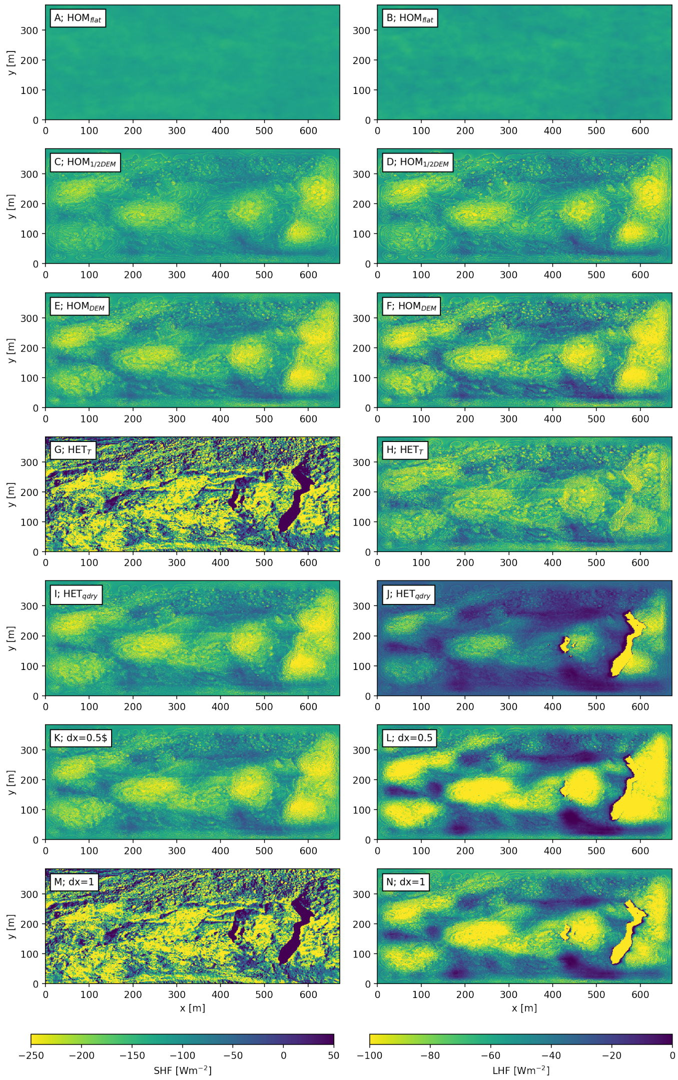
3. Results and discussion

3.1 Spatial distribution of LHF and SHF

Seven experiments are performed (Table 1) where key parameters are varied that control turbulent heat fluxes in order to investigate the relative importance of topography, humidity and surface temperature. In Figure 3 and 4 the average surface turbulent fluxes and spatial variability are shown respectively for all experiments. The effects of the experiments can be subdivided into effects of surface roughness (HOM_{flat}, $HOM_{1/2DEM}$ *and* HOM_{DEM}), spatial temperature (HET_T) and surface specific moisture (HET_{qdry} *and* HET_{qmoist}).

3.1.1. Surface roughness

The effect of the surface roughness on the SHF and LHF is evident (Figure 3A-F). The turbulent fluxes are intensified with increasing variability in topography, since increasing the surface roughness is directly related to the surface roughness length and the generation of turbulence. A homogeneous topography results therefore only in small spatial differences of the turbulent fluxes (HOM_{flat}, 5 and 2 Wm^{-2} for SHF and LHF respectively). Including a real topography (HOM_{DEM}) results in



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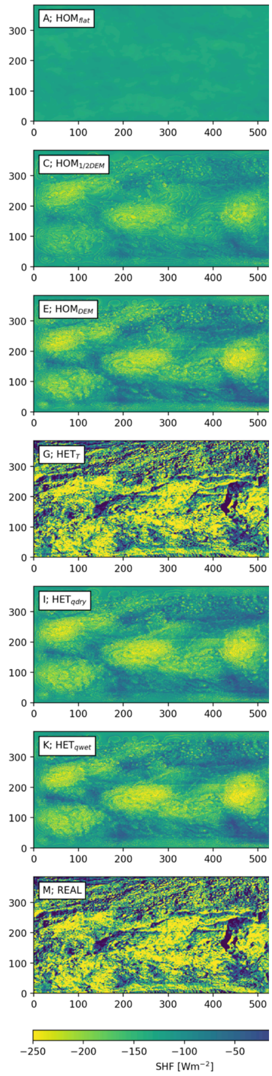

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Figure 3: 2D plots of average variables SHF (left panels) and LHF (right panels) for each experiment in the same order as presented in Table 1 (rows). Elevation increases from left to right and the main wind direction is from left to right.

more variation of the turbulent fluxes (64 and 30 Wm^{-2} for SHF and LHF respectively) with lowest fluxes at higher locations of the topography and the highest fluxes in the depressions of the topography. This is caused by the combination of accumulation of heat and moisture in the depressions of the topography and homogeneous surface temperature and specific humidity, resulting in high temperature and moisture gradients.

3.1.2. Surface temperature

The spatially variable temperature (HET_T) has the largest impact on the SHF (Figure 3G). Prescribing the surface temperature heterogeneously (HET_T) impacts the surface vertical temperature gradient and is therefore extremely important for the SHF. The LHF is less variable in space when including only spatial heterogeneous surface temperatures. This is because the surface temperature pattern is partly inversely related to the topography and the LHF is mainly driven by the moisture gradient. Cold surfaces are now located at the lowest parts of the domain, where it was warmer in HOM_{DEM} and LHF is positively related to temperature. Additionally, the spatial variability of the SHF is increased from 64 to 193 Wm^{-2}, while the spatial variability in the LHF stayed similar (30 vs 23 Wm^{-2}). Due to the heterogeneous temperatures also positive sensible heat fluxes are present at the locations where the surface is colder than the atmosphere. This is particularly important for understanding the energy balance of ice cliffs and ponds (Sect. 3.5).

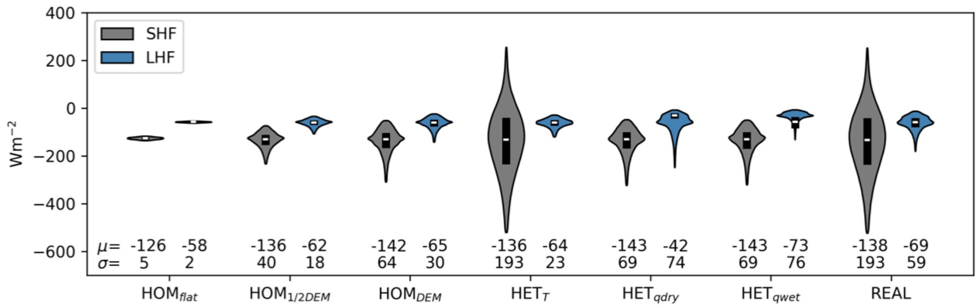

Figure 4: Violin plots to show spatial variability of time average fluxes (95% confidence interval) in domain for the SHF (grey) and LHF (blue). The numbers indicate the domain average (μ) and standard deviation (σ). Fluxes pointed to the surface are positive.

3.1.3. Surface specific humidity

The surface specific humidity has the greatest effect on the LHF. Assuming dry debris (HET_{qdry}) results in an average LHF of -42 Wm^{-2}, while it is -73 Wm^{-2} for moist debris, indicating the importance of the surface moisture to the LHF. A higher surface specific humidity results in more evaporation under the same conditions, since it increases the vertical moisture gradient at the surface. Moistening the surface (*HET*$_{qwet}$) results in less extreme differences spatially in the LHF, since both experiments include saturated areas at the locations where the real surface temperature is 0 degrees Celsius. Moistening the surface will increase the atmospheric specific humidity and since the relative humidity is fixed in both experiments at the cliffs at 100%, the variability in specific humidity decreases. Interesting is the high LHF at the leeward side of the ice cliff (the main wind flow is from left to right as noted in Figure 3), where wind transports the moisture originating from the ice cliff over the domain.

3.1.4. Spatial variation of elevation, surface temperature and specific humidity

Including spatial variation in specific humidity and surface temperature (*REAL*) does not affect the average turbulent fluxes compared to homogeneous conditions (*HOM*$_{DEM}$) much, however the spatial variability is nearly doubled for the sensible heat flux and tripled for the latent heat flux (Figure 4).

If we assume *REAL* as the truth, the sensible heat flux (latent heat flux) will be underestimated by 9% (8%) when ignoring the topography (*HOM*$_{flat}$). Assuming both homogeneous surface temperature and specific humidity (*HOM*$_{DEM}$) results in an overestimation of the SHF of 3% and an underestimation of 4% of the LHF (Figure 4).

Increasing the surface roughness has a larger effect on domain averaged turbulent fluxes than including spatial variations surface temperature or specific humidity. However, prescribing the surface temperature and specific humidity has largest effects on the spatial distribution of the SHF and LHF and results in a high spatial variability. So, for glacier tongue-wide averages, area averaging of the input variables is justifiable but if you are interested in detailed spatial patterns of melt this is questionable.

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3.2. Vertical distribution of temperature, wind and specific humidity

In Figure 5,6 and 7 cross sections and vertical profiles of all experiments are shown for the wind speed, specific humidity and potential temperature respectively for the lowest 100 meters of the domain. Increasing the surface roughness (*HOM*$_{1/2DEM}$ and *HOM*$_{DEM}$) leads to more mixing of heat and moisture in the atmosphere, due to the a higher associated surface roughness length. Close to the surface the topography has a direct influence on the wind speed; in depressions the wind speed is low and at high-elevated parts the wind speed is higher. Due to the differences in wind speed, the mixing of heat and moisture is also spatially heterogeneous close to the surface. In depressions moisture and heat accumulates and this is mixed into the lower atmosphere by mainly ejections.

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The vertical profiles are an average over all model grid points above the surface. The mixing of variables extends higher into the atmosphere when the real topography is included. In the *REAL* experiment, mixing occurs to an altitude of 40-60 meters above the surface, while this is only 20-30 meters in *HOM*$_{flat}$. On a larger scale it is established that debris influences the near-surface atmosphere (Collier et al., 2015). We show that the micro-scale meteorology is also strongly affected by debris and hence influences for example the local temperature and moisture lapse rates. Heterogeneous surface temperatures allow negative surface temperatures at ice cliffs, resulting in reversed temperature gradients close to the surface (HET_T and REAL; Figure 7).

The surface roughness causes local differences in wind speeds, especially where there are a lot of elevation differences over a small horizontal range. This is for example visible above the ice cliff (x=510-600m), where the wind gradient is decreasing to the bottom. This is confirmed with station observations, where higher located stations measure consistently higher wind speeds than at lower locations. The three dimensional approach used quantifies the spatial differences in wind speed and points out the differences with scarce point measurements. In local depressions accumulation of heat and moisture frequently occurs, and this is further amplified when including heterogeneous surface specific humidity and temperature. If the accumulated heat and moisture are removed regularly by cold and dry air, these heterogeneous differences create local hot spots of the SHF and LHF. Therefore surface roughness plays an important role and can alter the conductive flux into the debris. At locations where the air is stagnant, fluxes are attenuated since gradients in moisture and temperature between the surface and atmosphere are gradually decreasing by accumulation of heat and moisture. Specifically interesting are the locations where the specific surface humidity is high and temperature low, such as ice cliffs. We will look more in detail in those supraglacial features in Sect. 3.5.

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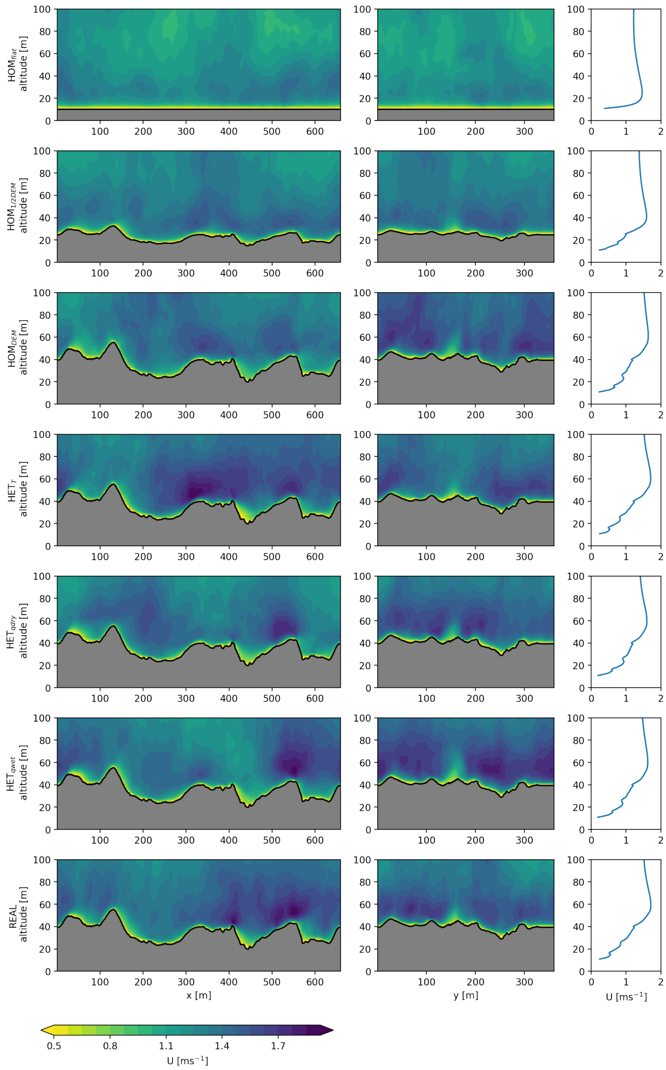

Figure 5: Cross sections (left and middle columns) and average vertical profile (right columns) of the wind speed for all experiments presented in the same order as in Table 1. The location of the cross sections is shown in Figure 2.

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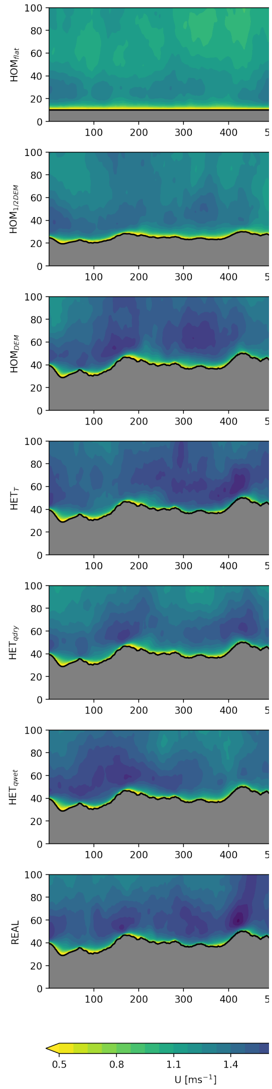

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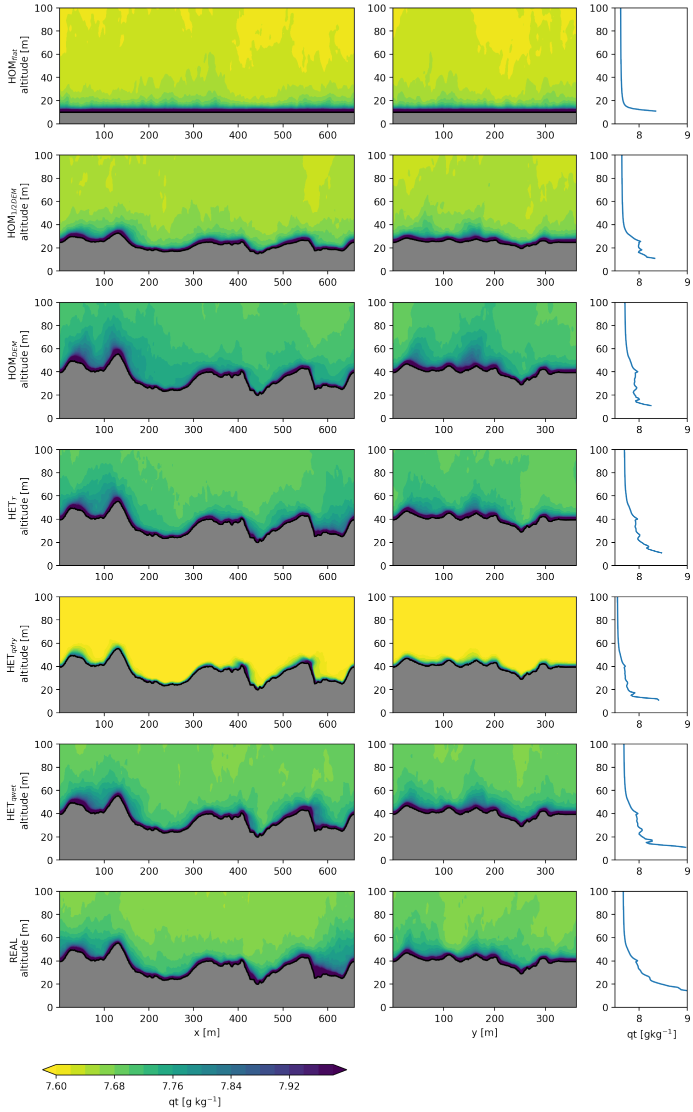

Figure 6: As Figure 5 but now for the specific humidity.

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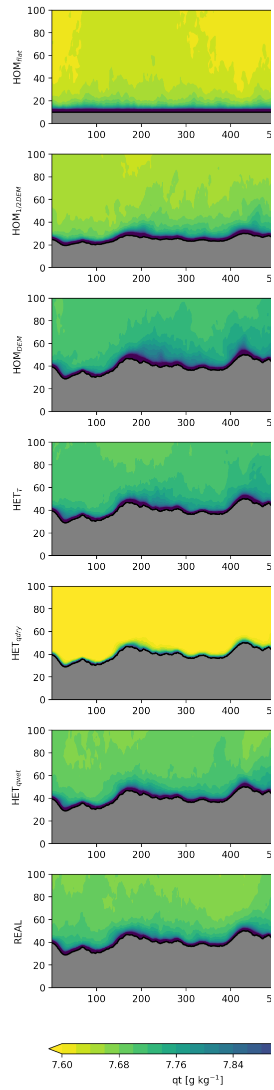

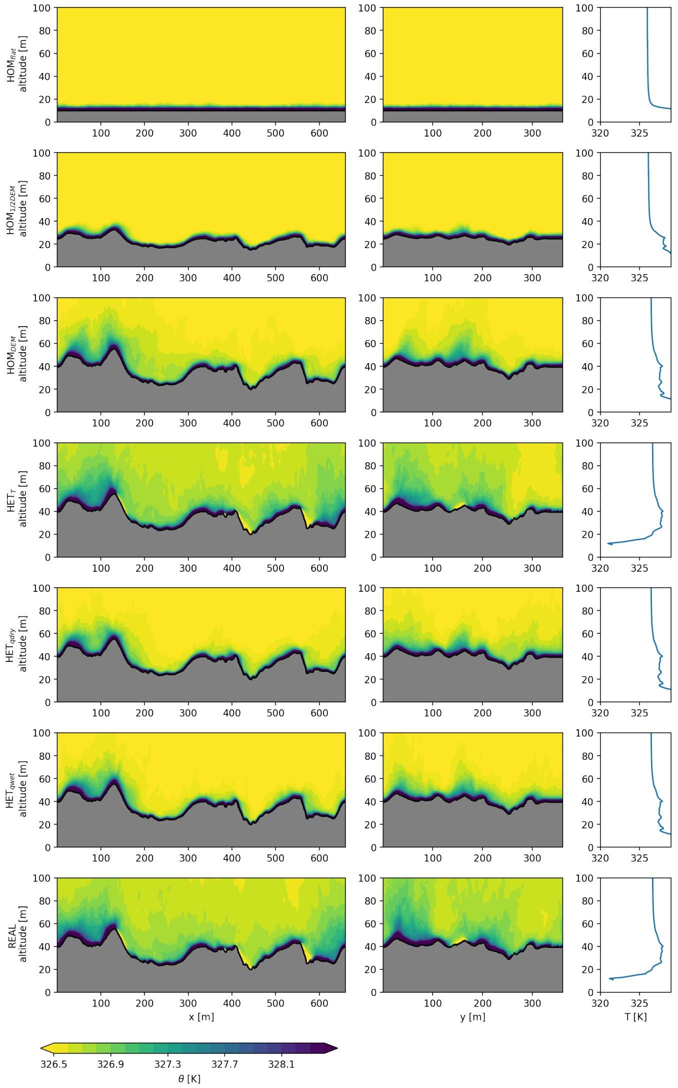

Figure 7: As Figure 5 but now for the potential temperature.

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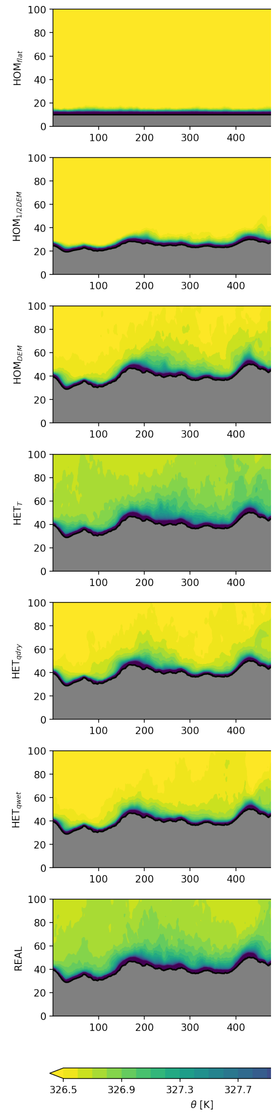

3.3 Spatial analysis

In Figure 8 the possible range of the SHF and LHF are plotted for four locations: dry debris (A), wet debris (B), an ice cliff (C) and the location of the AWS (D). The exact locations are indicated in Figure 2. The simulations represent a static state at 11:00 LT, and we interpret the results as possible range of outcomes of that state. Turbulent fluxes can vary greatly at one location, since they depend on the instantaneous turbulent conditions. This means the variability of turbulent fluxes is large, even with constant surface boundary conditions.

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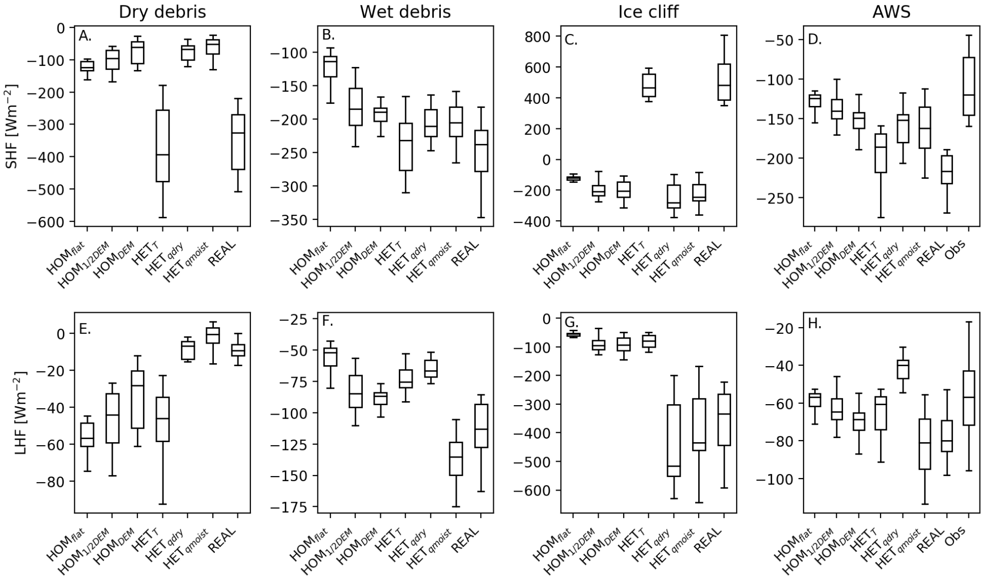

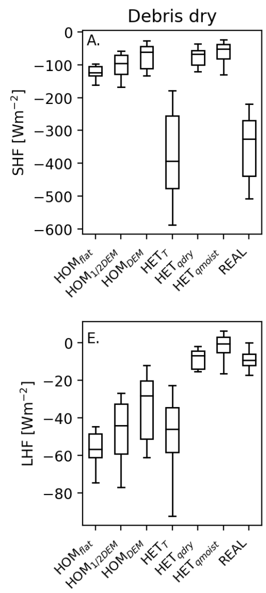

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Figure 8: Box plots to show variability in possible outcomes at four different locations: dry debris (A+E), wet debris (B+F), ice cliff (C+G; all three points are taken as average of 9 grid points) and AWS location (weighted average over the footprint; D+H), for all experiments (Table 1). Observations (Obs) of the SHF and LHF are shown in Figure D and H. For all simulations the last hour of simulation data is taken and is resampled to a 5 minutes average. Measurements are also 5-minute averaged and the time period taken from the AWS is 10:30-11:30 LT.

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3.3.1 Debris

For comparison between dry and moist debris, two locations are chosen where both surface temperatures are 291 K in the *REAL* experiment. Surface moisture for the dry and wet debris for HET_{dry} are 8.0 and 8.1 gkg^{-1}, and for HET_{qmoist} 8.5 and 9.0

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gkg^{-1} respectively. Attributing the differences in fluxes between wet and dry debris to surface moisture is not straightforward, since the spatial distribution of surface moisture is dependent on the DEM (dry debris is located at higher elevated parts, while moist debris is located at depressions) and in addition the surrounding grid points influence the turbulent fluxes as well. Dry debris is generally located in areas exposed to higher wind speeds and surface roughness, while the opposite holds for wet debris. The SHF is more sensitive to surface temperature for dry debris than for wet debris, and in the *REAL* experiment the LHF is approximately 10 times as high at wet debris compared to dry debris. Turbulent fluxes have different sensitivities to surface temperature and moisture indicating that the sensitivities are different in wet and dry climates. As a result surface boundary conditions should be chosen carefully for simulations.

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Domain averaged (with its spatial standard deviation) in the *REAL* case, the LHF at dry debris is lower (q_s<8.4 gkg^{-1}, 34±17 Wm^{-2}) than at wet debris (q_s>8.8 gkg^{-1}, 117+52 Wm^{-2}) and is caused by less moisture availability. The SHF over wet debris (-237 ± 247 Wm^{-2}, excluding ice cliffs) is considerably higher than at dry debris (-135.3±161 Wm^{-2}) and is caused by the location of the wet debris in the depressions, where accumulation of heat occurs that increases the vertical temperature gradient as discussed in Sect. 3.2.

3.3.2. Ice cliff

The surface conditions at an ice cliff are different than its surrounding debris surface, since the surface is at (or around) melting point and the near-surface air is saturated. As a result, the reversed (positive) SHF is the most pronounced difference compared to a debris surface. Additionally, spatially different surface temperatures result in cold and warm eddies that can pass over the ice cliff and increase the variation in the SHF. The variation in the LHF is mainly influenced by the surface specific humidity, since with heterogeneous surface variables dry and wet eddies can flow over the saturated surface causing different vertical moisture gradients above the ice cliff. This is described in more detail in Sect. 3.5.

3.3.3 AWS measurement comparison

The location of the AWS is included in order to be able to compare the simulations to the measurements. The measurements are an average of the footprint of the station, however, this footprint is varying in time and exceeds the domain slightly. We choose to take a weighted average over the grid points that are located in the domain. The averaged measured SHF is 49%, lower than the modelled SHF, the LHF is 23% lower. The range between the first and third quartile for the LHF (SHF) is 16 (36) for the *REAL* case and 29 (73) Wm^{-2} for the observations, which shows the model underestimates the variation. The ranges of simulated LHF overlap with the observed range, however for the SHF the observed and simulated ranges do not overlap. The comparison between the simulations and the observations give an indication of the model performance, however a one-to-one comparison is complex, since our simulations are an idealized representation of the reality in a limited domain and exclude effects from for example the moraines or glacier at higher altitude. The disagreement between simulated and observed fluxes may also be caused by the location of the AWS, which is located close to the moraines. Steiner et al.

(2018) estimated the average surface energy balance for Lirung Glacier, at the AWS location to be ±350 Wm^{-2} for clear-sky around 11:00 LT, in *REAL* this is 294.2 Wm^{-2}, calculated with a weighted average in the footprint of the AWS. However the model domain averaged conductive flux is 348.8 Wm^{-2}, indicating the model performs well and within a reasonable range.

3.4 Surface energy balance

Figure 9 shows conductive flux into the debris under the seven simulations. As input spatial heterogeneous shortwave and longwave radiation fields are used based on the real DEM, and the LHF and SHF are varying depending on the experiments to isolate the effects of the individual experiments. For example, the ice cliff signal in Figure 9A is visible, despite the homogeneous surface conditions in HOM_{flat} due to the longwave and shortwave signal derived from the real DEM. The energy reaching the ice below the debris is dependent on the thermal conductivity, density and heat capacity of the debris.

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With increasing surface roughness (HOM_{flat}, $HOM_{1/2DEM}$, HOM_{DEM}) the conductive heat flux becomes more variable, as is also observed for the SHF and LHF separately in Figure 3. Locally it is important to prescribe the surface specific humidity, e.g. for ice cliffs. A wetter environment results in a lower conductive flux (HET_{qdry} *and* HET_{qmoist}), while a colder surface results in a higher conductive flux (HET_T; Table 2). The effect of the surface temperature (HET_T) is larger than the surface specific humidity (HET_{qmoist}) and therefore the conductive flux of *REAL* is closely related to the signal imposed by the surface temperature.

Table 2, the average conductive flux averaged over the domain, ice cliff cells and debris cells with its standard deviation. Ice cliffs cover 2% of the domain.

	Domain average (Wm^{-2})	Ice cliff average (Wm^{-2})	Debris average (Wm^{-2})
HOM_{flat}	391±23	674±76	363±191
$HOM_{1/2DEM}$	377±67	259±111	378±65
HOM_{DEM}	368±102	210±187	370.8±98
HET_T	375±205	967±193	365±190
HET_{qdry}	389±136	-142±396	399±107
HET_{qmoist}	358±147	-81±366	366±128
REAL	368±193	674±76	364±191

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A heterogeneous conductive flux contributes to heterogeneous melting, depending on the debris thickness. For example in *REAL* the average conductive flux on the ice cliffs is 674±76 Wm^{-2}, while this is only 364+191 Wm^{-2} averaged over the debris. The conductive heat flux at ice cliffs can be used exclusively for ice melt, while for debris the conductive flux is partly used to penetrate and warm the debris. Turbulent fluxes decrease the energy available for melt by 39% for the *REAL* case averaged over the domain. Over debris, turbulent fluxes reduce the available melt energy by 40% and act as a sink of energy, while on ice cliffs turbulent fluxes enhance it by 51% and are a contributor to melt. Other studies found ice cliffs melt between 5.7 and 13.7 times faster than ice below surrounding debris debris (Brun et al., 2016; Sakai et al., 2002; Buri et al., 2016; Reid and Brock, 2014). Although those consider total melt rather than the surface energy balance, the pronounced differences between melt on ice cliffs and debris are in line with our research.

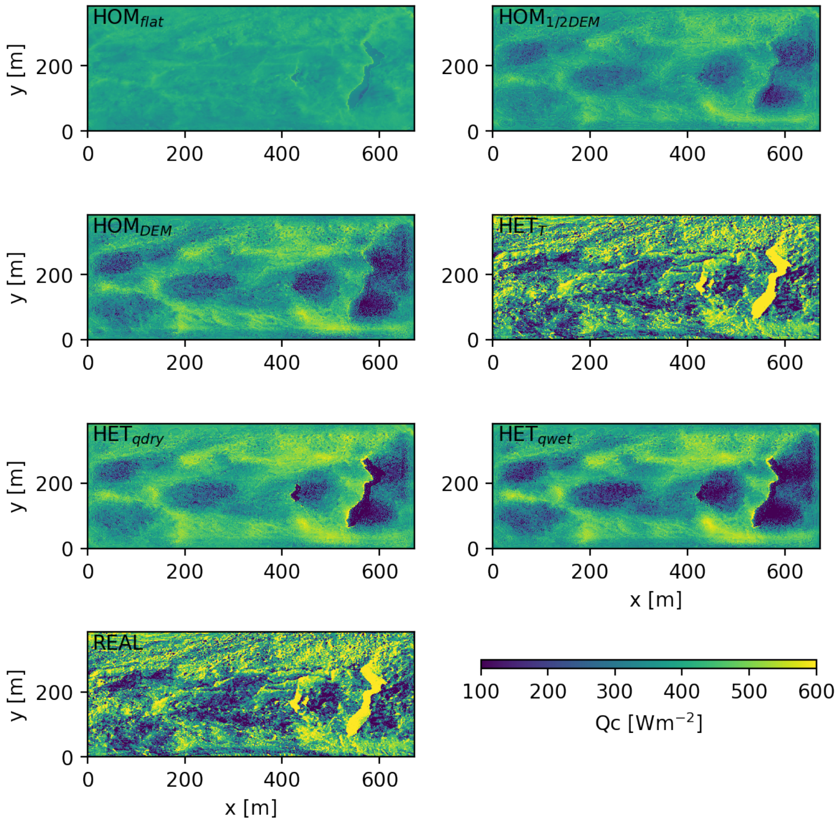

Figure 9: *Effect of turbulent fluxes to conductive flux into the surface for all experiments. A positive flux means energy available to go into surface.*

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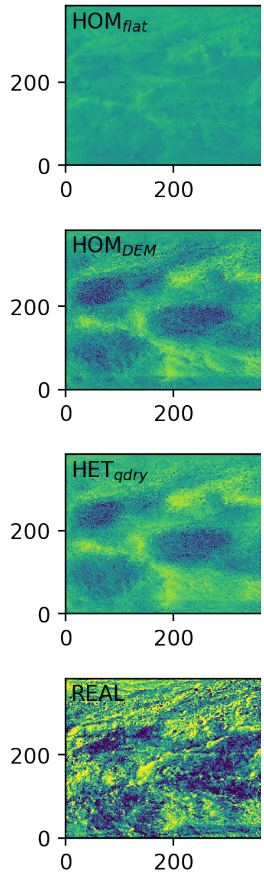

The surface specific humidity is relatively uncertain and the range used in the experiments is based on scare observation and spatially distributed using a simple relation with elevation. We performed additional sensitivity tests of two extreme cases of a homogeneous surface relative humidity of 20% and of 85%, with the relative humidity at ice cliffs at 100% to quantify the effect on the conductive heat flux. The domain averaged (±spatial variation) conductive heat flux when RH=20% is 490±201 Wm^{-2} and 89±276 Wm^{-2} when RH = 85%. This indicates that the mean conductive flux is positive, regardless the surface specific humidity. Second, if the surface relative humidity is lower than the atmosphere the latent heat flux is pointed towards the surface and contributes to the conductive heat flux, while the opposite occurs with a higher relative humidity, which can for example happen at ponds and ice cliffs. Moreover, the conductive heat flux decreases with increasing relative humidity, which shows the regulating effect of moisture to the total energy budget. At ice cliffs, the latent heat flux can become highly negative if the atmosphere is dry and can even reverse the sign of the conductive heat flux. During monsoon surface moisture will be higher than in the rest of the year, indicating the conductive heat flux at the surface will be higher during monsoon than in winter and spring.

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In summary, these results show turbulent fluxes can be key in the explanation of the formation of ice cliffs. Locations with already thick debris (and hence higher surface temperatures) do not melt as fast as its surrounding due to the SHF and LHF that reduce the conductive flux at those places, as well as the general insulation of the debris (Figure 9). A crest will develop introducing the topographic effects as discussed before. This acts as a positive feedback and pronounces the local topographic differences on debris-covered glaciers. These results show that turbulent fluxes can be an additional driver for the typically variable topography of a debris-covered tongue and the formation of ice cliffs besides collapsing channels as hypothesised before (e.g. Benn et al., 2012).

3.5 Ice cliff analysis

Ice cliffs on debris-covered glaciers are particularly interesting to study in terms of turbulence given their steep topography, anomalous surface temperature and moisture conditions compared with the surrounding debris. We showed in the previous section that on an irregular surface, local hot spots of the conductive flux into the surface exist, which amplify the melt. Such irregularities likely favour the formation of ever deeper depressions and eventually expose ice cliffs. Our simulations do not allow dynamic modelling of ice cliff evolution, however we can gain insight in the microclimate around it to better understand the fundamental mechanisms of ice cliff melting. Three dimensional modelling provides therefore insight in processes such as advection of heat and moisture.

In Figure 10 six vertical profiles of wind speed, potential temperature and specific humidity over an ice cliff are shown with a time interval of 10 seconds. On the leeward side of an ice cliff eddies are generated by the thermal and moisture gradients and the topography. In our case the clean ice is on the left side of the local depression and the dominant wind flow is from the left to right. When relatively warm air is advected over the ice cliff this air cools, falls down (first column) and generates an eddy where the accumulated moisture is transported out of the depression and the cold air is replaced by warmer air (columns 2-3). At this point the SHF and LHF are intensified, since the moisture and temperature gradients are increased

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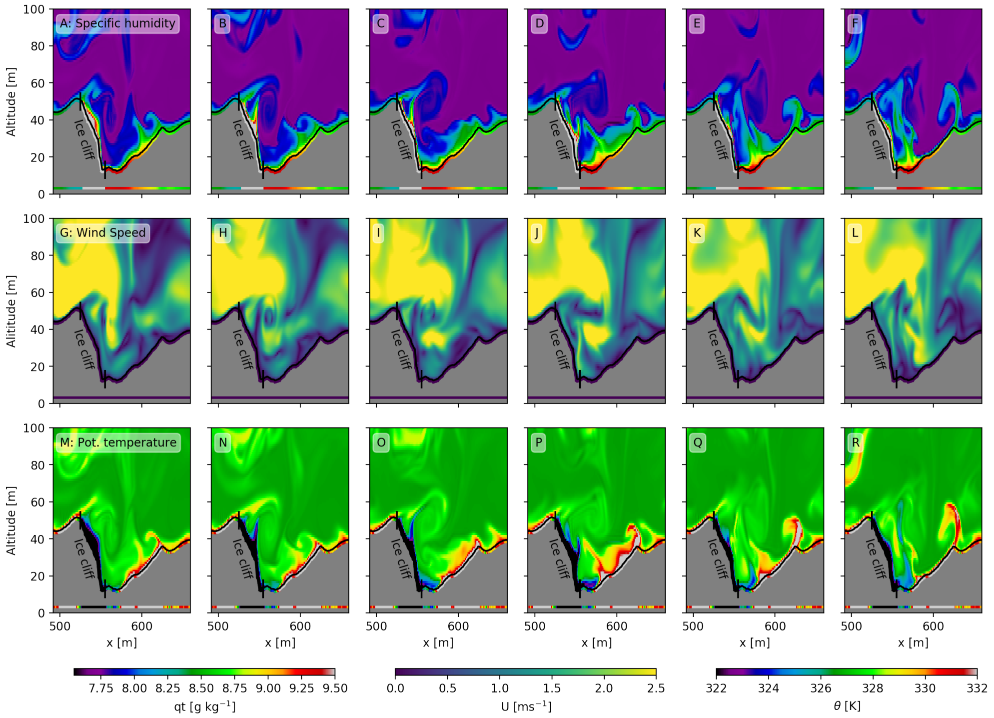
within the depression. Intensification of the turbulent fluxes occurs, since warm air from the right side of the depression is transported towards the clean ice by the rotating eddy (column 4). After such an advection event the ice will cool and moisten the air in the depression. The vertical moisture and temperature gradients decrease in time and the SHF and LHF decrease until the process of refreshment repeats itself.



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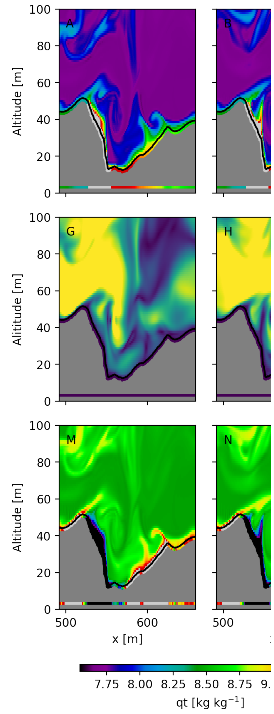

Figure 10: The specific humidity (A-F), wind speed (G-L) and temperature (M-R) for a zoom-in around an ice cliff (660<x>500m) at time=6570-6630s with 10s time interval. The black line indicates the topography. The surface boundary conditions are plotted directly below the surface and for clarity also at y=0.

During an advection event warm and dry air flows over the ice cliff and is transported into the depression. This causes temporarily a strong gradient and sensible heat contributes to melt, until the air has cooled down. This process gives an intensified melt signal at ice cliffs and causes the cliff to deepen and the ice cliff retreating in this specific case to the left. This is congruent with ice cliff backwasting found in previous studies (Reid and Brock, 2014; Steiner et al., 2015). Similar, Mott et al. (2014) found over snow patches that the net surface radiation is not the only driver of energy exchange between the surface and atmosphere in mountainous areas and that secondary flows induced by surface heterogeneities are also an important driver besides solar radiation. We hypothesize that ice cliff backwasting can also be related to the main wind direction in the domain. Cliffs that are in the leeward direction of the main wind direction during daytime receive additional warm dry air through the advection mechanism causing extra melt.

Ice cliffs typically have a knick-point shape that was previously explained by differences in local radiation (Sakai et al., 2002), however this explanation ignores the extra amount of longwave radiation in the depressions (Steiner et al., 2015) and does not explain why crests generally do not flatten in time. Turbulent fluxes likely play an important role in the shape of the ice cliffs as well, by the vertical variations in wind speed induced by the topography. This can be seen in Figure 5, where the wind speed decreases with depth at the ice cliff (x=550m), and the knick-point of the ice cliff is at the location of strongest decline in wind speed. The heat and moisture exchange are therefore strongest at the top of the ice cliff and lowest in the depression, as the main wind flow does flow over the depression, and does not reach the deepest parts of the ice cliff.

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4. Sensitivity to Reynolds number

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In order to simulate atmospheric turbulent flows there are two options: DNS and LES, and both options come with advantages and drawbacks. DNS is extremely computational expensive when resolving all scales in the flow and is impossible in our case study. An advantage of DNS is that the correctness of a simulation can be checked by testing the results of sensitivity tests converge, as we will do in this section. With LES however this approach would not be possible, as sensitivity tests can be evenly wrong caused by the inappropriate surface model under high Reynolds numbers in complex terrain. This means that even when resolving all scales in the flow this does not give direct confidence in the results and LES does not outperform DNS by definition.

The Reynolds number (Re) is a measure for the flow characteristics and is the ratio between inertial and viscous forces in a fluid (Eq. 18). A low Reynolds number would indicate a laminar flow and high Reynolds numbers a turbulent flow.

$$Re = \frac{uL}{\nu}, \qquad (18)$$

Where u is the velocity (m/s), L is the characteristic length scale (m) and ν is the kinematic viscosity (m^2/s) of the fluid. By decreasing the kinematic viscosity the fluid will become more turbulent and resolve smaller scales.

To show the turbulence is fully developed in our study, we double the Reynolds number by decreasing the viscosity from 0.2 to 0.11 m^2s^{-1}, and we repeated the *REAL* experiment. Computationally the run with low viscosity is 15 times more expensive than the high viscosity as the viscosity is halved and the number of grid points is doubled in x, y and z. The LHF and SHF have the same patterns and are in same order of magnitude at both viscosities (Figure A1). Furthermore, the averaged vertical profiles of potential temperature and specific moisture are also similar, which gives confidence in the use of 1 meter resolution for this type of simulations (Figure A2).

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The energy spectrum of specific humidity is shown in Figure A3; energy spectra of other variables (e.g. temperature and wind) show the same pattern. As this run is very complex and far from idealized, comparison of energy spectra of the viscosities is not straightforward. The energy spectra are derived from horizontal cross section at a fixed height of 65 meters above the lowest point in the topography, implying that the cross section is not at a constant height above the surface. As a result, the spectrum contains not only a signature of the turbulence but also of the topography. The peak of the spectrum is located around a wave number of 1, which corresponds to a wavelength of $2\pi/1 \approx 6$ meters and is resolved by both experiments. This shows that large structures are dominant in the flow and small structures are of minor importance. The spectra averages of both experiments differ, though are located in the centre of the bandwidth of one standard deviation.

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The simulation at low viscosity naturally resolves smaller scales than the simulation with a higher viscosity (see Equation 18). In Figure A3 we see that the additional variability does only add a small amount of variance to the signal and is therefore irrelevant for the flow (wave numbers>11). We therefore conclude a viscosity of 0.2 $m^2 s^{-1}$ in combination with a spatial resolution of 1 meter is fine enough to capture the bulk characteristics of the flow as well as its most important features.

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5. Limitations

The understanding of micro-meteorological processes for debris-covered glaciers with highly variable surface temperature and moisture conditions is limited. In particular the role that turbulent fluxes have in the net conductive energy flux towards the ice below the debris is unknown. For the first time, in study, a 3D turbulence resolving high-resolution model was used to gain understanding of these local processes and interactions between the surface and the overlying atmosphere. We showed that such turbulence-resolving models provide important insights into these processes, which may support a better quantification of debris covered glacier melt. However, we identified a number of limitations associated to data availability, the model assumptions and computational constraints, which we discuss in the following paragraphs.

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Information about surface moisture on debris-covered glaciers is scarce, highly variable and difficult to measure. However, it is an important variable for the surface energy balance of debris-covered glaciers, since it influences the latent and sensible heat flux and therefore the conductive heat flux that ultimately melts the ice. Studies normally deal with this limited information about surface moisture by assuming that the debris surface is either dry or fully saturated to indicate the range of outcomes (e.g. Rounce et al. 2015). The approach proposed in this study is a step forward to a better representation of

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surface specific humidity and shows the effect of a partly saturated surface and furthermore a heterogeneous distribution linked to the DEM. In reality the surface moisture is dependent on the surface material and texture, its relative elevation in the domain and aspect of the location (Qiu et al., 2001). In future, the spatial distribution could also be made dependent on debris grain size rather than the absolute height of the topography to make spatial patterns of surface specific humidity more realistic. During our observation period no large supra-glacial ponds were observed (Figure 1), but surface conditions of ponds can be included in MicroHH in upcoming studies to analyse those as well.

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In this study the conductive heat flux is considered, which will be used to gradually warm the debris and eventually melt the ice when the warming front has reached the debris-ice interface. How this energy is partitioned between warming of the the debris and melting depends on the debris thickness, the type of rock, the texture and the moisture content. Future studies can couple a debris energy balance model (e.g. Giese, 2019; Reid and Brock, 2010) to MicroHH and investigate the (timing of the) total energy reaching the ice, and the impact of debris properties such as thickness, surface moisture and the thermal conductivity.

One of our results is that using spatially variable surface boundary conditions for surface specific humidity and temperature result in similar domain averages of turbulent surface fluxes compared to a constant surface temperature or specific humidity. This all relies on the strong assumption that the homogeneous value (in reality taken from a station measurement) is representative of the whole domain. However, in reality it remains very hard to locate a station so that it is representative for the whole domain without having prior knowledge of the spatial distribution. This type of high-resolution modelling can therefore support the optimal site selection for meteorological observations and ensure its representativeness.

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High-resolution modelling is a useful tool to investigate small-scale meteorological processes, due to its explicit treatment of turbulent processes. However, the modelling is still conceptual, since not all processes and feedbacks are included in the model. In this study, only a part of Lirung Glacier is modelled and excludes local influences from the surroundings such as wind flows caused by the lateral moraines and circulations in the valley. Due to the high spatial resolution and computational constraints, the simulation time is now limited to 1 hour and the simulation is stationary; we simulated the domain for 1 hour assuming it is 1 hour 11:00 LT. Our study provided important insights, but also made clear that turbulence resolving, long-term and transient simulations are currently not feasible. However our results can be used to gain more understanding of surface processes on debris-covered glaciers and obtain parameterizations that can be used in coarser resolution models. In order to understand the small-scale processes at the surface-atmosphere interface on a debris-covered glacier we need high-resolution data and models. A correct representation of debris-covered glaciers would benefit climate, glacier and hydrological models to give a better estimation of melt water contribution to river discharge.

6. Conclusions

The exact melt processes of debris-covered glaciers are largely unknown and their total contribution to the total glacier melt remains uncertain to date. The surface of a debris-covered glacier is complex due to its topography, heterogeneous surface temperature and surface moisture resulting in highly heterogeneous micro-meteorological conditions. In this study, the impact of surface properties of debris (surface roughness, temperature and specific humidity) on the spatial distribution of small-scale meteorological variables, such as turbulent fluxes and near-surface wind fields, specific humidity and temperature for a debris-covered glacier is investigated. This is the first time an in-depth analysis is performed of micro-meteorological variables above a debris-covered glacier with a turbulent resolving model at high resolution (~1 m) and we gained insight in the spatial variability of turbulent fluxes on a debris-covered glacier and what drives these differences.

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The surface roughness has the strongest impact on the magnitude of turbulent fluxes and leads to more mixing to higher altitudes due to the higher topographic variability. Surface roughness causes spatial differences in wind speed, with generally lower wind speeds at lower elevated parts due to isolation, whereby accumulation of heat and moisture is possible. Increasing the surface roughness leads therefore to more pronounced spatial differences in turbulent fluxes.

Heterogeneous surface temperature impacts mainly the SHF, since it influences the temperature gradient between the surface and the atmosphere. A heterogeneous surface specific humidity affects mainly the LHF by influencing the moisture gradient between the surface and the atmosphere. Overall, including heterogeneous conditions lead to higher spatial variability and a larger range of possible outcomes. The variability of the turbulent fluxes can result in a feedback effect that eventually results in the hummocky terrain typical for debris-covered tongues in the Himalaya and in the extreme case can result in the formation of cliffs and ponds in such depressions where melt was accelerated.

We found that including heterogeneous surface temperature and specific humidity is extremely important when looking at sub-glacier features such as ice-cliffs as those allow both negative and positive turbulent fluxes in the domain. The microclimate around an ice cliff is influenced strongly by a combination of topographic, surface specific moisture and temperature effects, which favour high sensible and latent heat fluxes. Additionally the progression and persistence of ice cliffs can be dependent on the main wind direction, since at the leeward side of the cliff turbulent fluxes contribute to melt. Longer high-resolution turbulent resolving simulations are needed to investigate fundamentals of small-scale glacier features in detail further.

We showed turbulent fluxes can decrease the energy available for melt at the debris surface by 40% and act as a sink of energy, while on ice cliffs turbulent fluxes enhance it by 51% and are a contributor to melt. In combination with a low albedo this causes ice cliffs to be melt hot spots.

Including homogeneous surface temperature and specific humidity is a good alternative when spatial data is lacking but only when that value is representative for the whole domain and the interest is primarily in domain-averaged outcomes. However, in general the point measurement is not representative for the whole domain resulting in large biases in atmospheric variables when upscaling point measurements to a larger area.

Our results show high-resolution turbulent resolving models can be used to better quantify spatially variable melt and future studies could couple high-resolution models to a full energy balance model to determine the energy reaching the ice. This work is important for glacier mass balance modelling and for the understanding of the evolution of debris-covered glaciers. Subsequently our results can be used to improve the representation of debris-covered glaciers in hydrological and climatological models to determine their contribution to glacier melt.

Data availability

The data can be found at 10.5281/zenodo.3375325 and 10.5281/zenodo.3375490.

Video supplement

Supporting movies are available at 10.5281/zenodo.3375333

Author contributions

PB designed the study together with WI. CH adjusted the MicroHH model for this study. PB performed all numerical experiments and prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they do not have competing interests.

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Appendix A

This appendix presents the most relevant results of a sensitivity study to the Reynolds number. With this analysis, we demonstrate that the results in the main text do not change when halving the Reynolds number. To provide an intuitive insight into this, Figure A1 shows the computed surface sensible and latent heat fluxes for both simulations. This figure clearly demonstrates nearly identical patterns and magnitudes of the surface fluxes. The similarity can also be understood from scaling arguments. Over a rough surface, the wind-driven surface fluxes can be approximated as:

$$LHF = \rho \cdot L_v \cdot c_{dq} \cdot (u - u_0) \cdot (q - q_0),$$
$$SHF = \rho \cdot c_p \cdot c_{dh} \cdot (u - u_0) \cdot (T - T_0),$$

where ρ is the air density, c_p specific heat, C_{dh} and C_{dq} the exchange coefficient for heat and moisture respectively, u the wind speed, u_0 the wind speed at the surface, T the temperature and T_0 the temperature at the surface, L_v the latent heat of vaporization, q the specific humidity and q_0 the specific humidity at the surface. In our case, both simulations have the same boundary conditions for temperature and humidity, and resolve nearly identical atmospheric fields (Figure A2). As atmospheric profiles are identical, the only place where low Reynolds number effects could manifest itself is via C_{dh} and C_{dq}, and therefore in the magnitude of the surface fluxes, yet Figure A1 shows that this is not the case.

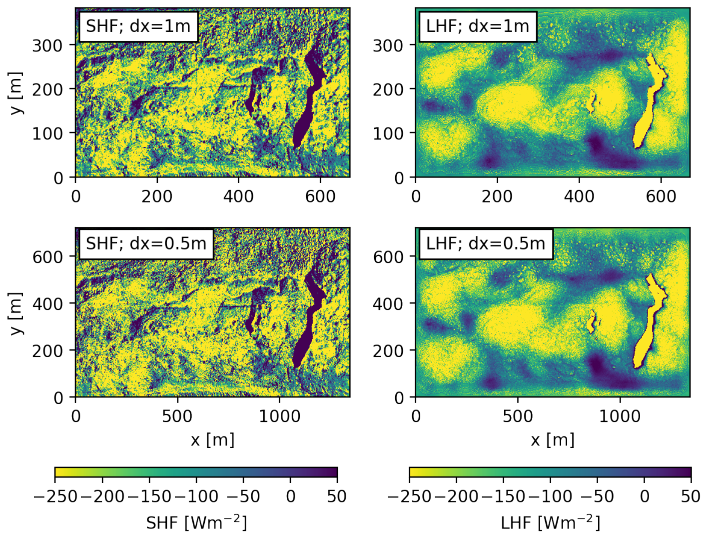

Figure A1: The averaged sensible (left panels) and latent heat flux (right panels) for the REAL experiment with a viscosity of 0.2 m^2s^{-1} (dx=1m; upper panels) and with viscosity of 0.11 m^2s^{-1} (dx=0.5m; lower panels).

Further proof of the independence of the bulk quantities (profiles of means and variances) can be found in the streamwise spectra of specific humidity (Figure A3). The additional variance that is resolved in wavenumbers >11 does not relevantly contribute to the total amount of variance. This can be visually inferred from Figure A3, as the total variance is the area under the graph, and the newly added variance is invisible to the eye.

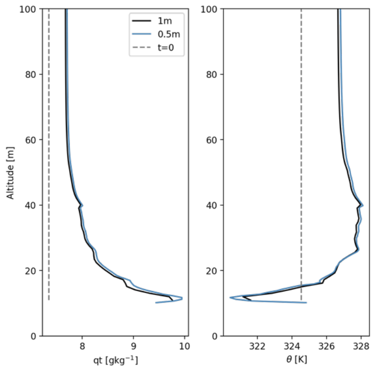

Figure A2: Total specific humidity (left) potential temperature (right) profiles for the REAL experiment with dx=1m (black), dx=0.5m (blue) averaged over the simulation hour and their initial profiles at t=0 (gray).

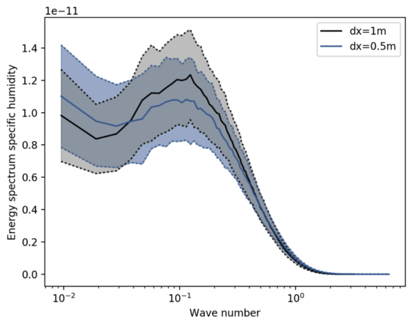

Figure A3: Energy spectrum for the total specific humidity at 65 meters above lowest point of the topography, averaged over the simulation hour. Shading indicates one standard deviation. The vertical axis is pre-multiplied with the wavenumber.