Dear Referee,

We would like to thank you for taking the time to review our paper and for all your constructive suggestions, which definitely helped to improve the quality of the manuscript. We reply to your comments below. Our response to the comments appears in bold and revised text as *italic*.

Minor comments:

- 110-115: It is correct that Monin-Obukhov assumptions are violated over patchy snow covers which means that models applying Monin-Obukhov will not be able to capture full dynamics leading to uncertainties in the turbulent flux estimates. However, the way this is stated in the manuscript leaves most of the readers with a big question mark. I ask the authors to give a clear explanation why Monin Obukhov assumptions are not valid over heterogeneous surfaces such as patchy snow covers – either in the introduction or in the discussion part.

  We agree that we should indicate for the reader what these assumptions are. We have added a sentence in this paragraph on the Monin Obukhov assumptions:
  As a consequence of the high resolutions, these simulations do not need any turbulence parametrizations based on stability corrections and the Monin-Obukhov assumptions, in contrast to numerical atmospheric boundary layer models (Liston, 1995; Marsh et al., 1999) or Large-Eddy simulations (Mott et al., 2015; Sauter and Galos, 2016). These methods assume horizontal homogeneity and constant turbulent fluxes throughout the surface layer, which is violated for a patchy snow cover and, as such, introduce a large uncertainty (e.g. Mott et al., 2018; Schlögl et al., 2018a). Bonekamp et al. (2020) successfully showed the potential
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- L469fff: The statement that ARPS is not able to resolve the leading edge effect at all is not correct and if the authors want to state that they need to be more precise. The authors Schlögl et al clearly state that the leading edge effect is not FULLY resolved mainly due to two reasons (1) the resolution is still too coarse to resolve the very thin internal stable boundary layer and (2) Monin Obukhov assumptions are violated.
  Please revise this paragraph.

  We agree that this statement was not precise enough. We have adapted these lines following your suggestions:
  When comparing the average sensible heat fluxes for all the snow patches in the domain, clear differences arise between all simulations (Figure 6). The highest sensible heat fluxes towards the snow (i.e. most negative) are found in the simulation without buoyancy effects. This also causes the total sensible heat flux for this simulation to be significantly lower than the other simulations. Furthermore, increasing snow patch size reduces the heat fluxes into the snow patches. The heat fluxes of the simulation with doubled snow patch size (P30m) decrease with approximately 15% relative to the P15m simulation. For the simulation with quadrupled snow patch size (P60m), the heat fluxes reduce with approximately 25%. This is in contrast to the results of Schlögl et al. (2018a), who reports a minor influence of snow patch size on the amount of melt. Our findings are more in line with the results of Marsh et al. (1999), who based there work on a 2D Boundary Layer Model with a regular tiled surface pattern. Potentially, the differences with Schlögl et al. (2018a) are caused by the disability of ARPS to fully resolve the leading edge effect, due to a too coarse resolution to resolve the thin internal stable boundary

layer formed over snow patches and the violation of the Monin-Obukhov assumptions. Both of these limitations do not apply for DNS.

- The sentence "Especially, considering that DNS does not violate the assumptions for the Monin-Obukhov bulk formulations and is able to resolve the leading-edge effect, in contrast to modelling studies with coarser spatial resolutions, which could lead to major errors (Schlögl et al., 2017). As such, the simulations are expected to provide a more realistic behaviour of the turbulent heat fluxes." I do not fully agree as you miss the driving factors resulting in the leading edge effect which is the diurnal cycle of radiation which is heating the surface leading to instable conditions over bare ground affecting the leading edge effect which changes depending on the strength of the heating and the associated change in stability. I think the term "more realistic" is not correct as you need exact knowledge on the boundary conditions getting the realistic turbulent heat flux estimates. The unrealistically high values of turbulent heat fluxes indicate that model results are not really realistic, probably due to too extreme boundary conditions/model settings. Furthermore, in your simulations, heat advection appears to be dominant over very long distances, which is not in agreement with measurements so far. I would highlight the strength of the DNS model to capture the leading edge effect in a relative sense, i.e. the percentage of the increase in the turbulent heat flux depending on fetch distance. We also know that the leading edge effect strongly depends on wind speed – this is not addressed in the current form of the manuscript. Please revise this paragraph.

In this final part of the paragraph, we agree with your suggestions to emphasise the general strength of DNS to capture the leading edge effect. To highlight this, we have adapted the paragraph following your comments:
Moreover, we identify some inaccuracies during the nondimensional scaling of the wind speed and temperature difference between the snow and atmosphere. As Harder et al. (2017) reported a wind speed of 6.4 m s^{-1}*, this value is also considered in our dimensional analysis and related to 0.11 m* s^{-1}*, which was the average wind speed over the whole channel in the case of Moser et al. (1999). However, the reported wind speed was measured at 1.8 meter above the ground, thus implying that the average wind speed for the whole air column under consideration would be higher. Consequently this affects the leading edge effect, due to increased wind shear and, thus, also the fluxes towards the surface. Also, the temperature difference between the atmosphere and snow has been possibly overestimated, causing an increased sensible heat flux. The graphs presented by Harder et al. (2017) show the temperatures of bare ground and atmosphere to be constant near the surface, being 6.4 ◦C. However, for the dimensional analysis, the atmospheric temperature mentioned by Harder et al. (2017), i.e. 7.9 ◦C, has been used. Overall, these differences in assumptions between the simulations and the field observations make a one-to-one comparison difficult. Yet, the general behaviour found in the simulations is similar to previous literature, i.e. temperature profiles and melting patterns (e.g. Harder et al., 2017; Mott et al., 2016), and shows the potential of DNS as a modelling tool to understand the melting of a patchy snow cover. Especially, considering that DNS does not violate the assumptions for the Monin-Obukhov bulk formulations and is able to resolve the leading edge effect, in contrast to modelling studies with coarser spatial resolutions, which could lead to major errors (Schlögl et al., 2017). As such, this type of simulations is expected to provide a more realistic behaviour of the leading edge*

effect on the turbulent heat fluxes, especially when combining with case-specific boundary conditions.

- The authors still switch between the terms “local advection of sensible heat” and “local advection of turbulent heat”. Please stick to the original definition (see first review for more details).

  Our apologies, we misinterpreted your comment in the first review. When we discussed the *local advection of turbulent heat*, we meant the advection of both sensible and latent heat. However, this usage indeed is incorrect. We have adopted this and refer now to *local advection of sensible and latent heat.* Moreover, we have added the words *vertical* and *horizontal* (or comparable) when discussing both the vertical turbulent heat fluxes and local advection, in order to create a clear distinction between the two. For example:

  …When a wind blows over this horizontally heterogeneous surface, downwind of the transitions internal boundary layers form, due to changes in the surface conditions (e.g. Garratt, 1990). The heterogeneity of these internal boundary layers induces a system in which the turbulent heat fluxes can highly vary spatially, partly due to the advection of sensible and latent heat (Essery et al., 2006; Mott et al., 2013; Harder et al., 2017). These systems are often described as….

  …Therefore in this study, we aim to assess the role of horizontal advection of the sensible and latent heat on snowmelt for a snow patch in a real world case and idealized environment. In the real world case, we will identify the role of the locally advected sensible and latent heat on a melting snow patch in the Finseelvi catchment through studying the vertical turbulent heat fluxes with SfM photogrammetry observations over the course of multiple days. The resulting snowmelt is compared to local meteorological measurements to put the snowmelt in perspective and extract the role of the turbulent fluxes on this melt. Subsequently, we try to uncover the behaviour of the vertical sensible heat fluxes on snowmelt, including the local-scale advection of sensible heat, in an idealized environment with DNS, allowing to extract detailed information on wind blowing over a small flat domain with a patchy snow cover….

  Instead of using our own measurements, the idealised system is based on the measurements on a single snow patch done by Harder et al. (2017), due to the availability of relatively high resolution measurements and similarity to an idealized system in which the contribution of the local-scale advection of the sensible and latent heat to the total melt is relatively large….

  Our simulated vertical sensible heat fluxes into the snow are approximately 500 W m^{-2} and at the upwind edge and 200-300 W m^{-2} at the downwind edge. In comparison to our field observations, at both edges these sensible heat fluxes are relatively high. At the upwind edge, the simulated sensible heat fluxes are approximately 5 times larger than the derived contribution of the combined turbulent heat fluxes to the measured snowmelt. We reckon that the simulated values are large, though it should be noted that the simulations are based on highly ideal conditions for turbulence-driven melt and local-scale advection of sensible and latent heat, whereas the conditions during the measurements were not ideal (e.g. nighttime *melt is included). At the downwind edge, the measurements suggest an approximately negligible contribution of the vertical turbulent heat fluxes to the snowmelt, whereas the simulations show at comparable snow patches a significant contribution of the vertical sensible heat flux (~ 200-300 W m^{-2}).*

We used an idealised system (Fig. 2) to study the turbulent heat fluxes in detail and understand the behaviour observed in the field. As this is one of the first studies using DNS to investigate the role of the vertical turbulent heat fluxes and local heat advection in these systems, we focus on the sensible heat flux, even though MicroHH allows to include the latent heat flux (e.g. Bonekamp et al., 2020). Instead of using our own measurements…

Relating the meteorological circumstances (Table 4) to the measured snowmelt, allows to estimate the contribution of the vertical turbulent heat fluxes to the total amount of snowmelt.

As the snow patch was approximately 50 meter in length, the turbulent heat fluxes into the snow have likely reduced to negligible values at the downwind edge (e.g. when extrapolating the measurements of Harder et al., 2017)

Compared to Harder et al. (2017), our estimates of the horizontally advected sensible heat are relatively high. The measurements done by Harder et al. (2017) show values slightly above 400 W m^{-2} for the first 3.6 m (Figure 7). In our simulations the horizontal advection of sensible heat decreases in the first 3.6 m from 577 W m^{-2} to approximately 400 W m^{-2}. For the following 4.8 m, Harder et al. (2017) reported an average reduction in horizontally advected sensible heat to approximately 20% of values found for the first 3.6 m. In the comparable simulation with a similar dominant snow patch pattern, this reduction is not found. Yet, further downwind the advected sensible heat does reduce to values in the same order of magnitude. It should be noted that, due to setting the integration height at 2 m in Eq. 17, not all changes in the vertical temperature profile over distance from the leading edge are included, such that the horizontally advected sensible heat is underestimated. When considering a 4 m integration height, the horizontally advected sensible heat is approximately equal to the vertical sensible turbulent heat fluxes at the snow surface, especially for the first half of the patch, implying also a power of -0.35 for the decay of the horizontally advected sensible heat. This also illustrates the major contribution of the horizontally advected sensible heat to the sensible heat flux into the snow...

- I think that the manuscript would benefit from language editing.
- Some sentences are not clear to me, e.g.: “Overall, these mechanisms are the main factors that prevent a direct match between the simulations and observation.“ I do not fully agree here as not considering these factors increases the uncertainty …

We have thoroughly reread the manuscript and have adopted multiple sentences. We agree that this has made the manuscript easier to read and more clear. For example:

For the stable internal boundary layers, i.e. over snow patches, the air close to the snow surface can decouple from the warmer air above, either due to large temperature differences between *both or through cold-air pooling, eventually limiting the exchange of sensible and latent heat from the atmosphere towards the snow (Fujita et al., 2010; Mott et al., 2016).*

As a consequence, more field observations should be performed to study its importance in various environmental settings. Additionally, these should be combined with other modelling approaches that can serve as a tool to improve our understanding of the process on small and larger scales. (splitted sentence)

Overall, these mechanisms greatly increase the uncertainty and make us decide not to directly compare between the simulations and observation.

The simulations reveal that the reducing sensible heat fluxes over distance from the leading edge are caused by the reducing temperature gradients, pointing out the major role of the horizontally advected sensible heat, which we expect to behave similarly in our field observations.

Moreover, the common formation of snow patches in topographical depressions causes atmospheric decoupling and reduced vertical turbulent heat fluxes at low and moderate wind speeds, especially downstream of the upwind edge (Mott et al., 2016). In the Finseelvi catchment snow patches have formed to some extent in these depressions, while this does not hold for Harder et al. (2017). (splitted sentence)

We expect that the important role of the horizontally advected sensible heat and the identical behaviour of the vertical sensible heat flux between patches, both found in the simulations, is also applicable to our field observations, given the probable larger-scale approximate equilibrium of the atmosphere. Though anomalies in this behaviour can be found due to varying micrometeorological conditions. (splitted sentence)

As multiple studies suggest the role of stability on snowmelt (e.g. Dadic et al., 2013; Essery et al., 2006), stable regions (i.e. snow patches) could have a much larger impact on the amount of wind-driven snowmelt, especially when reducing the turbulence towards the edge of collapsing.