Review of ”Investigating the influence of changing ice surfaces on gravity wave formation and glacier boundary-layer flow with large-eddy simulations” by Goger et al.

Michael Haugeneder, michael.haugeneder@slf.ch

September 5, 2024

The authors present a case study of large-eddy simulations of the atmosphere above the highly heterogeneous high-mountain terrain surrounding Hintereisferner (HEF). They compare a reference simulation featuring realistic ice surfaces with two sensitivity analyses comprising different surface properties. In one run, they only replace the upstream glacier surfaces, while in the other sensitivity run, all glacier surfaces are replaced by bare ground. With these different setups, the authors aim at investigating the influence of upstream surface properties on the flow dynamics over the HEF ultimately affecting the heat fluxes in the near-ice atmosphere at HEF.
Their work contributes significantly to understanding the larger-scale (and non-local) influences on the local flow field. Comparing runs with modified surface properties to verified ”real-world” runs offers promising insights advancing the current understanding of process interactions at a wide range of scales. However, I suggest revising the presentation of the results to facilitate better understanding.
If the authors have any questions, please don’t hesitate to ask.

Major Comments

1. language and spelling: The manuscript will strongly profit from a thorough revision of the language including syntax and spelling. At this stage, it is sometimes difficult to follow the author’s line of argumentation.

2. It should be possible for the reader to follow the main ideas of the study without completely reading Goger et al. (2022). This particularly refers to the model setup. What is the vertical and horizontal grid spacing of the inner domain? What is the height of the lowest model level? Can you briefly summarize the main findings of the comparison of the REF run with the measurements during HEFEX? Why do the REF run and observations diverge after 1200?

3. Although the authors state in l. 324ff. that "we cannot assume that the local glacier boundary layer [...] is simulated realistically", RQs 2 and 3 and Section 4 focus on the effects of the overlying flow on the near-surface heat exchange in the local glacier boundary layer over HEF. I suggest giving a more comprehensive reasoning as to why analyzing the effects on the near-surface atmosphere is valid or focusing the manuscript on larger-scale interactions between the (breaking) gravity wave and other flows and leaving out near-surface processes.

4. Can you include a brief review on gravity waves (generation, overturning, breaking, hydraulic jump (l. 154)) and their influence on the isentropes and the turbulent kinetic energy as this is an important part of your study?

5. The introduction should present a comprehensive motivation for the conducted research. Can you clearly state the knowledge gap you address with this study? Your RQs 2 and 3 leave the impression that the study aims to investigate the effects of artificial surface modifications on the atmosphere. However, I think the authors performed the ice-removed runs as a method to gain more information on upstream influences on the atmosphere above HEF.

6. A separate method section that contains the definitions you use (e.g. Scorer parameter, up-valley wind index, advection formula, ...) can enhance the readability of the results section. Additionally include a description of the surface parameters used for ice and replaced ice surfaces in section 2.

7. In the discussion, add ideas on how to cope with the lack of near-surface process representation in your model. Would nesting with a finer-scale model, such as HICAR (Reynolds et al., 2023), close to the surface improve the results?

8. The discussion lacks a clear storyline. Please revise the structure of this section. Furthermore, a main part of the results section is dedicated to the surface energy exchange, but the results are not discussed.

Specific Comments

1. At the first occurrence, state that all times are in UTC and then remove the "UTC" throughout the rest of the manuscript.

2. l. 32f.: Mott et al. (2020) found the same over HEF

3. l. 51: High-resolution → decameter-resolution

4. l. 51: Introduce the "LES" abbreviation at the first occurrence

5. l. 51f.: Include Mott et al. (2019). They investigated the near-surface boundary layer over a perennial ice field using measurements and a high-resolution modelling setup.

6. l. 55: Can you detail more on why you are confident that the LES can resolve the "relevant mesoscale flow"? Here, it would help to talk about the results from Goger et al. (2022)
7. l. 69: What do you mean by "stronger due to the ice surfaces"?
8. Figure 1: color contours → contour lines and colors
9. l. 90: Can you give a number for ice melt during "extreme mass loss [...] in some recent years" to compare to the 1 m over the last 20 years?
10. l. 101: add a reference to Figure 1b in Goger et al. (2022)
11. l. 114: How do you define the upstream glacier surface replaced in NO_UP? What do you set as the "new" parameters describing the replaced surfaces in contrast to glacier ice?
12. l. 119: In addition, you use the current (ice-covered) DEM just replacing surface properties, right? So the topography of the replaced surfaces is also not representative of a melting ice cover under the influence of climate change.
13. l. 124ff.: This sentence fits in l. 106.
14. l. 127: More concise caption. Maybe: "Flow structure"?
15. l. 132ff.: Remove that sentence. Already stated above
16. l. 136ff.: That sentence would fit earlier in the manuscript when you talk about the selection of the period
17. all following figures: Can you make the color of the glacier outline consistent with Figure 1?
18. Figure 2: The x-labels of the color plots are overlapping.
19. Figure 2 caption: Height of the lowest model level?
20. l. 140: Height of the lowest model level?
21. Figure 3 caption: Indicate, that the cross sections are taken looking up valley along the black line in Fig. 1b.
22. interpretation of figure 3: If you talk about stability, you mean "static" stability, right? Could you note that when you talk about stability inferred from the isentropes?
23. interpretation of figure 3: Include the Scorer parameter plots in figure 3 and discuss the parameter in the course of figure 3 in connection with the gravity waves to improve the storyline.

24. l. 145: Can you support your note on "weakening of the cross-glacier flow" with values? I find it hard to see in Fig. 2e,f.

25. l. 150f.: repetition of the previous sentence

26. l. 157: $\Delta\text{TKE} = -5\,\text{m}^2\,\text{s}^{-2}$

27. l. 171: Indicate the upstream point in figure 1

28. l. 176: lower → weaker

29. l. 180: Fig. 4e?

30. l. 179ff.: Briefly note that the near-surface stratification is often different from further aloft.

31. l. 180f.: Do you have a hypothesis as to whether the jet height is different?

32. l. 183: maxima → extrema, large decrease → peak

33. l. 185: within $\approx 600\,\text{m}$ above the surface

34. Figure 4: Set the upper limit for the y-axes to 4000 m like figure 3. Consider creating separate subplots for the wind direction to enhance the readability of the plots. i,j,k,l) Sc → l^2

35. l. 186: potential temperature difference close to the surface

36. l. 187f.: The REF simulation at the upstream location also shows a $\approx 100\,\text{m}$ deep near-neutral or slightly unstable layer adjacent to the surface.

37. l. 192f.: Check sentence structure

38. l. 195: differences in the potential temperature profiles close to the surface

39. l. 199: the flow changes direction at 4000 m, which is above crest height

40. Figure 6: Could you indicate the cross-glacier and along-glacier flow directions in panel a? Why did you leave the thermally-driven regime out in panel b? Spell out "UWI" in the caption and add a reference to (2).

41. l. 205f.: Where do you identify the neutral layer and the inversion in fig. 5e?

42. l. 210: Upper part of HEF

43. l. 204 – 215: challenging to follow

44. l. 233ff.: At which location and height do you extract the upstream wind direction? The same as before? Can you indicate that in fig. 1?

45. l. 235: add a reference to figure 1 in Whiteman and Doran (1993)

46. l. 250f.: Is the model capable of resolving thermally-driven winds so you can say their influence is negligible? Please add a brief comment on that.

47. l. 257ff.: Split this sentence and be more precise about the indirect dependence of the heat fluxes on the wind direction (via air temperature) in the Monin–Obukhov formulation. Consider presenting the formula and indicate how you diagnose sensible heat fluxes from your model output.

48. section 4.1: Make clear when you refer to positive in contrast to negative heat fluxes. I suggest using the terms more/less pronounced or stronger/weaker when you relate fluxes of the same sign instead of higher/lower. Indicate, when you compare fluxes of different signs (mainly in the presentation of fig. 8).

49. l. 262f.: negative heat flux corresponds to the transport of heat from the atmosphere into the ice (atmospheric notation)

50. l. 264: Which pattern are you referring to?

51. l. 275: SH fluxes: be consistent with abbreviations

52. l. 274−281: Consider moving fig. 8 and this paragraph to the supplements and just give a summary in the main study. The results of NO_GL do not seem surprising and there is already a lot of information.

53. l. Figure 7 interpretation: Can you go into more detail about different sensible heat flux magnitudes on HEF and how they relate to the local wind direction? That would help to highlight the importance of the local wind direction on the surface energy exchange and reinforce the manuscript.

54. Figure 7: x-labels overlap

55. Figure 7 and 8: Consider focusing the color bar extent to HEF to make the differences on the glacier more apparent. Include a sentence about the wind arrows in the captions.

56. Figure 8 right column: outlines of replaced ice surfaces missing

57. Figure 9: Consider splitting this figure into two figures: The first containing the left column and the second the right column. The subfigures in the right column miss y-axis labels. Furthermore, referring to the right column, in l. $298 - 308$, you are mostly analyzing the heating effects at the glacier surface. Consider a simpler time-series diagram with just the surface values or discuss the vertical structure in more detail.

58. l. 282: Heat Advection and Heat Budget? Consider splitting this into two subsections.

59. l. 283: At which height are you extracting the data from the model?

60. l. 285 – 295: Please revise this paragraph. I can not follow your presentation.

61. l. 296: What do you mean by vertical heat budget? The temperature tendency equation? add original citation (Wyngaard, 2010)

62. l. 297: what terms have you neglected and why?

63. l. 300: a.g.l.

64. l. 300: what do you mean by wavy structure? Spatially or temporally?

65. l. 302: but there are periods of $\frac{\partial \theta}{\partial t} < 0$ at the surface between 0945 – 1000 and 1145 – 1200

66. l. 309 – 321: I suggest focusing on the effects on HEF.

67. l. 335: you noted earlier that REF is not reliable after 1200

68. l. 345f.: missing end of sentence

69. l. 346: Which forces? Refer to Whiteman and Doran (1993)

70. l. 350: A large part of the results section is dedicated to the surface energy exchange, but the results are not discussed here

71. l. 380: The transition between the summarizing sentences and the outlook is abrupt.

References

Brigitta Goger, Ivana Stiperski, Lindsey Nicholson, and Tobias Sauter. Large-eddy simulations of the atmospheric boundary layer over an alpine glacier: Impact of synoptic flow direction and governing processes. *Quarterly Journal of the Royal Meteorological Society*, 148:1319–1343, 4 2022. ISSN 0035-9009. doi: 10.1002/qj.4263.

Rebecca Mott, Andreas Wolf, Maximilian Kehl, Harald Kunstmann, Michael Warscher, and Thomas Grünewald. Avalanches and micrometeorology driving mass and energy balance of the lowest perennial ice field of the alps: a case study. *The Cryosphere*, 13: 1247–1265, 4 2019. ISSN 1994-0424. doi: 10.5194/tc-13-1247-2019.

Rebecca Mott, Ivana Stiperski, and Lindsey Nicholson. Spatio-temporal flow variations driving heat exchange processes at a mountain glacier. *The Cryosphere*, 14:4699–4718, 12 2020. ISSN 1994-0424. doi: 10.5194/tc-14-4699-2020.

Dylan Reynolds, Ethan Gutmann, Bert Kruyt, Michael Haugeneder, Tobias Jonas, Franziska Gerber, Michael Lehning, and Rebecca Mott. The high-resolution intermediate complexity atmospheric research (hicar v1.1) model enables fast dynamic downscaling to the hectometer scale. *Geoscientific Model Development*, 16:5049–5068, 9 2023. ISSN 1991-9603. doi: 10.5194/gmd-16-5049-2023.

C. David Whiteman and J. Christopher Doran. The relationship between overlying synoptic-scale flows and winds within a valley. *Journal of Applied Meteorology*, 32:1669–1682, 11 1993. ISSN 0894-8763. doi: 10.1175/1520-0450(1993)032¡1669:TRBOSS¿2.0.CO;2.

John C. Wyngaard. *Turbulence in the Atmosphere*. Cambridge University Press, 1 2010. ISBN 9780521887694. doi: 10.1017/CBO9780511840524.