

Assessment of snow model uncertainty in relation to the effect of a 1 °C warming using the snow modelling framework openAMUNDSEN

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Responses to Reviewers

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Florian Hanzer, Elena Bertazza and Ulrich Strasser

Dear Editor and Reviewers,

thank you very much for reviewing our manuscript. We are grateful for your insightful comments and suggestions. Below, we provide detailed point-by-point responses to all comments. When we cite line numbers, we refer to the tracked-changes version of the manuscript uploaded during the revision process.

On behalf of all authors,
sincerely,

Erwin Rottler

Reviewer 1 (Richard L.H. Essery)

This is a worthwhile and well-written paper (although it will benefit from some copy editing). I only have a few minor comments.

Thank you very much for taking the time to review our manuscript. We appreciate your thoughtful comments and suggestions. We scanned through the manuscript, improving the language and correcting spelling and grammatical errors.

83 Resampling the DEM to coarser resolution could be taking elevations of the 10 m cells closest to the centre of the coarser resolution grid cells. Please confirm if this is the case. Block averaging would be more representative of the inputs to coarser-resolution models and would, I expect, give larger differences between simulations at different resolutions. Related to that, how are the 1 km meteorological variables downscaled?

The original DEM provided by the Berchtesgaden National Park administration had a resolution of 10 m. We aggregated this raster to coarser resolutions by computing the mean of the 10 m cells within each coarser cell. For the 50 × 50 m DEM, for example, each cell value is the average of the 25 underlying 10 m cells. Alternatively, one could assign the value of the 10 m cell closest to the centre of each coarser grid cell. We will keep this option in mind for future work and treat the method used to generate coarser-resolution DEMs as a potential source of uncertainty. To run the snow simulations, we

used scattered point measurements. These station observations were interpolated to each grid cell of the modelling domain. A detailed description of the elevation- and station-distance-dependent interpolation scheme is presented in Section 3.3 of Strasser et al. (2024) (<https://doi.org/10.5194/gmd-17-6775-2024>). The exact parameterization, including the lapse rates used to obtain the regression fields at each time step, is available in the configuration files of the model set-up published alongside the manuscript.

112 The statement “The incorporation of a radiation-driven melt component leads to seasonally and spatially varying snowmelt factors” is immediately followed by invariant values.

Thank you for pointing this out. In the enhanced T-index approach, the degree-day factor (DDF) and radiation factor (RF) are constant. Our intention was to emphasize that the radiation-driven component, $(1 - RF) \times G$ (with G denoting radiation), enables seasonally and spatially varying snowmelt dynamics in the study area. By incorporating radiation, this component accounts for aspect (e.g., south vs. north), shading by neighbouring mountains, and the general seasonal cycle. We adapted the corresponding sentence to: “The incorporation of a radiation-driven component supports seasonally and spatially varying snowmelt dynamics [...]” (Line 119)

255 The authors caution against using the stochastic climate generator to produce climate change scenarios. Moreover, it will not produce expected elevation- and season-dependent changes.

Yes, we point at the limitations of the stochastic climate generator and caution against using it to produce climate change scenarios. We agree that this is a limitation of the climate generator and that this should be explicitly mentioned. We added this aspect into the discussion section of the manuscript: "Moreover, it needs to be noted that the climate generator cannot adequately produce elevation- and season-dependent features of long-term climatic changes." (Line 271–272)

263 Although km-scale atmospheric models are commonly referred to as “convection permitting”, better resolution of topographic forcing of precipitation might be of more significance here.

We updated the corresponding sentence: "These high resolution climate model runs better capture the topographic forcing of precipitation and allow for an explicit, physical description of deep convection without having to use parametrization schemes." (Line 278–280).

292 “spatial resolutions considerably below 1 km are required” is not an unexpected conclusion, but how is this shown by the comparison of model simulations?

We base this conclusion on the observation that SCD and SDD from coarser model runs (especially at 500 and 1000 m) often differ substantially from higher-resolution runs, particularly at high elevations (see Fig. 7 in the manuscript). In terrain such as the BGNP, increasing grid size from 100 to 1000 m can markedly alter SCD and SDD for elevation bands. Accordingly, for the BGNP, we consider results robust only at resolutions well below 1 km.

Reviewer 2 (Maheswor Shrestha)

This manuscript presents the assessment of snow model uncertainty in relation to the effect of a 1°C warming using the snow modelling framework openAMUNDSEN. This is a well written manuscript and the content of the manuscript is of weighted significance in cryosphere modeling community as this paper investigates the uncertainty induced by the selection of the snow model configuration with degree-day as well as physically based snowmelt methods and varying land cover maps and spatial resolutions. I would recommend to accept the paper for publication after minor revisions as per the specific comments given below.

Thank you very much for taking the time to review our manuscript. We appreciate your thoughtful comments and suggestions.

1. Line 114 model runs at 3-hourly time scale whereas line 107, the model runs at daily resolution. Please clarify.

In this study, we apply three snowmelt approaches: (1) T-index, (2) enhanced T-index, and (3) energy balance. In our configuration, the T-index simulations are run at daily time steps, while the enhanced T-index and energy balance simulations use 3-hourly time steps.

2. Line 120, please clarify combined lapse rate/inverse distance weighting scheme.

To conduct fully distributed snow simulations, we use the meteorological pre-processor integrated in the openAMUNDSEN model to spatially interpolate scattered point measurements. A detailed description of the interpolation scheme is provided in Section 3.3 of Strasser et al. (2024) (<https://doi.org/10.5194/gmd-17-6775-2024>). We added the following details to the Methods section: “First, lapse rates are applied to generate a distributed elevation-dependent field for each meteorological variable (i.e., the regression field). Next, residuals between the regression field and station observations are computed and interpolated to the grid using inverse distance weighting (IDW), yielding the residual field. The superposition of the regression and residual fields produces the final meteorological input grid. This interpolation procedure is performed at each model time step.” (Line 127–131)

3. openAMUNDSEN models snow-canopy interactions. Such interaction modeling gives SWE over canopy which would be evaluated with satellite derived snow cover fraction in the forest region too. Please consider it.

Thank you for pointing this out. Evaluating snow simulations in forested areas is indeed crucial, and we agree that further research is needed to improve the assessment of model performance in such environments. To our knowledge, Sentinel-2 products typically provide top-of-canopy fractional snow cover (FSC), which could potentially be used to evaluate the presence of snow within the model's canopy interception storage. While additional investigation of this aspect would be valuable, it is beyond the scope of the present study.

4. Please mention that the model evaluation mentioned at lines 176-181 is valid for non-forest area (canopy free region) only.

We modified the corresponding sentence in the Results section: “The evaluation of the openAMUNDSEN snow simulations in non-forested areas [...]” (Line 188) and ensured that the captions of the corresponding figures clearly state that this evaluation uses only non-forested cells. An evaluation of snow simulations in both open and forested areas of the BGNP, along with a more detailed description of snow–canopy interactions, is presented in Storebakken et al. (2025) (<https://doi.org/10.1002/hyp.70197>).

5. Figure 4-8 are for the entire BGNP area or non-forest area of BGNP. Please clarify.

Yes, in Figures 4–8 we present results for the entire BGNP. One aspect we plan to investigate is how strongly the snow model results differ depending on which land-cover map (particularly the forest representation) is used in combination with each snowmelt approach.

6. What about the sensitivity of albedo value in snow melt simulation?

Yes, we expect snow-model results to be sensitive to the snow-albedo parameterization. Snow albedo and its decay function are used only in the enhanced T-index and energy-balance simulations. A detailed description of the air-temperature-dependent albedo decay function implemented in openAMUNDSEN is provided in Section 3.4 of Strasser et al. (2024) (<https://doi.org/10.5194/gmd-17-6775-2024>). In this study, we use the default maximum and minimum snow-albedo values and a temperature-dependent recession factor.