StartClim 2023

SNOWLINE

Exploring nonlinear developments of the snowline in a changing climate in Austria

Bundesministerium
Klimaschutz, Umwelt,
Energie, Mobilität,
Innovation und Technologie

Bundesministerium
Bildung, Wissenschaft
und Forschung

klima+ energie fonds

LAND OBERÖSTERREICH

ober österreich

umweltbundesamt

BOKU

Bundesanstalt für Geologie, Geophysik, Klimatologie und Meteorologie

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Diese Publikation sollte folgendermaßen zitiert werden:

Günther, D.; Koch, R.; Olefs, M. (2024): SNOWLINE - Exploring nonlinear developments of the snowline in a changing climate in Austria. Endbericht von StartClim2023.D in StartClim2023: Biodiversität, Klimakippeffekte und sozioökonomische Klimaindikatoren, Auftraggeber: BMK, BMWFW, Klima- und Energiefonds, Land Oberösterreich.

Wien, im September 2024

StartClim2023.D

Teilprojekt von StartClim2023

Projektleitung von StartClim:

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www.startclim.at

StartClim2023 wurde aus Mitteln des BMK, BMWFW, Klima- und Energiefonds und dem Land Oberösterreich gefördert.

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D-1 Kurzfassung

Die saisonale Schneedecke in Österreich ist entscheidend für Tourismus, Wasserressourcen, Ökosysteme und Infrastruktur. Diese Studie untersucht die sich verändernden Dynamik der Schneefallgrenze, der Höhe, in der Schnee zu Regen übergeht, und konzentriert sich auf die Auswirkungen der Niederschlagskühlung in einem sich verändernden Klima. Niederschlagskühlung ist ein Prozess, der zu einer Abkühlung der Atmosphäre während Niederschlagsereignissen führt.

Unter Abschätzung der Energiebilanz haben wir berechnet, wie viel Niederschlag benötigt wird, um die Höhe der Schneefallgrenze bis auf Bodenniveau zu senken. Diese Methode berücksichtigt die reale Topographie und den Effekt des reduzierten Luftvolumens in Tälern. Unsere Simulationen zeigten, dass selbst geringe Niederschlagsmengen die Schneefallakkumulation signifikant erhöhen können, insbesondere in Tälern. Die Ergebnisse deuten darauf, dass die Sensitivität der Schneefallgrenzen gegenüber Temperaturänderungen variiert. Schneefallereignisse, bei denen dieser Prozess der Niederschlagskühlung aktiv ist, können potenziell eine Pufferfunktion gegenüber steigenden Temperaturen aufweisen, indem sie Schneefall auf dem Talboden ermöglichen. Wenn jedoch steigende Temperaturen zu ungünstigen Bedingungen für die Niederschlagskühlung führen, sind starke Veränderungen in der Schneefallakkumulation zu erwarten (vlg. Abb. D-1)

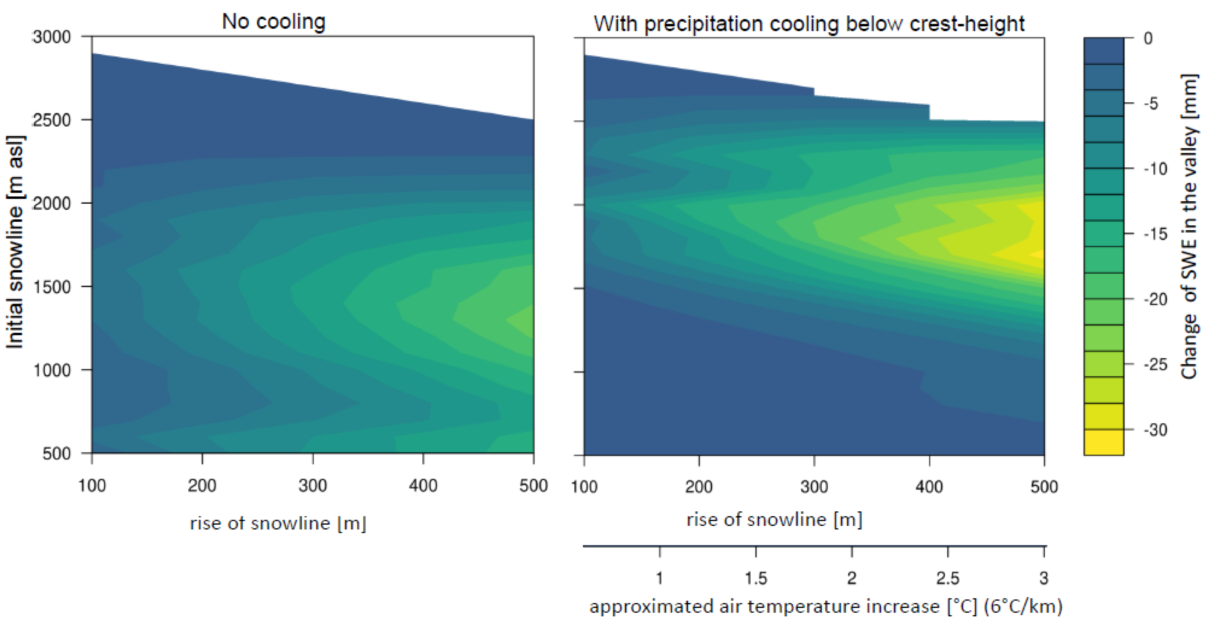

Abb. D-1: Änderung der Schneeakkumulation mit zunehmenden Schneefallgrenzen (x-Achse) basierend auf den Ausgangsschneefallgrenze (y-Achse) im Gailtal.

Weitere Forschung ist erforderlich, um die Häufigkeit und Intensität von Niederschlagskühlungsereignissen zu verstehen. Das Verständnis dieser Prozesse ist für Sektoren, die auf saisonale Schneedecken angewiesen sind, von entscheidender Bedeutung. Die Quantifizierung der Schneemenge und der zu erwartenden Änderungen für einzelne Regionen in ganz Österreich kann für eine fundierte lokale Entscheidungsfindung entscheidend sein.

D-2 Abstract

The seasonal snow cover in Austria is crucial for tourism, water resources, ecosystems and infrastructure. This study delves into the changing dynamics of the snowline, the elevation where snow turns to rain, focusing on the impact of precipitation cooling in a shifting climate. Precipitation cooling is a process, that leads to a cooling of the atmosphere during precipitation events.

Using an energy balance formula, we estimated how much precipitation is needed to lower the snowline elevation to allow snowfall on the ground. This method accounts for real topography and the effect of reduced air volume in valleys. Our simulations revealed that even modest precipitation rates can significantly increase snowfall accumulation, particularly in valleys. The results demonstrate that sensitivity of snowlines to temperature changes varies. Snowfall events where this precipitation cooling process is active can potentially show a buffer function to warming temperatures. Allowing snowfall at the valley floor even with rising initial snowline elevations. However, when rising temperatures lead to unfavourable conditions for precipitation cooling, strong changes are expected in snow accumulation (fig D-2).

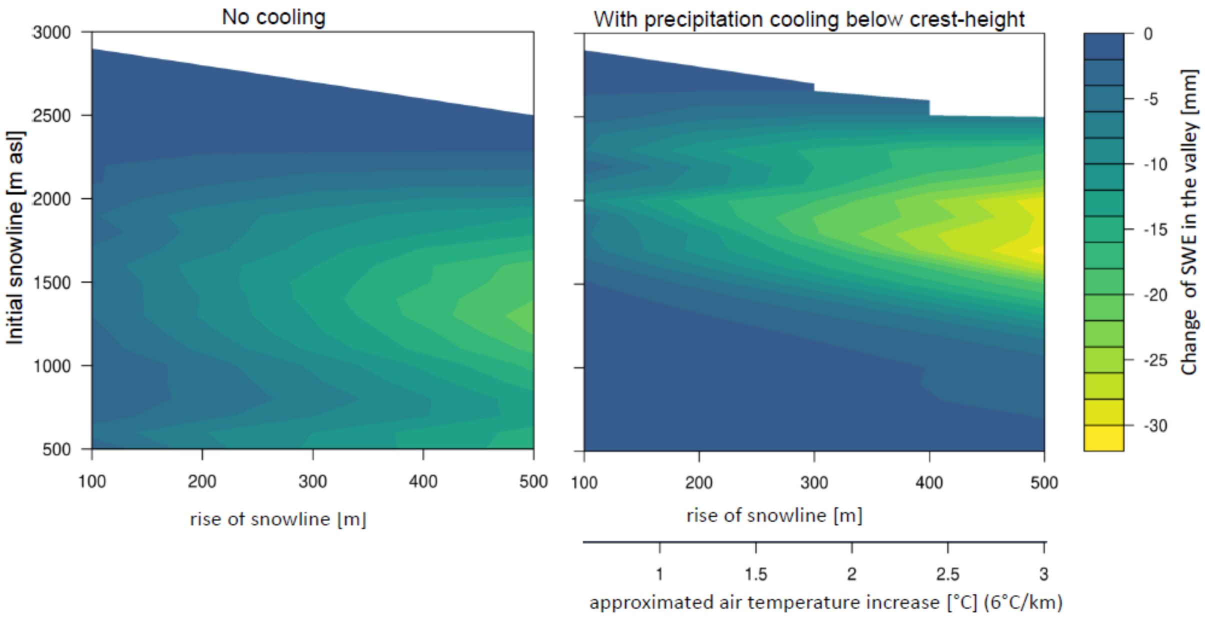

Abb. D-2: Change of area-wide accumulated snowfall with increasing snowlines (x-axis) based on initial snowlines (y-axis) for the Gailtal

Further research is needed to understand the frequency and intensity of precipitation cooling events. Understanding these processes is vital for sectors reliant on seasonal snow cover. Quantifying the snowfall amount and the rate of change for individual regions across Austria can be crucial for informed decision-making.

D-3 Project Report

D-3.1 Background

The seasonal snow cover is of great interest in Austria due to its immense importance for numerous economic, ecological and social sectors. Seasonal snow builds the foundation for various winter sports and the tourism economy around it, is crucial for water resources and hydropower generation, but also poses risks to infrastructure and human health in the form of flooding, avalanches, and snow load.

The accumulation of snowfall is paramount for the development of seasonal snow cover during winter, alongside processes such as snowmelt and redistribution. While most winter precipitation emerges from clouds in a frozen state, the meteorological conditions of the atmosphere that the falling liquid or solid precipitation droplets (i.e. hydrometeors) need to pass through on their way to the ground, dictate whether they reach it as snowfall or rainfall. If the atmosphere contains enough energy, snow crystals will completely melt, resulting in liquid water droplets reaching the surface. These meteorological conditions are often summarized as the snowline altitude, expressing the altitude band in which most of the phase transition between solid snowfall and liquid rainfall occurs. Melt processes are driven by net positive energy gradients towards hydrometeors (Harder and Pomeroy, 2013). A wet-bulb temperature of 0°C proved to be a good proxy for these conditions, as it includes evaporative cooling, as opposed to dry air temperature.

In this study, we focus on the described melting process of falling hydrometeors, its effect on the snowline, and explore possible consequences that might arise in the context of a changing climate. As solid precipitation melts, the energy required for the phase transition is provided by the atmosphere, which in turn, remains with a lower energy content - it cools down. If the intensity of precipitation is sufficiently high and there is little atmospheric mixing, the melting of solid precipitation and the subsequent cooling of the atmosphere can translate to a drop in the snowline. This phenomenon - often described as the precipitation cooling effect - is particularly pronounced in valley regions, where air masses may become decoupled from the adjacent flow, and where air volumes are smaller compared to the open area. Here, this transfer of energy corresponds more closely to a drop of the 0°C line of the wet-bulb temperature (Steinacker, 2007).

In the course of a changing climate, an increase in snowline altitude is projected (166 m/°C (Olefs et al., 2020)). However, these projections do not consider the described effect of precipitation cooling. It is to be expected from the theory, that the increase of the snowline has nonlinear consequences for the frequency and intensity of the subsequent precipitation cooling effect, mainly due to two factors:

1. A quadratic relation between the amounts of melt energy transfer (i.e. the amount of melted precipitation (P)) that is required to lower the snowline to the ground and increasing initial snowline elevations emerges from the theory. On the basis of an energy balance estimation, the linearized Clausius-Clapeyron equation, and the assumption of a linear temperature gradient (γ) below the initial snowline (H), a first estimation of the precipitation cooling can be calculated as:

$$\rho_{air} * c^* * \int_0^H \gamma(z-H)\,dz = PL_s \qquad \text{Eq. 1}$$

and integrated to:

$$P(H) = -\frac{\rho_{air}\, c^* \gamma}{2L_s} H^2 \qquad \text{Eq. 2}$$

Where ρ_{air} is the air density, c^* is the effective heat capacity as the sum of a condensation term and the specific heat capacity of air, and L_s is the latent heat of fusion. See Pehsl (2010) equation 5.1 to 5.5 for a more detailed mathematical description. It is apparent that this solution is nonlinear.

2. For the described precipitation cooling to be effective in terms of lowering the initial snowline, only little mixing of air masses and general favourable advective conditions are necessary. When the air mass in a mountain valley decouples from the adjacent airflow, the precipitation cooling can lower the snowline effectively. However, if the initial snowline is above the crest height - i.e. above the ridge of the surrounding mountains - the mixing of air masses and the energy transfer involved, slow or prevent the cooling of lower air masses and hence the snowline does not decent. In this context, the crest-height can be acting as a threshold bound, below which precipitation cooling is much more likely and more efficient than above. In a warming climate, with rising air temperatures and rising snowline elevations, the probability of precipitation events with initial snowlines below the crest-height decreases.

D-3.2 Objectives

This study intends to explore the precipitation cooling effect and the subsequent snowline decent, show its influence on seasonal snow accumulation and analyse possible changes in a warming climate. The aim of the presented project is to investigate the future development of the snowline under consideration of the precipitation cooling effect, to identify occurring nonlinearities and to work out the significance. Based on a series of simulation experiments employing a simplified process parametrization, we aim to quantify the amount of seasonal snow that was enabled to accumulate due to precipitation cooling and explore a possible change in the context of a warming climate, to test the hypothesis of a nonlinear future development.

Therefore, the project SNOWLINE strives to contribute towards answering the following questions about the future development of the snowline: (1) Are we able to detect long-term changes of the precipitation cooling qualitatively and quantitatively? (2) Does the effect respond noticeably nonlinear to ongoing global warming? (3) Does this have a significant impact on future snowfall quantities in Austria? (4) Can we identify regions with such abrupt changes or tipping points?

D-3.3 Methods and Datasets

D-3.3.1 Proposed Method

As outlined in the research proposal, the initial workflow aimed to enhance quantitative and qualitative analyses of snowline development through numerical snow cover simulations that employ a simplified parametrization of the precipitation cooling effect. The plan involved developing and evaluating this parameterization using data from automatic weather stations, and incorporating it into simulations spanning both historical and future periods. The simulations, employing the SNOWGRID-CL model (Olefts et al., 2020), were planned to run on a daily time-step to simulate snowpack evolution in Austria based on gridded long-term observational data. However, feedback from experts during the first workshop highlighted two key shortcomings in the datasets: i) the daily time-step was deemed insufficient to accurately capture the precipitation cooling effect, because higher precipitation rates cannot be resolved; ii) Surface air temperature observations already reflect the influence of precipitation cooling, rendering them inadequate as a reference for snowline calculations.

These valuable comments lead us to move towards working with automatic weather stations and a higher resolved Nowcasting dataset INCA (Kann and Haiden, 2011) - incorporating observation of a station network, radar and satellite data. Here, depending on the parameter, meteorological information stand available in 15 min and 1 hourly time-step, respectively. As comment ii) is also valid for this data-set, we tested NWP model output for the reference snowline altitude. Therefore, old ECWMF forecasts initialized at 0am and 12pm were stitched together to create time-series of continuous forecasts of the snowline altitude. The reasoning behind employing the ECWMF with its comparatively coarse spatial resolution (~8 km), was the assumption that here, snowline estimations are closer to that of the free atmosphere and the valley effects (such as precipitation cooling), are less pronounced, compared to other forecast products (AROME-Aut ~2.5 km), which resolve the real topography more closely. Naturally, for most AWS, INCA follows stations recordings very closely. We planned on developing and testing a parametrization on point-scale AWS data and employ it over the INCA dataset in a spatially distributed way.

Based on these datasets, precipitation events were identified where precipitation cooling played a major role in the snowline development. This is a crucial step, as it is the basis for the development of a simplified process parametrization. However, it was found that this is not a straightforward task with the given data-set. In section D-3.4.1 we do present examples, discuss challenges, but also describe in detail why these findings are not suitable to robustly validate a parameterization to allow quantitative assessments. Therefore, the development of a reliable parametrization scheme was not successful, and hence, the analysis of the precipitation cooling effect and its climate sensitivity was approached from a more theoretical standpoint.

D-3.3.2 Energy Balance Considerations

Given the complex nature of various atmospheric processes that act simultaneously during precipitation cooling events, and the difficulties to untangle them from observations, we want to explore the isolated effect of precipitation cooling from physical considerations. On the basis of an energy balance approximation, we can infer the amount of solid precipitation needed to melt, in order to cool the atmosphere to such a degree that snowfall is possible on the ground surface. Following Pehsl (2010), starting from the differential form of the energy balance equation:

$$\int_0^{h^*} (h - h)\, dh = -\frac{L_s}{\rho_{air}\, c^*\, \gamma}\, P(H, h^*)$$

Eq. 3

where $h^*$is the change of the snowline elevation after the cooling. We can write the left site of the term as a sum by assuming a step-length of Δh. When using an equidistant layering, this limits the summation to $h^*/\Delta h$:

$$\sum_{i=1}^{\frac{h^*}{\Delta h}} \frac{f[(i-1)\Delta h] + f[i\Delta h]}{2} \Delta h = \sum_{i=1}^{\frac{h^*}{\Delta h}} \frac{2H-(2i-1)\Delta h}{2} \Delta h$$

Eq. 4

Using this sum and resorting equation 3 gives us:

$$P(H, h^*) = \left[\sum_{i=1}^{\frac{h^*}{\Delta h}} \frac{2H-(2i-1)\Delta h}{2} \Delta h\right] \frac{\rho_{air}\, c^*\, \gamma}{L_s}$$

Eq. 5

In order to incorporate the effect of the reduced air volume in valleys on the basis of the real topography, the topographic amplification factor (*TAF*) is employed (Whiteman, 2000). In principle, the *TAF* gives the ratio of air volume in the open and the air volume inside a valley. Because very different topographic characteristics of individual valleys can lead to the same overall *TAF*, it is necessary to calculate this volume reduction in a step-wise manner over increments (layers, *i*). Hence, the differential form of the *TAF* (*DTAF*) is used in the calculation (Steinacker, 2007).

$$TAF(i) = \frac{V(i)_{open}}{V(i)_{valley}} = \frac{[H-(i-1)\Delta h]*A_i}{\sum_i^{\frac{h^*}{\Delta h}} \Delta h * A_i * \frac{1}{DTAF(i)}}$$ Eq. 6

We employ a moving window to calculate DTAF and TAF over the real topography on the basis of a digital elevation model. Too large window sizes lead to a mixing of different valleys, too small values can potentially be unrealistic for larger valleys. Like Pehsl (2010), we follow a suggestion from Steinacker et al. (2006) and set the size of the moving window to 10 km, but employ a circular kernel (radius 5km).

Incorporating the air volume reductions into equation 5 yields:

$$P(H,h^*) = \left[\sum_{i=1}^{\frac{h^*}{\Delta h}} \frac{2H-(2i-1)\Delta h}{2} \Delta h * \frac{1}{TAF(i)}\right] \frac{\rho_{air}\, c^*\, \gamma}{L_s}$$ Eq. 7

These idealized energy balance considerations involve a stack of assumptions such as: No advection processes, no mixing of air masses, no outflow of cold air, linear wet-adiabatic temperature gradient below the snowline, and that all solid precipitation melts in the atmosphere. These approximations may be idealized and hence show the precipitation cooling effect with full efficiency, which might not be reached in most natural occurring events. However, it poses a useful tool to address and understand the sensitivities of this process without masking effects such as advection and mixing.

The numerical scheme summarized in equation 7 was set-up over a domain of over 280 000km² at a horizontal resolution of 1km x 1km (covering roughly the region between Nürnberg to Trient and Zürich to Bratislava), and a vertical resolution of 100m (up to 3000 m a.s.l.).

D-3.4 Results

D-3.4.1 Identification of Example Events

Station recordings of 34 automated weather stations (AWS), together with historic ECMWF forecast of the snowline (up to 12 hours lead-time) were used to identify possible precipitation cooling events. Figure D-1 to D-3 show examples of possible precipitation cooling events.

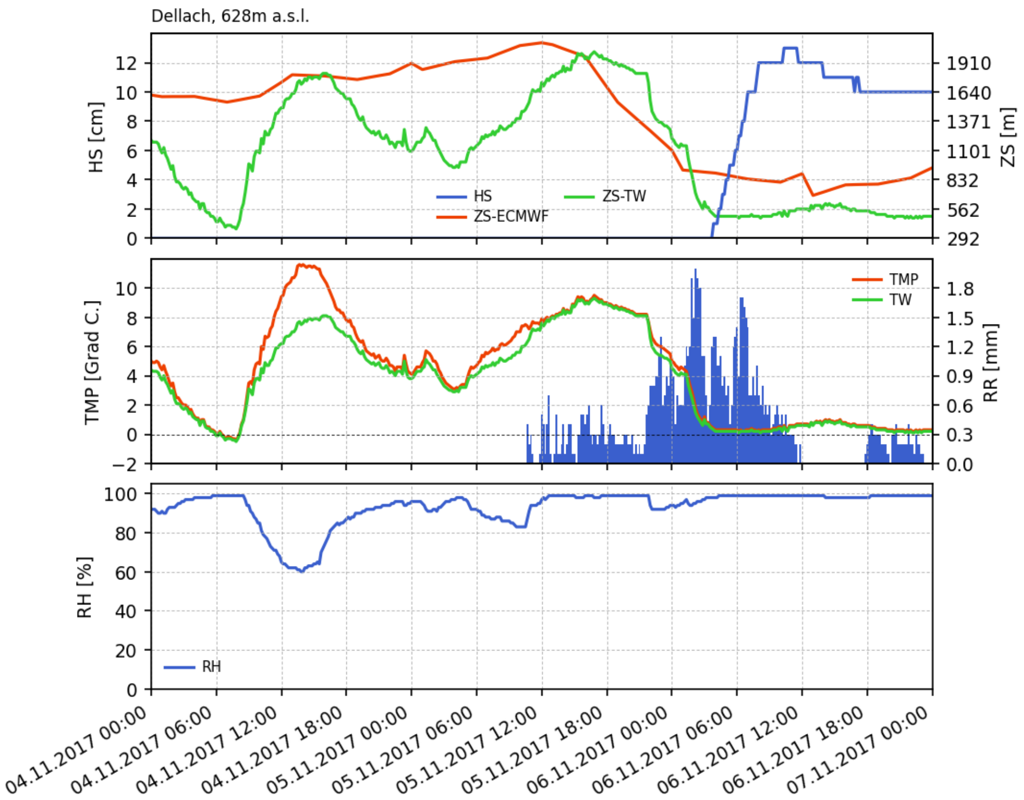

Abb. D-3: Station recordings at the automated weather station Dellach (628 m a.s.l): snow depth (HS), Air temperature (TMP), relative humidity (RH), calculated wet-bulb temperature (TW), snowline elevation calculated from TW (ZS-TW, (Steinacker, 1983)), and snowline elevation forecasts (ZS-ECMWF).

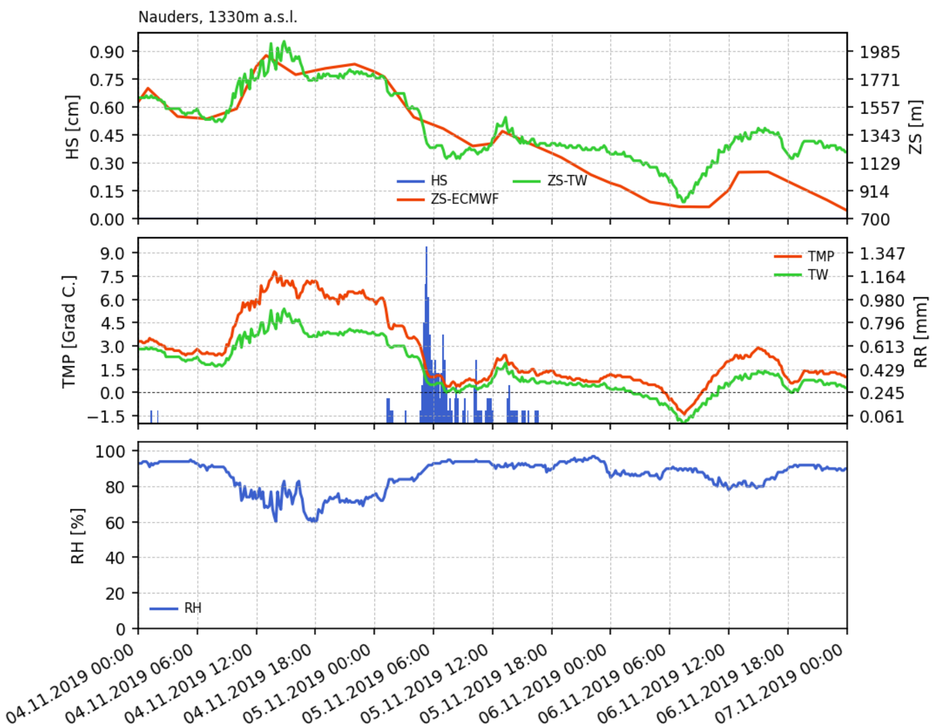

Abb. D-4: Station recordings at the automated weather station Nauders (1330 m a.s.l): snow depth (HS), Air temperature (TMP), relative humidity (RH), calculated wet-bulb temperature (TW), snowline elevation calculated from TW (ZS-TW, (Steinacker, 1983)), and snowline elevation forecasts (ZS-ECMWF).

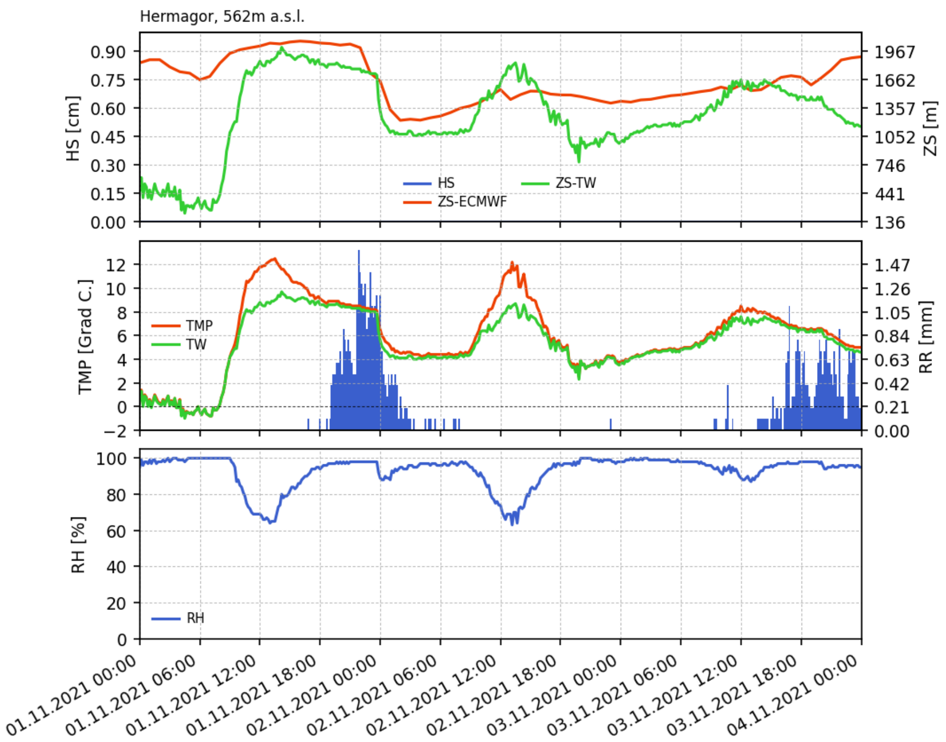

Abb. D-5: Station recordings at the automated weather station Hermagor (562m a.s.l): snow depth (HS), Air temperature (TMP), relative humidity (RH), calculated wet-bulb temperature (TW), snowline elevation calculated from TW (ZS-TW, (Steinacker, 1983)), and snowline elevation forecasts (ZS-ECMWF).

In each of the three time-series examples presented, a noticeable decline in both the observed 2 m air temperature and the calculated wet-bulb temperature coincides with periods of intense precipitation. During the event in Dellach (see fig. D-1), this cooling and the corresponding snowline decent (illustrated by the green line in the upper panel) aligns well with the observed snow accumulation on the ground (indicated by the snow depth in blue). During the events, we see that the NWP also predicts a drop in snowline elevation, however, to a lesser degree. This could suggest the models limitation to resolve small-scale valley effects during the precipitation cooling. Nonetheless, while temperature and snowline trajectories generally follow the expected patterns during such cooling events across the three examples, it is important to underscore that these observations are not universally consistent across many investigated heavy precipitation events for several reasons:

- Frontal systems with colder air masses often dominate temperature observations before and during precipitation event.
- The diurnal temperature cycles might either obscure or exaggerate the thermal trends during extended precipitation events.
- The meteorological variables analysed do not allow for the inference or quantification of mixing processes.
- The snowline forecasts are not ideal benchmarks since the NWP already accounts for energy transfer processes, including precipitation cooling, and may only lack detail in modelling small-scale topographic effects. Furthermore, inherent forecast inaccuracies introduce significant uncertainties in snowline predictions during these events. Notable discrepancies between NWP and actual station observations in snowline estimation are evident (for example, compare the green and red lines in the upper panels of plots D-1 to D-3).

Consequently, a robust calibration and validation of a simple process parametrisation was not feasible. Assertions regarding the frequency, quantity, and spatial distribution of precipitation cooling events would be speculative at best. Therefore, as outlined in section D-3.3.1, we adopt an idealized approach to assess the isolated impact of precipitation cooling and explore its sensitivity to changes in initial snowline elevation.

D-3.4.2 Simulation Results over Austria

Based on the numerical scheme described in section D-1.3.3, it is possible, given an initial snowline elevation, to estimate the amount of precipitation that is required to cool the atmosphere to such a degree that the new snowline reaches the ground elevation. Figure D-4 shows this amount as an example for an initial snowline of 2000 m a.s.l., including the effect of the reduced air volume inside valleys. Figure D-5 shows this effect in an isolated way (precipitation cooling without TAF minus precipitation with TAF). We can observe that for this example, the effect of the limited air volume inside mountain valleys reduces the required precipitation amount by around 10mm. Including the assumption that only a decent in the snowline elevation can occurs, if the air masses are decoupled from the adjacent air flow below the crest-height, restricts this phenomenon to mountain valleys (see Figure D-6).

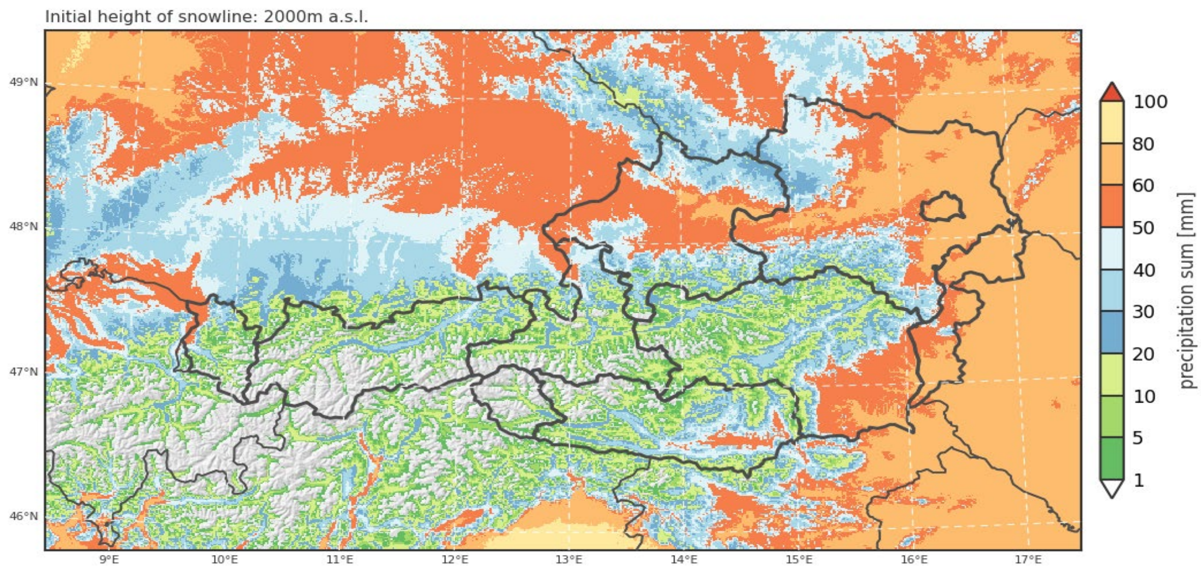

Abb. D-6: Amount of solid precipitation that is required in the melt process to lower an initial snowline of 2000 m a.s.l. to ground elevation. When the initial snowline is already below topography elevation, the hillshade in the background becomes visible.

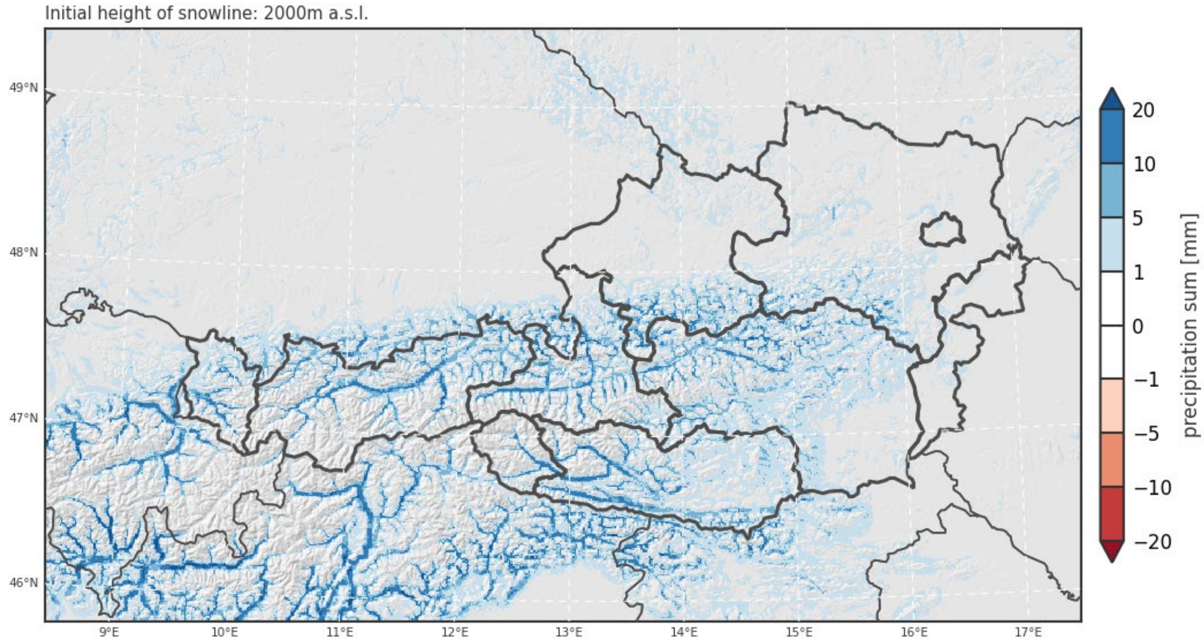

Abb. D-7: Effect of the reduced valley air volume in the precipitation cooling. Displayed values indicate the amount of additional precipitation required if this topography effect is neglected.

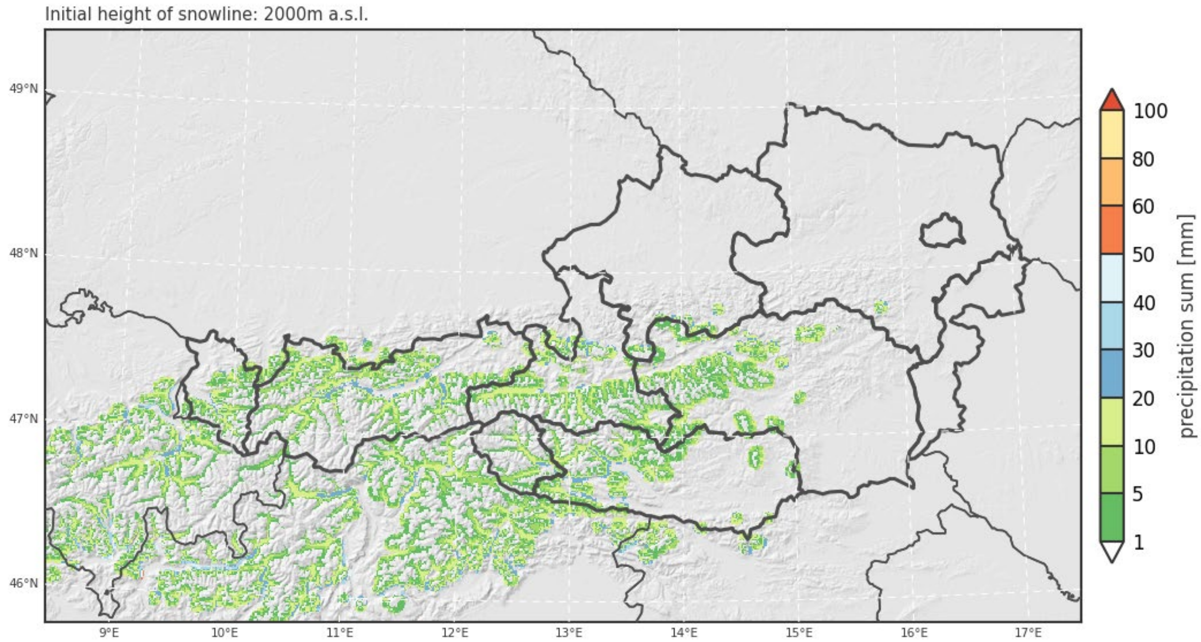

Abb. D-8: Same as D-4, but only for areas where the initial snowline (here 2000 m a.s.l.) is below the local crest-height.

D-3.4.3 Examples from the Gailtal

In order to explore potential impacts of precipitation cooling on snow conditions within specific regions, we present example outcomes for the Gailtal, an east-west oriented valley in upper Carinthia. Situated between the Gailtaler Alps to the north and the Carnic Alps to the south, this valley is significantly influenced by orographic precipitation due to its position south of the main Alpine ridge.

In Figure D-7, we explore how the amount of accumulated snowfall in the valley varies in response to precipitation cooling, considering different initial snowline altitudes (columns) and a fixed precipitation event (here 60mm). The first row of subplots illustrates accumulated snowfall solely based on topography, without factoring in precipitation cooling. Here, we see only accumulation where the terrain elevation is above the given snowline. The middle row depicts accumulation while incorporating the full impact of precipitation cooling. We can observe, that this leads to snowfall throughout the catchment up to snowlines of 2000 m. Finally, the bottom row introduces an additional condition restricting precipitation cooling to areas where the initial snowline is below the local crest-height. Now, with increasing initial snowline altitudes, the limiting effect of this condition becomes apparent - less and less areas can benefit from the precipitation cooling.

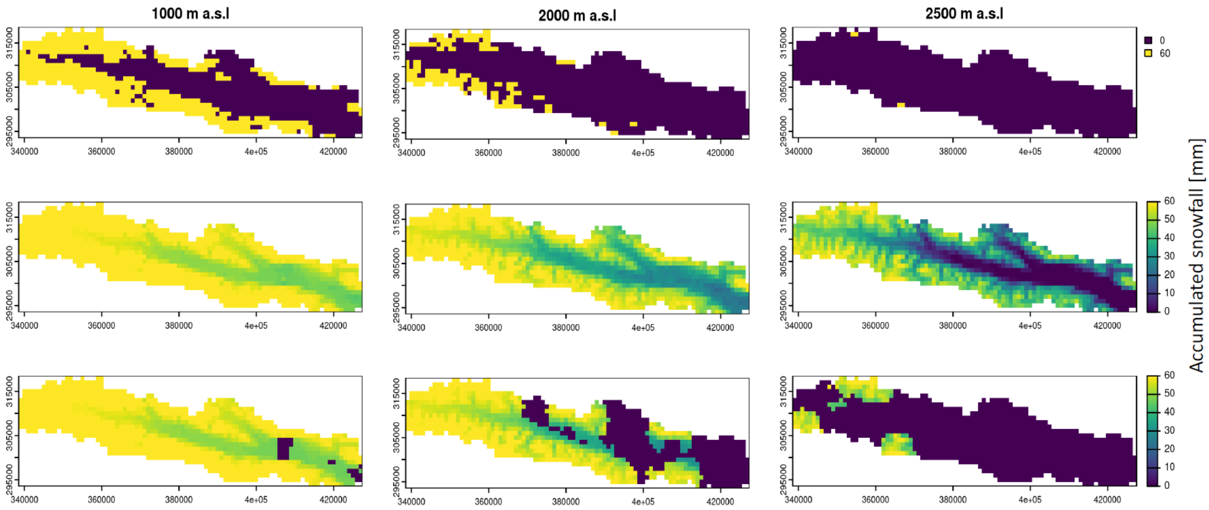

Abb. D-9: Amount of accumulated snowfall on the ground for different initial snowline altitudes (columns). Top row: no precipitation cooling; middle row: full precipitation cooling; bottom row: precipitation cooling only in areas where the local crest-height surpasses the initial snowline.

Aggregating the area wide accumulated snowfall can help to highlight the differences between the simulations. In Figure D-8, the three lines correspond to the three scenarios depicted in Figure D-7. The black line represents the case without precipitation cooling, mirroring the area-elevation distribution (hypsometry) information. The red line, incorporating unconditional precipitation cooling, exhibits a slower decrease, indicating minimal reduction in snowfall accumulation with rising initial snowline elevations. When precipitation cooling is confined by the crest-height (blue), we also observe this gradual decline until a significant portion of the area meets the threshold condition. At that point, we observe a more pronounced decrease in accumulated snowfall.

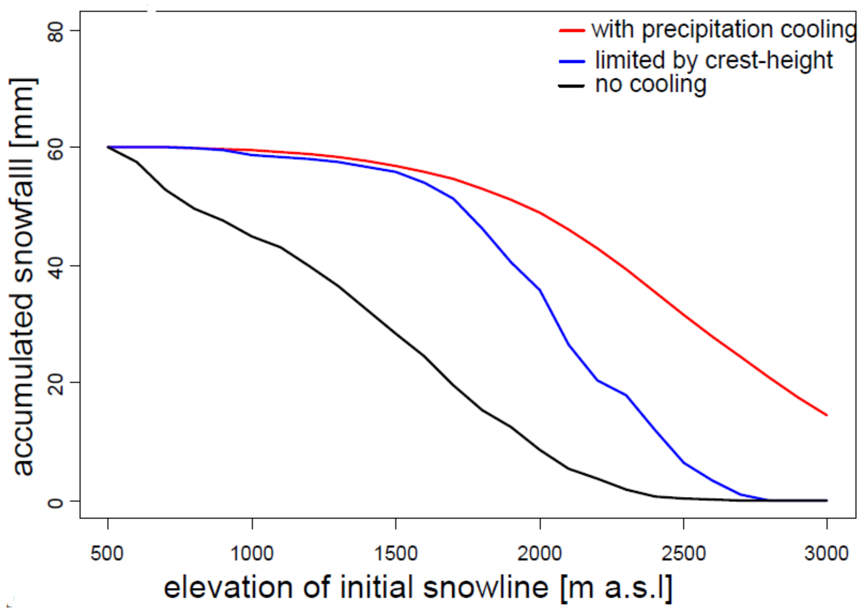

Abb. D-10: Area wide accumulated snowfall in the Gailtal for different initial snowline elevations and a given precipitation event of 60 mm.

The distinct trajectories and their gradients indicate varying sensitivities to changes in the initial snowline. One effective method to visualize this sensitivity is by plotting the slopes of the lines across different intervals. Thus, in Figure D-9, we illustrate the change in area-wide accumulated snowfall resulting from raising a given initial snowline by up to 500 m. Given the expected rise in snowlines in a warming climate, we correlate this increase in snowline to a temperature rise, approximating a snowline-temperature relationship of 166 m/°C (equivalent to 6°C/km). The left subplot depicts the scenario without precipitation cooling, providing solely the terrain information of the Gailtal, which serves to contextualize the right subplot (incorporating precipitation cooling).

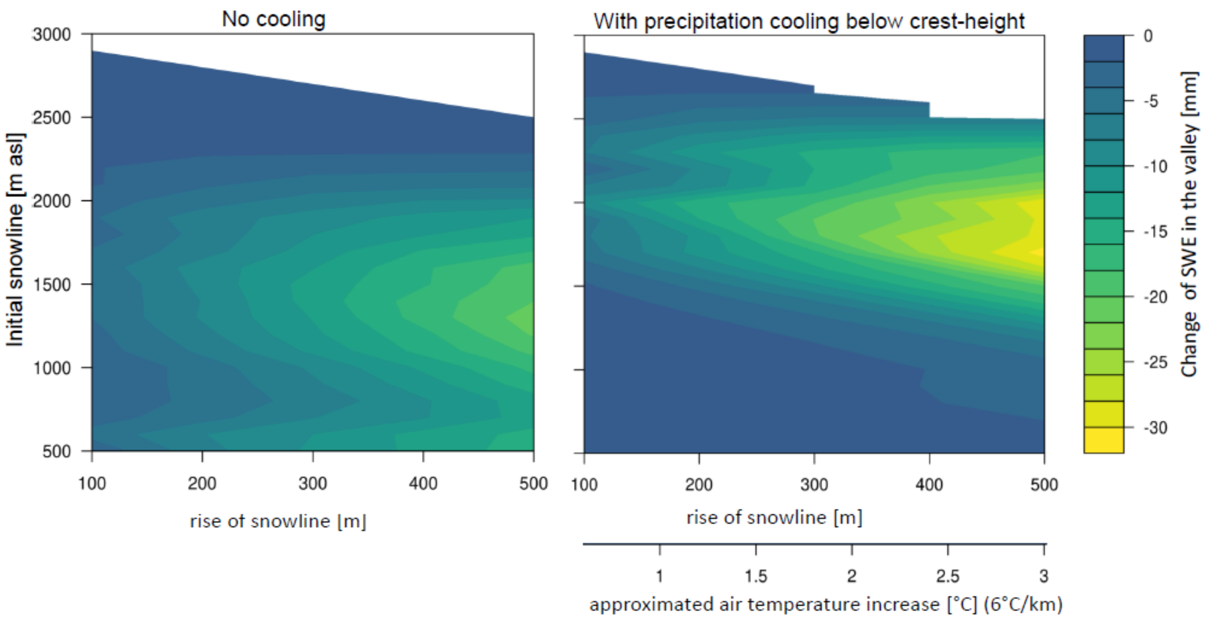

Abb. D-11: Change of area-wide accumulated snowfall with increasing snowlines (x-axis) based on initial snowlines (y-axis)

It becomes evident that when factoring in precipitation cooling below the crest-height, a markedly different sensitivity pattern emerges compared to typical precipitation events. For lower initial snowlines (up to approximately 1500 m a.s.l), an increase in the snowline does not significantly reduce the accumulated area-wide snowfall in the valley. This suggests that when conditions facilitate efficient precipitation cooling, snow accumulation is relatively insensitive to a rise in the snowline (i.e., warming). However, with higher initial snowlines, a zone of heightened sensitivity emerges. When rising snowlines are more strongly correlated with a decrease in areas below the crest-height, a substantial change in accumulated snowfall becomes apparent.

The approximation of precipitation cooling relies on assuming a linear wet-adiabatic temperature gradient beneath the snowline. However, this assumption doesn't always hold true in mountain valleys. During winter, temperature inversions and cold air pooling in valleys are frequent occurrences. In such conditions, even a small amount of precipitation could lower the snowline enough to cause snowfall on the ground (provided favourable advective conditions). This means only the air volume between the initial snowline and the 0°C line needs to be cooled. Figure D-10 demonstrates how, with a modest precipitation of just 5 mm, the snowline shifts for three different initial elevations. In the plot, these values are given in meters above the surface. Notably, for a typical thickness of a cold air layer near the surface (a few hundred meters), this adjustment becomes significant for generating snowfall.

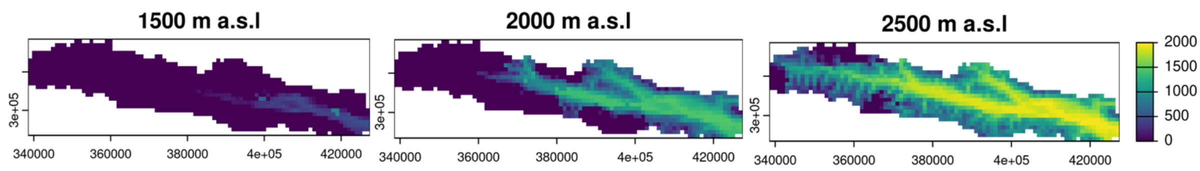

Abb. D-12: Snowline above surface elevation that results from a low precipitation event of 5 mm, for three different initial snowline elevations.

D-3.5 Outlook and Recommendations for Future Research

Based on the utilized data-sets, this study could not quantify the frequency, intensity and seasonal importance of precipitation events where the cooling effect is significant. Consequently, comprehensively grasping the future trajectory and relevance of precipitation cooling in real-world scenarios remains subject to future research. In this regard, our work lays a foundation for future research endeavours. To gain a deeper insight into both, the physical processes under real world conditions, as well as quantifying the importance for snow accumulation in Austria, we invite researchers to consider the following suggestions for future studies:

- We propose conducting a series of field observations during precipitation events where precipitation cooling is anticipated. Utilizing drones or balloon-based instruments to measure atmospheric state variables along vertical transects will enhance our understanding of energy transfer processes.
- Analyzing precipitation events based on three-dimensional output from numerical weather prediction models will aid in event identification. Synoptic information is crucial for identifying conditions when precipitation cooling becomes a relevant mechanism.
- High resolution (valley-resolving) atmospheric model experiments, validated with data from the first two suggestions could then be employed to quantify the effect of precipitation cooling on seasonal snowfall sums.

D-3.6 Summary and Conclusion

The study highlights the influence of precipitation cooling on snowfall accumulation. Precipitation cooling can play an important role for certain snowfall events and increases the amount of snowfall that reaches the valley floor. Simulations based on an idealized energy balance approach reveals the potential importance of precipitation cooling and its sensitivity to raising snowline altitudes in a warming climate. Even though it was not feasible to develop a simplified process parametrization and explore the precipitation cooling effect using real data, this idealized theoretical approached still yields insights into possible consequences of such events.

We show the impact of precipitation cooling on snow conditions, demonstrating varying snow accumulation patterns in response to different initial snowline altitudes and precipitation cooling scenarios. Especially when considering cold air pools at the valley floor, even moderate precipitation rates can lead to a significant cooling effect, increasing the accumulated snowfall. It was found that the assumption of decoupling air masses under the crest-height has a higher effect on accumulated snowfall than the reduced air mass in the valley itself.

The results indicate that when considering precipitation cooling, snow accumulation remains relatively insensitive to rising snowline elevations, particularly for lower initial snowlines. There might be a buffer potential to warmer temperatures due to these kind of snowfall events. However, with higher initial snowlines, a more pronounced sensitivity emerges, especially when correlated with decreases in areas below the crest-height. If the efficiency of the precipitation cooling is low or shut down (e.g. with a rise of the snowline above the crest-height), snowfall events become highly sensitive to warmer temperatures. Based on the theory it could be shown that the effect of precipitation cooling will respond noticeably nonlinear to global warming.

D-3.7 References

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