PERMAFROST SIMULATIONS FOR ADVENTDALEN AND NY-ÅLESUND

PCCH-ARCTIC REPORT NR. 5

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ABSTRACT

This report presents modeling of permafrost regime for cultural heritage objects in Adventdalen and Ny-Ålesund. Modeling is performed under the high emission scenario SSP5-8.5, and covers the period from the 1980s to 2100. 15 model scenarios characterized by different soil stratigraphies, drainage conditions and snow dynamics were simulated to represent the diverse conditions across Adventdalen and Ny-Ålesund. The results provide a data set which can be used to evaluate the risk to individual historical structures.

Aga, J. Westermann, S., Sinitsyn, A.O.

PCCH-Arctic

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1. Introduction

The project “Climate and Cultural Heritage – Preservation and Restoration Management” (PCCH-Arctic, (PCCH-Arctic, 2025) aims to create a knowledge base for the preservation of cultural heritage in the Arctic, focusing on the conditions of changing climate. The Arctic region faces substantial threats due to climate change, which affect the natural environment but also the unique cultural heritage in the region.

Adventdalen and Ny-Ålesund, situated on Svalbard, are the key areas under investigation of the PCCH-Arctic project. The region is rich in cultural heritage from mining operations, trapping activities and polar exploration. The preservation of these historical structures is important to maintain the cultural history of the region. However, the structures are threatened by natural hazards, which are intensified by ongoing climatic changes. Case study objects of PCCH-Arctic are presented in (Sinitsyn et al., 2022). For Adventdalen, the case study objects are presented mostly by cableway posts (but also include special objects such as mine entrances and turning stations), in Ny-Ålesund – it is small houses and special objects such as the airship mast.

As part of the project, the impact of natural hazards on historical structures in Adventdalen and Ny-Ålesund is assessed and cultural heritage objects with the highest risk are identified. To do so, a variety of natural hazards are considered, such as permafrost degradation, solifluction, landslides and debris flows, rockfalls, snow avalanches, coastal erosion, riverine flooding, surface erosion and gullying, and weathering (Sinitsyn & Bekele, 2023). One of the most important hazards in the study areas is permafrost degradation, manifested through ground temperature increase and thickening of the active layer (active layer is the layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost (Everdingen, 2005)). These changes in the permafrost conditions affect the bearing capacity of foundations and can lead to settlement of the ground (Sinitsyn & Bekele, 2023). The objective of this report is to contribute to further clarification (i.e. compared to assessment in (Sinitsyn & Bekele, 2023)) of the significance of permafrost degradation to the case study objects in Adventdalen and Ny-Ålesund.

To assess the risk associated with permafrost degradation on cultural heritage objects in Adventdalen and Ny-Ålesund, the thermal regime of the ground was modeled from the 1980s to 2100 under the high emission scenario SSP5-8.5. We simulated 15 model scenarios, characterized by different soil stratigraphies, drainage conditions and snow dynamics, to represent the diverse conditions across Adventdalen and Ny-Ålesund. The results provide a data set which can be used to evaluate the risk to individual historical structures.

2. Methods

The permafrost thermal regime in Adventdalen and Ny-Ålesund was modeled with the CryoGrid community model (Westermann et al., 2023), using forcing data from ERA5 (Hersbach et al., 2018) and CESM2 (Danabasoglu et al., 2020).

2.1 The CryoGrid community model

The CryoGrid community model (hereafter named CryoGrid) is a land surface model designed to simulate permafrost and ground ice dynamics. It integrates various physical processes to understand the thermal and hydrological dynamics within permafrost environments. CryoGrid simulates heat transfer within soil layers, accounting for the phase change of water to ice and vice versa, which is crucial for permafrost modeling. The model includes components for hydrological processes, such as soil water movement, affecting moisture distribution and freeze-thaw cycles. Furthermore, it can simulate the effects of vegetation and snow cover.

CryoGrid uses meteorological data as input, such as air temperature, precipitation and radiation, to drive the model and simulate seasonal and long-term changes in the permafrost thermal regime. The model is designed to be applied to different spatial scales, from a point scale to large regional analyses. The model's modular structure enables the addition or modification of specific components as needed. A detailed description of the model is given in Westermann et al. (2023).

2.2 Model setup

Ground temperatures are simulated between the surface and 100 m depth, where different stratigraphy classes are applied:

> 0 m: SNOW_crocus_bucketW_seb: surface energy balance, snow microphysics, bucket scheme snow hydrology.

0–5 m: GROUND_freezeC_bucketW_seb: surface energy balance with evapotranspiration, Painter and Karra (2014) freezing characteristics, bucket scheme water balance.

< 5 m: GROUND_freeW_seb: free water freezing characteristics, no flow water balance.

For a detailed description of the applied stratigraphy classes, see Westermann et al. (2023).

We set three soil stratigraphies, which are used in different model scenarios (Sect. 2.4 and 2.5). Stratigraphy 1 describes a well-drained blocky terrain, which is representative for (steep) slopes with scree. Stratigraphy 2 is characterized by silty soil and is fairly drained, which is representative for flat or slightly sloping terrain. Stratigraphy 3 has an organic top layer and is not drained, which is representative for the valley bottoms where organic occurs. The three stratigraphies are given in Table 1 and the setup for the drainage conditions in Table 2.

Table 1. Soil stratigraphies with respective water and ice content, mineral content, organic content, field capacity, soil type and saturated hydraulic conductivity. Note that water contents in the active layer can fluctuate in response to precipitation, evaporation and runoff.

Depth [m]	Water and ice content [-]	Mineral content [-]	Organic content [-]	Field capacity [-]	Soil type	Saturated hydraulic conductivity [m/s]
Stratigraphy 1:						
0 - 5	0.25	0.75	0	0.15	silt	1E-8
> 5	0.03	0.97	0	0.03	rock	-
Stratigraphy 2:						
0 - 5	0.4	0.6	0	0.3	silt	1E-8
> 5	0.03	0.97	0	0.03	rock	-
Stratigraphy 3:						
0 – 0.3	0.6	0.3	0.1	0.5	sand	1E-6
0.3 - 5	0.4	0.6	0	0.3	silt	1E-8
> 5	0.03	0.97	0	0.03	rock	-

Table 2. Soil stratigraphies with respective water and ice content, mineral content, organic content, field capacity, soil type and saturated hydraulic conductivity.

Drainage conditions	Overland flow	Lateral water reservoir (LWR)	LWR elevation difference [m]	LWR distance [m]
Stratigraphy 1:				
well drained	yes	yes	5	1
Stratigraphy 2:				
fairly drained	yes	yes	1	100
Stratigraphy 3:				
not drained	yes	yes	0	1

Other model parameters are set as following: During snow-free season, the albedo of the ground surface is set to 0.2 and the aerodynamic roughness length to 0.01 m. The evaporation depth is set to 0.1 m. The vertical resolution of the grid cells increases with depth: 0-1 m depth: 0.05 m; 1-5 m depth: 0.10 m; 5-10 m depth: 0.20 m; 10-20 m depth: 0.50 m; 20-50 m depth: 1.00 m; 50-100 m depth: 5.00 m.

Initial ground temperatures are set to: 0 m depth: 0 ˚C; 2 m depth: -1.75 ˚C; 10 m depth: -5.3 ˚C; 100 m depth: 0 ˚C. The geothermal heat flux at the lower boundary of the model domain is 50 mW/m^2. Since the uppermost meters become independent of the initialization after some decades, the initial temperature profile does not affect the simulation results, as we performed 50 years of spin up, which are not part of the results.

2.3 Climatic forcing

The model is driven by climatic forcing, including the parameters air temperature, wind speed, incoming shortwave radiation, incoming longwave radiation, air pressure, snowfall and rainfall.

We used reanalysis data based on ERA5 (Hersbach et al., 2018) for the time period 1940 to 2022. For Adventdalen, the data was processed similar to Wendt (2024): We used ERA5 at surface level, and bias-corrected the data with in-situ observations of the UNIS meteorological station in Adventdalen with a quantile mapping approach. For Ny-Ålesund, we used the data processed by Westermann et al. (2023), which were bias-corrected with in-situ observations from the Bayelva climate station with a linear regression.

The time period 1930 to 1940 (used for spin up) and 2022 to 2100, are based on the CESM2 (Danabasoglu et al., 2020) historical period and SSP5-8.5 high emission scenario (fossil-fueled development), respectively. To do so, we trend the CESM2 data to the bias-corrected ERA5 data based on monthly offsets, to get a continuous model forcing until 2100.

We multiply the snowfall from the climatic forcing with a snowfall factor between 0.1 and 1.5 (Sect. 2.4) to account for different snow dynamics, such as wind-blown ridges with little snow and depressions where snow accumulates.

2.4 Model scenarios for Adventdalen

We simulate 12 different model scenarios, which are the combination of three soil stratigraphies with different drainage conditions (Sect. 2.2) and four snowfall factors (Sect. 2.3). To characterize the permafrost thermal regime for case study objects in Adventdalen, the best-fitting scenario can be selected based on the observed snow conditions and expected soil stratigraphies and drainage conditions.

Table 3. Adventdalen: model scenarios based on soil stratigraphies and snowfall factors.

	Very little snow: Snowfall factor = 0.1	Little snow: Snowfall factor = 0.5	Average snow: Snowfall factor = 1.0	Above average snow: Snowfall factor = 1.5
Soil stratigraphy 1: Blocky terrain, drained	01	04	07	10
Soil stratigraphy 2: Silty soil, fairly drained	02	05	08	11
Soil stratigraphy 3: Organic layer, not drained	03	06	09	12

2.5 Model scenarios for Ny-Ålesund

We simulate 3 different model scenarios. Hereby we keep the same stratigraphy throughout all scenarios (stratigraphy 2, which is characterized by silty soil that is representative for the flat terrain in Ny-Ålesund, Sect. 2.2), but vary the snowfall factor to account for variable snow conditions in the village, which can be mainly traced back to snow redistribution and artificial snow ploughing (Aga et al., 2025, Sect. 2.3). To characterize the permafrost thermal regime for case study objects in Ny-Ålesund, the best-fitting scenario can be selected based on the observed snow conditions.

Table 4: Ny-Ålesund: Model scenarios based on soil stratigraphies and snowfall factors.

	Little snow: Snowfall factor = 0.5	Average snow: Snowfall factor = 1.0	Above average snow: Snowfall factor = 1.5
Soil stratigraphy 2: Silty soil, fairly drained	13	14	15

3. Results

We present the development of the active layer thickness (ALT) and the mean annual ground temperatures (i.e. mean annual temperature of the ground at a particular depth (MAGT), (Everdingen, 2005)) in 1 m depth and 3 m depth. Hereby, we analyze the median decadal values between 1980 and 2100. The following sections give an overview of the results, including the influence of snow dynamics and soil stratigraphy.

The results of all model scenarios are given in *Appendix 1. Data for Adventdalen* and *Appendix 2. Data for Ny-Ålesund*, including the MAGT in 5 m and 10 m depth for each scenario.

3.1 Mean annual ground temperatures (MAGT) and active layer thickness (ALT) in Adventdalen

Our results show an increase in MAGT and ALT between 1980 and 2100, following the climatic warming of the high emission scenario SSP5-8.5. However, both parameters differ substantially between the 12 model scenarios, indicating diverse permafrost conditions across Adventdalen.

Fig. 1 and 2 show the development of median decadal MAGT for all 12 model scenarios. The median MAGT range from -8 ˚C and 0 ˚C in the 1980s in both 1 m and 3 m depth. Hereby, the scenarios with a low snowfall factor of 0.1 (scenarios 1-3) feature the lowest median MAGT, while scenarios with the highest snowfall factor of 1.5 (scenarios 10-12) show the highest median MAGT between -1 ˚C and 0˚C (Sect. 3.2). The median MAGT then increased notably until the 2020s, ranging between -4.5 ˚C and 0 ˚C (3 m depth) and -4 ˚C and 0.2 ˚C (1 m depth). Following the future climatic warming, the median MAGT are projected to increase further towards the end of the century, with the most substantial increase for model scenarios with low snowfall factors, so that median MAGT of all model scenarios converge with time. In the 2080s, all model scenarios project median MAGT between -1 ˚C and 0 ˚C in both 1 m and 3 m depth, and in the 2090s, median MAGT above 0 ˚C are reached for all model scenarios in 1 m depth and for 3 model scenarios in 3 m depth.

Furthermore, the ALT increases between the 1980s and 2100, but also here, notable differences are simulated depending on the model scenario (Fig. 3). In the 1980s, an ALT between approximately 0.5 m and 1.3 m was simulated, which increased to values between 0.8 m and 2.5 m in the 2020s. In the following decades, the ALT slowly increased further, before the development accelerated in the 2070s, leading to a projected ALT between 1.4 m and 4.8 m towards the end of the century. Typically, the highest ALT are found for scenarios characterized by blocky terrain and drained conditions. They show as well the strongest increase in ALT. The scenarios with an organic layer and undrained conditions have the smallest ALT increase until 2100. In scenario 12, the active layer first increases strongly, but then decreases again due to overall reduced snow depths in future winters dominated by more melt events. This indicates that in localized spots, the ground may even cool and stabilize the permafrost in the near future, while sustained warming towards the end of the century again leads to warming and an increase of the active layer.

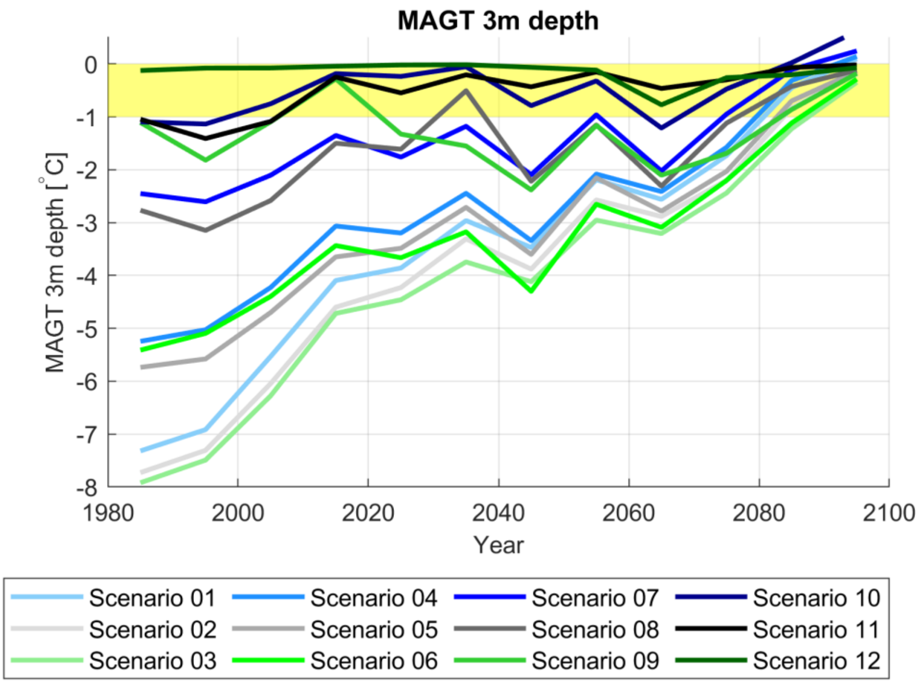

Figure 1. Adventdalen: MAGT in 3 m depth with median decadal values for all 12 model scenarios.

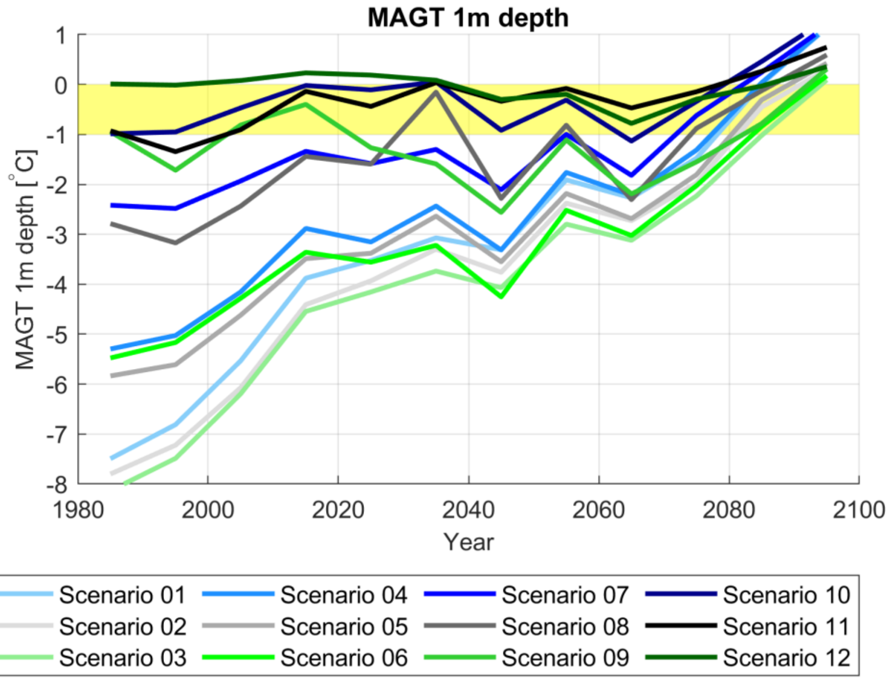

Figure 2. Adventdalen: MAGT in 1 m depth with median decadal values and for all 12 model scenarios.

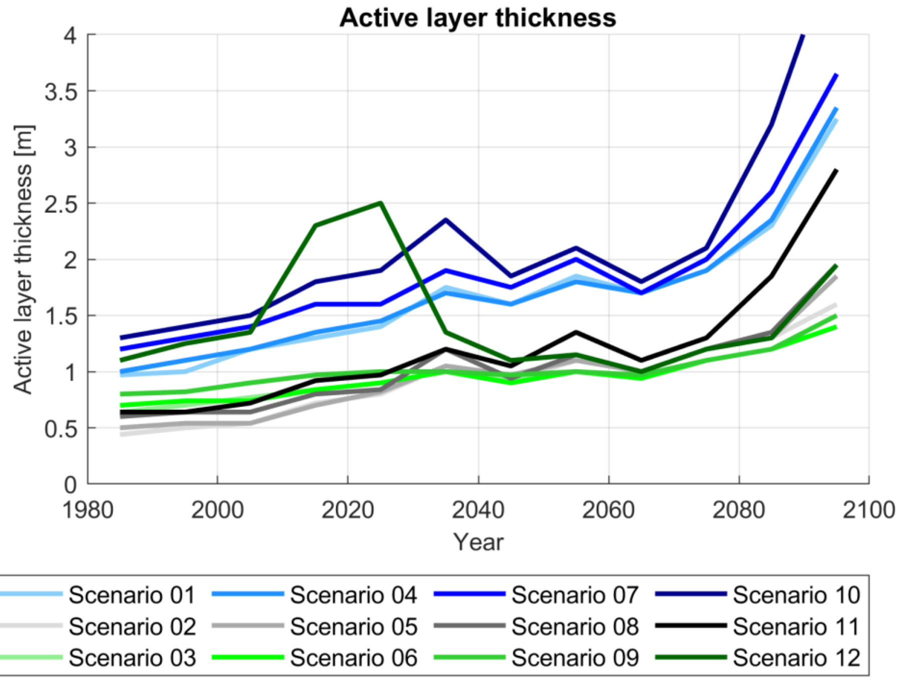

Figure 3. Adventdalen: ALT with median decadal values for all 12 model scenarios.

3.2 The influence of the snow cover in Adventdalen

To analyze the influence of the snow cover, we compare the results of the model scenarios 02, 05, 08 and 11 (soil stratigraphy 2, varying snowfall factors, Sect. 2.4). The median MAGT in 1 m and 3 m depth are shown in Fig. 4 and 5, respectively, and the ALT in Fig. 6.

The results show that snow cover has a pronounced influence on the MAGT in both 1 m depth and 3 m depth, which can be explained by the insulating effect of the snow cover in winter, leading to low median MAGT for scenarios with little snow (e.g. scenario 02) and higher median MAGT for scenarios with high snowfall rates (e.g. scenario11). The differences in MAGT are especially pronounced in the 1980s but are diminish throughout the simulation, until similar MAGT are simulated towards 2100.

The scenarios 02 and 05 with little snow simulate low median MAGT of approximately -8 ˚C and -6 ˚C in the 1980s, before increasing to around -4 ˚C in the 2020s. The median MAGT are projected to rise further in the coming decades and reach the critical temperature range in the 2080s for both 1 m and 3 m depth. In contrast to that, the scenario 08 with average snowfall shows median MAGT of -3 ˚C in the 1980s and reaches the critical temperature range (i.e. the range from -1 ˚C to 0 ˚C) already in the 2030s and the 2050s, before staying consistently in this range from the 1970s for both 1 m and 3 m depth. Scenario 11, with the highest snowfall simulates median MAGT of approximately -1 ˚C in the 1980s, and values in the critical temperature range from the 2000s for both 1 m and 3 m depth.

While variations in the snow cover have a strong impact on the ground temperatures as described above, the influence on the ALT is minor. A median ALT of about 0.5 m is simulated for all four scenarios in the 1980s, increasing to approximately 0.9 m in the 2020s. In the future projection, the median ALT increases slowly to 1.30 m in the following decades, before increasing sharply towards the end of the century, reaching median values between 1.60 m and 2.8 m. However, even Q75[1] values of 3.8 m were simulated for scenario 11.

[1] The IQR (interquartile range) is a measure of statistical dispersion that represents the spread of the middle 50% of a dataset. It is a robust measure of variability, meaning it is less influenced by outliers compared to when showing minimum and maximum. Therefore, it is often used for showing data such as we have them. As the IQR represents the middle 50% of the data, it is the difference between Q75 and Q25. Therefore, we mentioned the Q75 here as we analysed it.

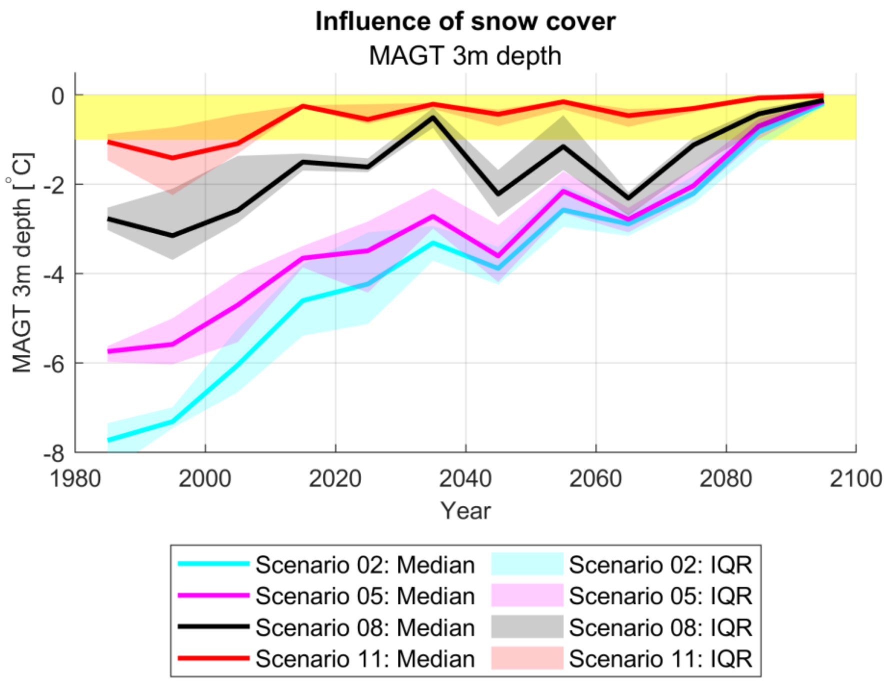

Figure 4. Adventdalen: MAGT in 3 m depth with median decadal values and decadal IQR for model scenarios with a fairly drained, silty soil and varying snowfall factors: scenario 02 (snowfall factor = 0.1), 05 (snowfall factor = 0.5), 08 (snowfall factor = 1.0) and 11 (snowfall factor = 1.5).

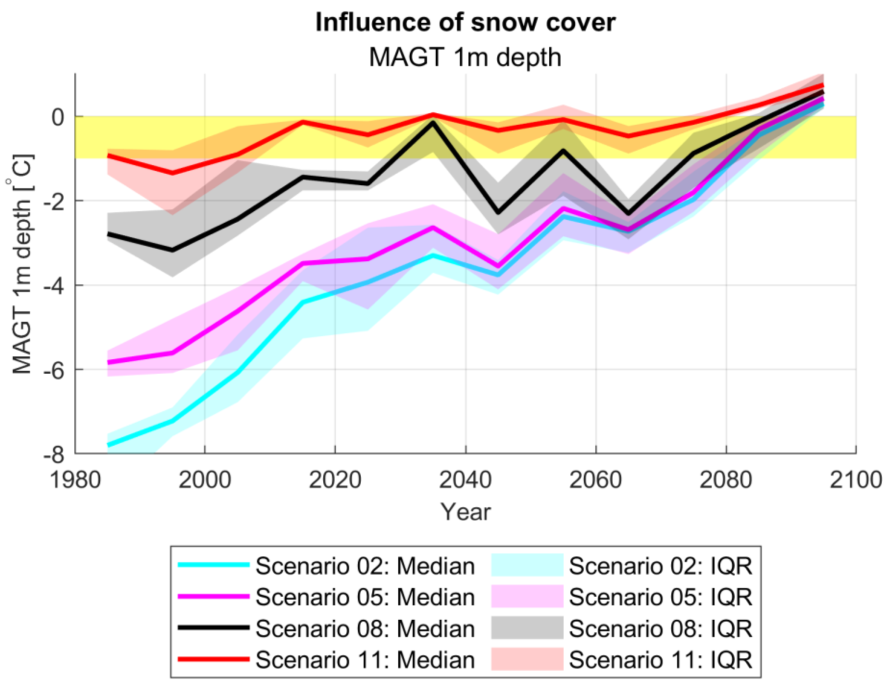

Figure 5. Adventdalen: MAGT in 1 m depth with median decadal values and decadal IQR for model scenarios with a fairly drained, silty soil and varying snowfall factors: scenario 02 (snowfall factor = 0.1), 05 (snowfall factor = 0.5), 08 (snowfall factor = 1.0) and 11 (snowfall factor = 1.5).

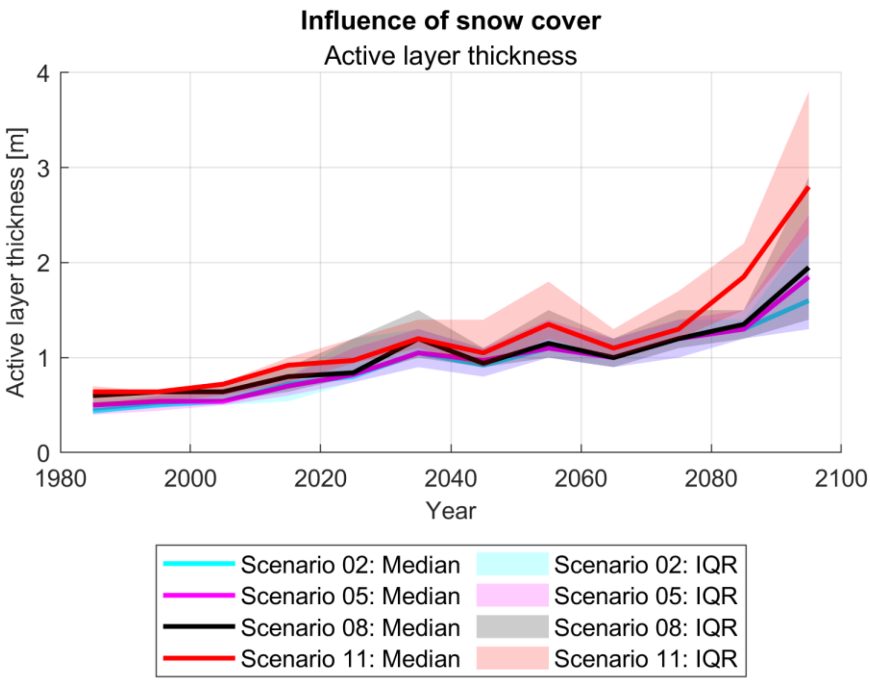

Figure 6. Adventdalen: ALT with median decadal values and decadal IQR for model scenarios with a fairly drained, silty soil and varying snowfall factors: scenario 02 (snowfall factor = 0.1), 05 (snowfall factor = 0.5), 08 (snowfall factor = 1.0) and 11 (snowfall factor = 1.5).

3.3 The influence of the soil stratigraphy and drainage

To analyze the influence of soil stratigraphy and associated drainage conditions, we compare the results of the model scenarios 04, 05 and 06 (snowfall factor = 0.5, varying soil stratigraphies and drainage conditions, Sect. 2.4). The median MAGT in 1 m and 3 m depth are shown in Fig. 7 and 8, respectively, and the ALT in Fig. 9.

The results show that the soil stratigraphy and drainage conditions have little influence on the median MAGT in both 1 m and 3 m depth. In all three scenarios, the median MAGT increases from -5 ˚C to -6 ˚C in the 1980s, to -3 ˚C to -4 ˚C in the 2020s, before rising towards the end of the century to values close to or slightly above 0 ˚C. The critical temperature range between 0 ˚C and -1 ˚C is reached in the 2080s for all three scenarios.

However, small differences can be detected when analyzing the results. The highest median MAGT are simulated for scenario 04, characterized by a high mineral content and a low soil moisture content. The lowest median MAGT resulted from scenario 06 with an organic layer in the uppermost soil layers and typically saturated conditions.

In contrast to the median MAGT, variations in the soil stratigraphy and drainage conditions resulted in pronounced differences of the ALT. Scenario 04 with a high mineral content and dry conditions had the deepest active layer with around 1 m in the 1980s, increasing to approximately 1.50 m in the 2020s, before reaching a median MAGT of 3.35 m towards the end of the century. The Q75 even showed maximum values of 4.6 m. The ALT of scenario 05 with silty soil and fairly drained conditions increased from 0.5 m in the 1980s, over 0.8 m in the 2020s to 1.9 m at the end of the century. Scenario 06 showed ALT values of a similar magnitude as scenario 05, however, with a less pronounced increase, reaching only a median MAGT of 1.4 m in the 2090s.

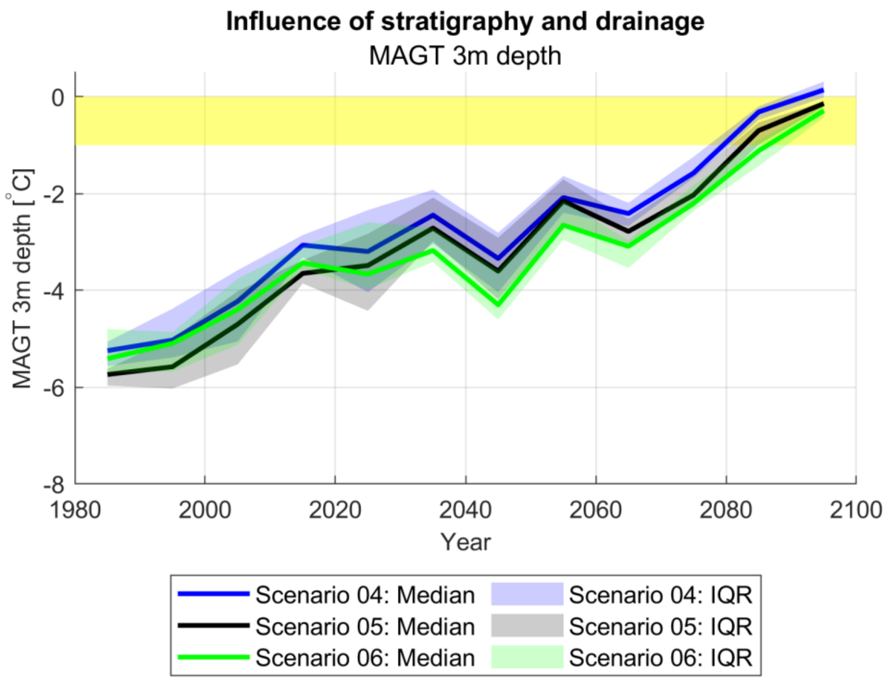

Figure 7: Adventdalen: MAGT in 3 m depth with median decadal values and decadal IQR for model scenarios with a snowfall factor of 0.5 and varying soil stratigraphies and drainage conditions: scenario 04 (blocky terrain, well drained), 05 (silty soil, fairly drained) and 06 (organic layer, not drained).

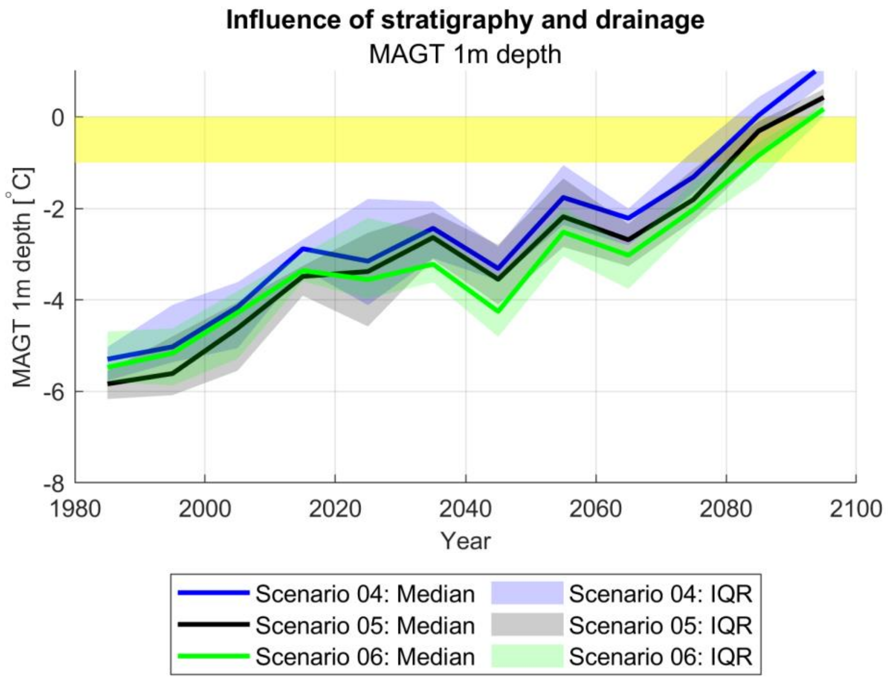

Figure 8. Adventdalen: MAGT in 1 m depth with median decadal values and decadal IQR for model scenarios with a snowfall factor of 0.5 and varying soil stratigraphies and drainage conditions: scenario 04 (blocky terrain, well drained), 05 (silty soil, fairly drained) and 06 (organic layer, not drained).

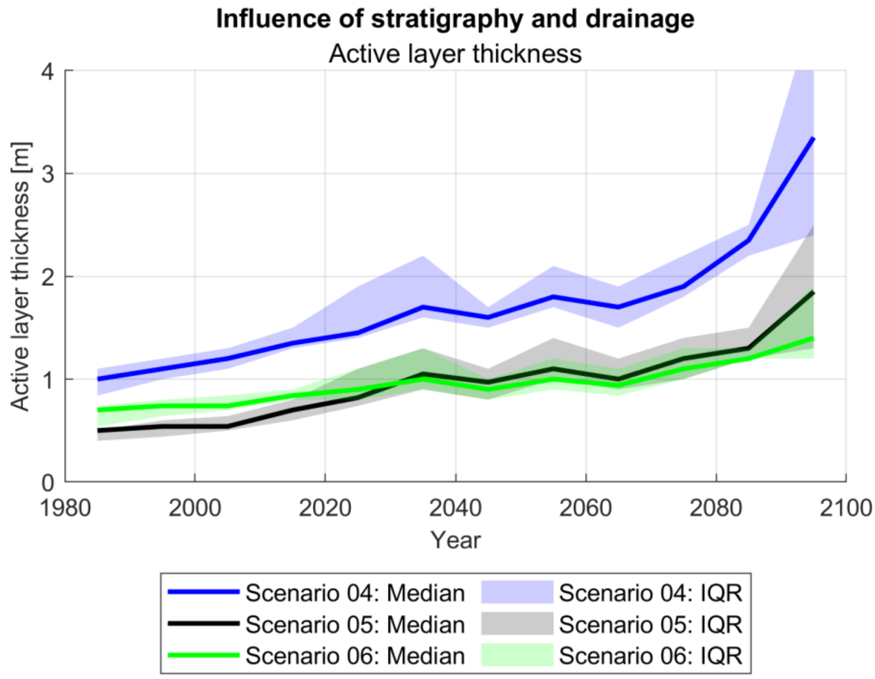

Figure 9. Adventdalen: ALT with median decadal values and decadal IQR for model scenarios with a snowfall factor of 0.5 and varying soil stratigraphies and drainage conditions: scenario 04 (blocky terrain, well drained), 05 (silty soil, fairly drained) and 06 (organic layer, not drained).

3.4 Mean annual ground temperatures (MAGT) and active layer thickness (ALT) in Ny-Ålesund

Our results show an increase in MAGT and ALT between 1980 and 2100, following the climatic warming of the high emission scenario SSP5-8.5. However, both parameters differ substantially between the 3 model scenarios, indicating diverse permafrost conditions in Ny-Ålesund. It is important to note that we kept the same soil stratigraphy and drainage conditions throughout the 3 scenarios and only varied the snowfall factor to represent the permafrost conditions in Ny-Ålesund.

Fig. 10 and 11 show the development of median decadal MAGT for all 3 model scenarios in 3 m and 1 m depth. The median MAGT range from –6.4 ˚C and –1.8 ˚C in the 1980s for both 3 m and 1 m depth. Hereby, the scenario with the lowest snowfall factor of 0.5 (scenario 13) features the lowest median MAGT, while the scenario with the highest snowfall factor of 1.5 (scenario 15) shows the highest median MAGT. The median MAGT then increased notably until the 2030s, ranging between –2.5 ˚C (scenario 13) and –0.4 ˚C (scenario 15). After a slight cooling in the 2040s to the 2060s, the median MAGT are projected to increase further towards the end of the century, with the most substantial increase for model scenarios with low snowfall factors, so that median MAGT of all model scenarios converge with time. In the 2080s, all model scenarios project median MAGT above -1.0 ˚C in both 3 m and 1 m depth. In the 2090s, median MAGT above 0 ˚C are reached for model scenarios 14 and 15 for 1 m depths.

Furthermore, the ALT increases between the 1980s and 2100 (Fig. 12). In the 1980s, an ALT between approximately 1.0 m and 1.2 m was simulated, which increased to values between 1.4 m and 1.7 m in the 2020s. In the following decades, the ALT is modelled to be rather stable, before the development accelerated in the 2070s, leading to a projected ALT between 2.3 m and 2.7 m towards the end of the century.

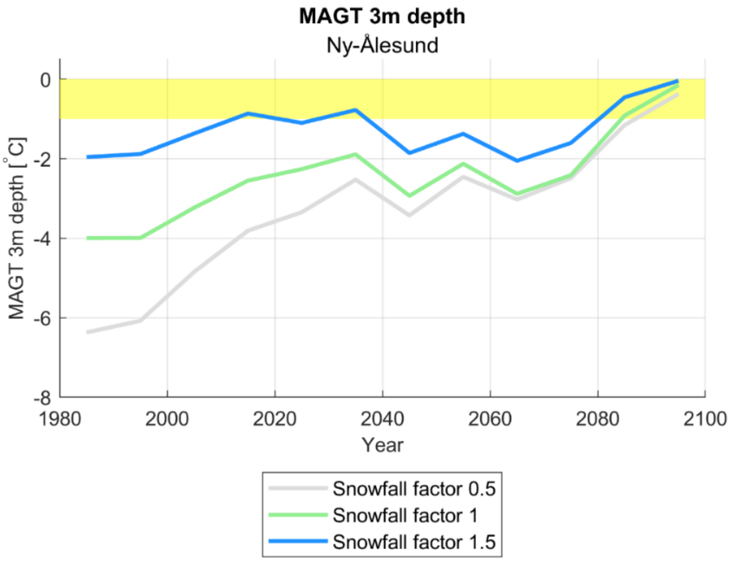

Figure 10. Ny-Ålesund: MAGT in 3 m depth with median decadal values for model scenarios with a fairly drained, silty soil and varying snowfall factors: snowfall factor 0.5 (scenario 13), snowfall factor 1.0 (scenario 14), and snowfall factor 1.5 (scenario 15).

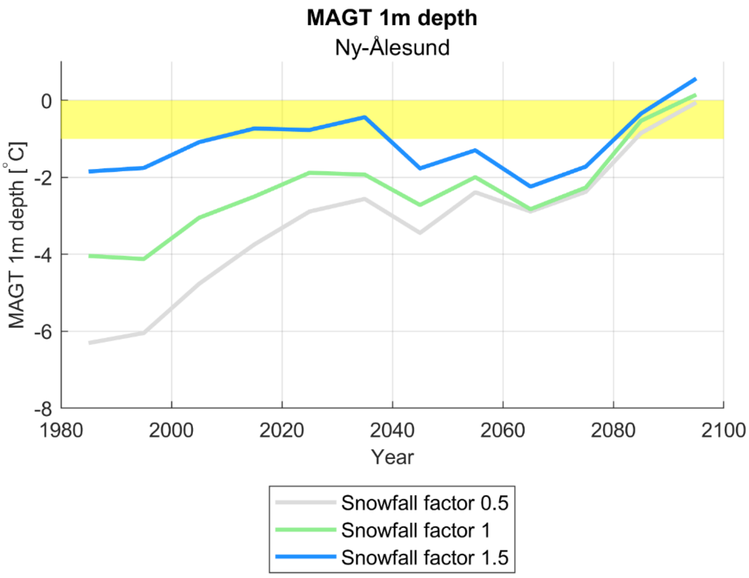

Figure 11. Ny-Ålesund: MAGT in 1 m depth with median decadal values for model scenarios with a fairly drained, silty soil and varying snowfall factors: snowfall factor 0.5 (scenario 13), snowfall factor 1.0 (scenario 14), and snowfall factor 1.5 (scenario 15).

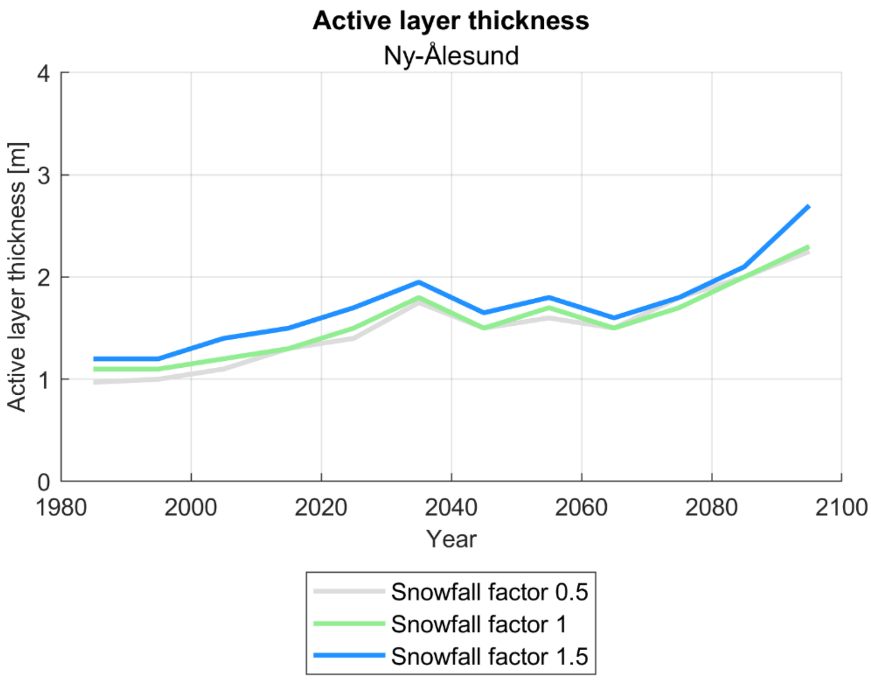

Figure 12. Ny-Ålesund: ALT with median decadal values for model scenarios with a fairly drained, silty soil and varying snowfall factors: snowfall factor 0.5 (scenario 13), snowfall factor 1.0 (scenario 14), and snowfall factor 1.5 (scenario 15).

3.5 The influence of the snow cover in Ny-Ålesund

Similar to the results from Adventdalen, the simulations from Ny-Ålesund show (Fig. 13) that snow cover has a pronounced influence on the MAGT in both 1 m depth and 3 m depth, which can be explained by the insulating effect of the snow cover in winter, leading to low median MAGT for scenarios with little snow (scenario 13) and higher median MAGT for scenarios with high snowfall rates (scenario 15). The differences in MAGT are especially pronounced in the 1980s but are diminish throughout the simulation, until similar MAGT are simulated towards 2100.

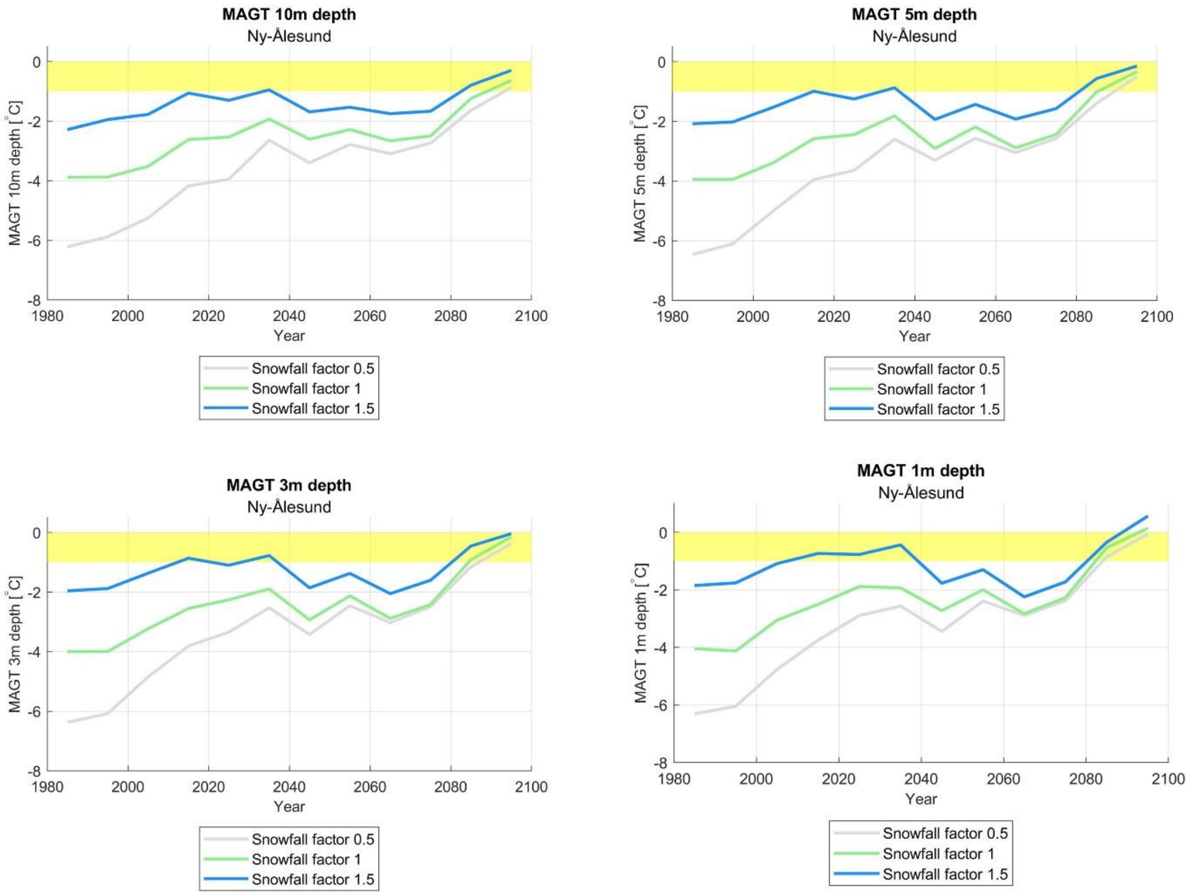

Figure 13. Ny-Ålesund: MAGT in 10 m, 5 m, 3 m and 1 m depths.

The scenario 13 with little snow simulate low median MAGT of –6.3˚C in the 1980s, before increasing to around -2.9˚C in the 2020s. The critical temperature range is reached in the 2080s in 1 m depth and in the 2090s for 3 m depth. In contrast to that, the scenario 14 with average snowfall shows median MAGT of –4.0˚C in the 1980s and reaches the critical temperature range in the 2080s for both 1 m and 3 m depth. Scenario 15, with the highest snowfall simulates median MAGT of approximately –1.9 ˚C in the 1980s, and values in the critical temperature range are reached from the 2010s to the 2030s, and after a cooling period again from the 2080s. In both 1 m and 3 m depth.

While variations in the snow cover have a strong impact on the ground temperatures as described above, the influence on the ALT is minor (Fig. 14). A median ALT of about 1.1 m is simulated for all three scenarios in the 1980s, increasing to approximately 1.5 m in the 2020s. Towards the end of the century, the scenarios reach median values between 2.3 m and 2.7 m.

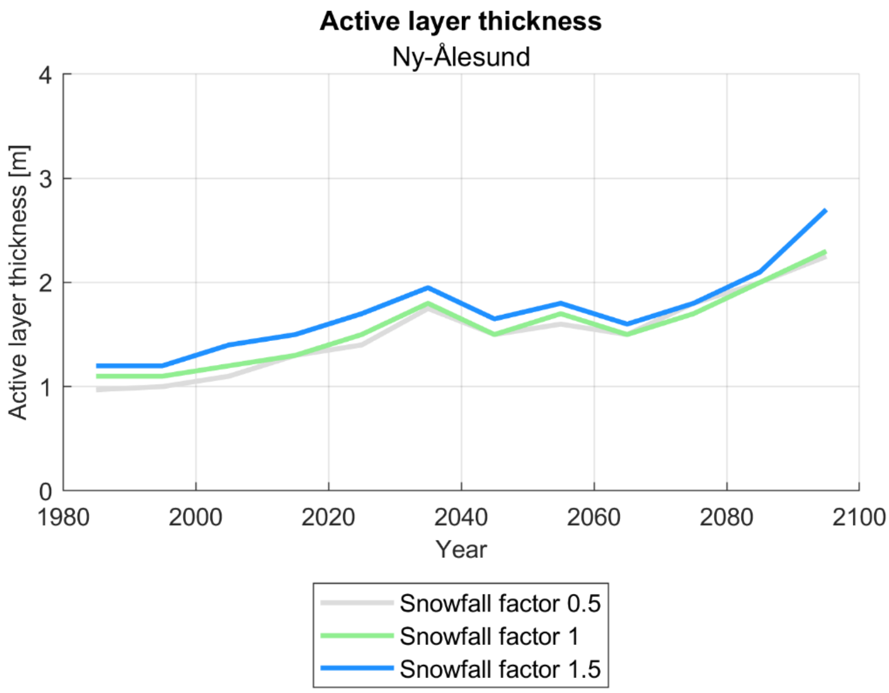

Figure 14. Ny-Ålesund: ALT according to scenario 13, 14 and 15.

4. Discussion

We set up the CryoGrid community model to simulate the permafrost thermal regime in Adventdalen and Ny-Ålesund, Svalbard, between 1980 and 2100 under an SSP5-8.5 emission scenario. Twelve different model scenarios represent different soil stratigraphies, drainage conditions and snow dynamics for Adventdalen, and three for Ny-Ålesund. Given these varying conditions, different mean annual ground temperatures (MAGT) and active layer thicknesses (ALT) are simulated.

4.1 MAGT and ALT in Adventdalen and Ny-Ålesund

Following the climatic warming of the SSP5-8.5 scenario, an increase in MAGT and ALT was simulated for all 15 model scenarios. In the 2000s and 2010s, the simulated values are in the range of observed MAGT and ALT in Adventdalen and Ny-Ålesund (Hanssen-Bauer et al., 2019), however, the variation in MAGT highlight, that permafrost conditions might vary substantially depending on the soil stratigraphy, drainage conditions and snow cover. While some model scenarios already feature MAGT between -1 ˚C and 0 ˚C nowadays, others reach the critical temperature range towards the end of the century. As the ground temperatures might have a strong impact on the stability of structures built on the permafrost, the conditions for each object should be evaluated separately and based on that, the best fitting model scenario should be selected to avoid an over- or underestimation of MAGT and ALT.

4.2 Influencing factors

The differences in MAGT are very pronounced in the 1980s, while they converge towards the end of the century. This can be explained with a predicted trend in snowfall: Even though the total precipitation is projected to increase in the coming decades due to higher temperatures in the atmosphere and thus increased moisture content, the amount of precipitation falling as snow is expected to decrease, a trend that can already be observed today (Hanssen-Bauer et al., 2019). This is also reflected in the applied forcing data, leading to a reduced difference in snow depth between scenarios with varying snowfall factors. As snow is highly impacting the ground temperatures, the median MAGT converge towards the end of the century.

The reduced amount of snowfall also affects the warming trend in ground temperatures. With a thinner snow cover and consequently less insulation, the ground is more directly exposed to cold air temperatures in winter. This can lead temporarily to a lowering in MAGT in the future projections, however, an overall trend in ground warming is simulated for all model scenarios.

Our results show that the snow cover highly affects the MAGT. Due to its insulation, the snow keeps the ground temperatures rather stable. This means that less extreme cold penetration into the ground, resulting in higher ground temperatures during snow season and consequently higher mean annual values. The thicker the snow cover, the greater the insulating effect. Therefore, model scenarios with higher snowfall factors result in higher MAGT.

However, the snow cover only influences the ALT to a minor extent. During summer, after the snow has melted, the ground is exposed to the atmosphere, absorbs the heat and the active layer begins to thaw. At the same time, the depth to which it thaws is more significantly influenced by the thermal properties of the soil, the moisture content and the duration and intensity of summer air temperatures, rather than the previous snow cover.

In contrast, soil stratigraphy and drainage conditions strongly influence the active layer thickness. The highest values are simulated for blocky terrain with well drained conditions. These scenarios are characterized by a higher mineral content and due to the drainage by very low soil moisture contents. During the thawing season, the small amount of ground ice means that there is less latent heat required for the phase change from ice to water. This allows the soil to warm up more quickly and to greater depths. Additionally, soils with a low porosity tend to be denser and have a lower specific heat capacity, which means they can heat up and cool down more rapidly than soils with a higher porosity. As a consequence, this stratigraphy is strongly affected by climatic warming, leading to a pronounced increase in ALT towards the end of the century.

In contrast, the scenario with stratigraphy 3, characterized by an organic layer at the uppermost soil layers, has a smaller ALT, which increases only slightly towards the end of the century. Organic soils have a high heat capacity due to their high water content compared to mineral soils. This means that more energy is required to change their temperature, which limits the extent of warming and thus the depth of thawing in summer. Furthermore, the loose structure of organic soils provides insulating effects. During summer, the organic layer reduces the amount of heat that reaches the underlying permafrost. In winter, the same properties help to retain the cold, thereby protecting the permafrost and limiting the extent of seasonal freezing and thawing.

4.3 Impact on cultural heritage

Ground temperatures critically influence the stability of infrastructure built in permafrost environments. This is especially true for historical structures, which were not designed to withstand the current climatic changes.

Frozen soil is characterized by a high shear strength as the ground ice bonds the soil particles together. As permafrost warms and the ground temperatures approach 0 ˚C, the ground ice begins to thaw, leading to a loss of these bonds. Higher permafrost temperatures also lead to higher settlements of foundations due to higher creep rates of warmer frozen soils. This reduces the shear strength of the soil and its bearing capacity, which can endanger the stability of structures. Furthermore, thawing permafrost can lead to ground settling or subsidence. This effect is especially pronounced in ice-rich soils, which may result in differential settling, leading to tilting, cracking or collapse of structures.

Our model results show that the ground temperatures approach 0 ˚C towards the end of the century for all model scenarios. However, while some scenarios do not reach the critical temperature range before the 2080s, other already experience nowadays ground temperatures close to 0 ˚C. Therefore, it is crucial to select the most appropriate model scenario for each case study object depending on the soil stratigraphy, drainage conditions and snow dynamics, to assess the permafrost thermal regime and its development in future.

5. Conclusion

This report presents the results from the permafrost simulations conducted for Adventdalen and Ny-Ålesund as part of the PCCH-Arctic project. Using the CryoGrid community model, we evaluated the ground thermal regime from the 1980s to 2100 under the high emission scenario SSP5-8.5. Twelve different model scenarios were used to reflect the variable soil stratigraphies, drainage conditions and snow dynamics in Adventdalen, and three different model scenarios were used for Ny-Ålesund. These scenarios provided insights into the mean annual ground temperature and active layer thickness that significantly affect the stability of cultural heritage objects in Adventdalen and Ny-Ålesund.

The results show that both MAGT and ALT show an increasing trend towards the end of the century. However, notable differences were simulated across the 12 and three model scenarios respectively, influenced by variations in soil stratigraphy, drainage conditions and snow dynamics. Scenarios with high snowfall factors resulted in higher MAGT compared to model scenarios with little snow due to the insulating properties of the snow cover. Scenarios with blocky terrain and drained conditions exhibited greater ALT increases due to faster warming and deeper thaw into the soil. Conversely, scenarios with an organic layer and undrained conditions showed a lower ALT increase, which can be explained by the thermal buffer provided by the organic content and soil moisture.

The simulated permafrost warming implies a potential risk on the stability of cultural heritage objects due to expected changes in the bearing capacity of the ground. Structures built on warming permafrost may be impacted by ground settlement, tilting and possible collapse as frozen ground thaws. Therefore, it is essential to select the most suitable model scenario to identify the individual risk for each object. This report underscores the importance of considering changes in the permafrost thermal regime into cultural heritage risk assessments to mitigate the potentially severe impacts of climate change in the region.

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Appendix 1. Data for Adventdalen

In the following, the median MAGT in 1 m depth and 3 m depth as well as the ALT is shown for all 12 model scenarios.

Scenario 01: snowfall factor 0.1, blocky terrain, well drained

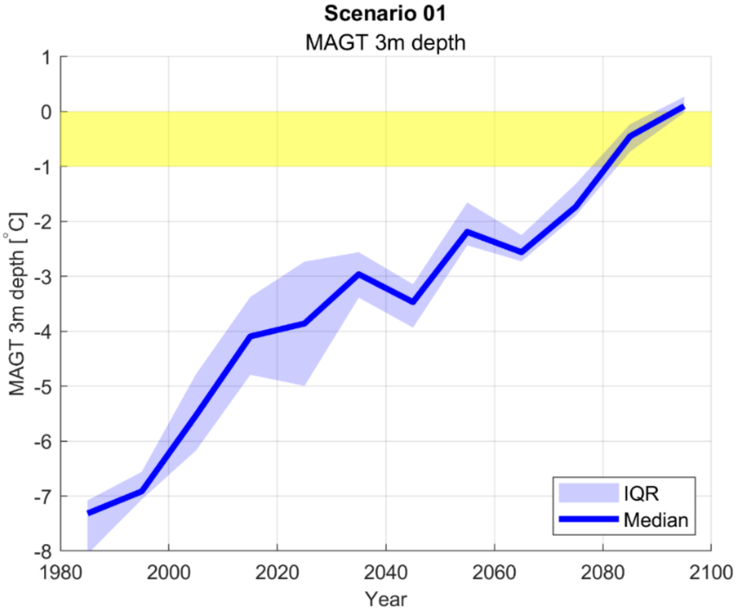

Figure A1 A-1. Adventdalen: MAGT in 3 m depth with median decadal values and decadal IQR for model scenario 01 (snowfall factor 0.1, blocky terrain, well drained).

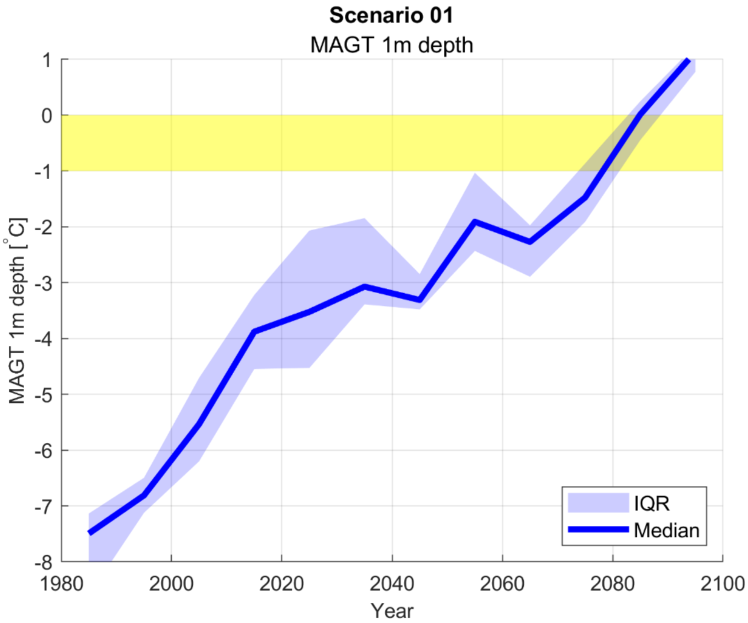

Figure A1 A-2. Adventdalen: MAGT in 1 m depth with median decadal values and decadal IQR for model scenario 01 (snowfall factor 0.1, blocky terrain, well drained).

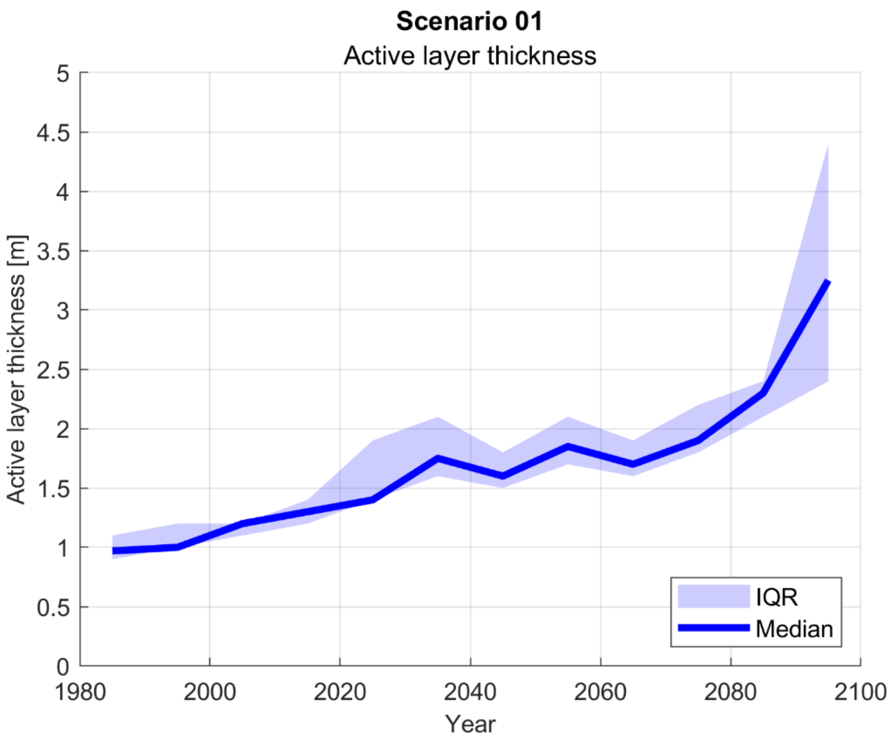

Figure A1 A-3. Adventdalen: ALT with median decadal values and decadal IQR for model scenario 01 (snowfall factor 0.1, blocky terrain, well drained).

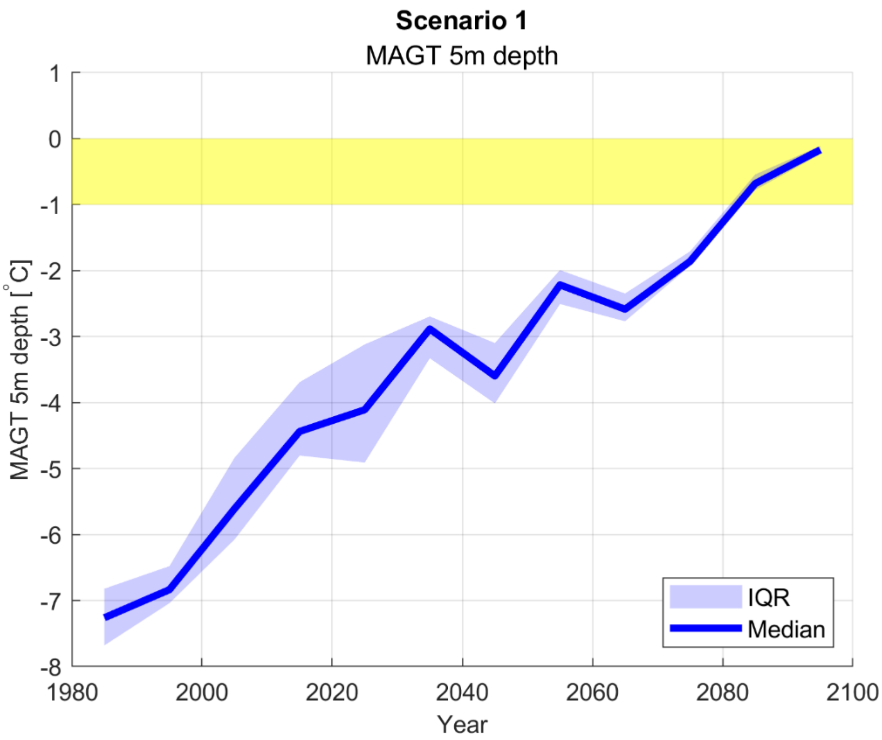

Figure A1 A-4. Adventdalen: MAGT in 5 m depth with median decadal values and decadal IQR for model scenario 01 (snowfall factor 0.1, blocky terrain, well drained).

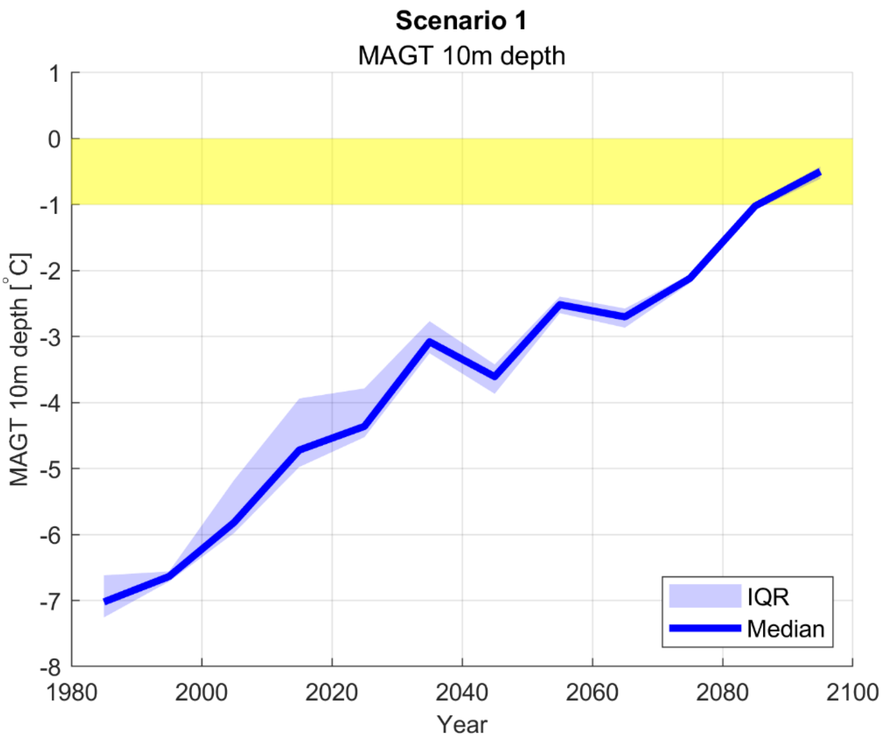

Figure A1 A-5. Adventdalen: MAGT in 10 m depth with median decadal values and decadal IQR for model scenario 01 (snowfall factor 0.1, blocky terrain, well drained).

Scenario 02: snowfall factor 0.1, silty soil, fairly drained

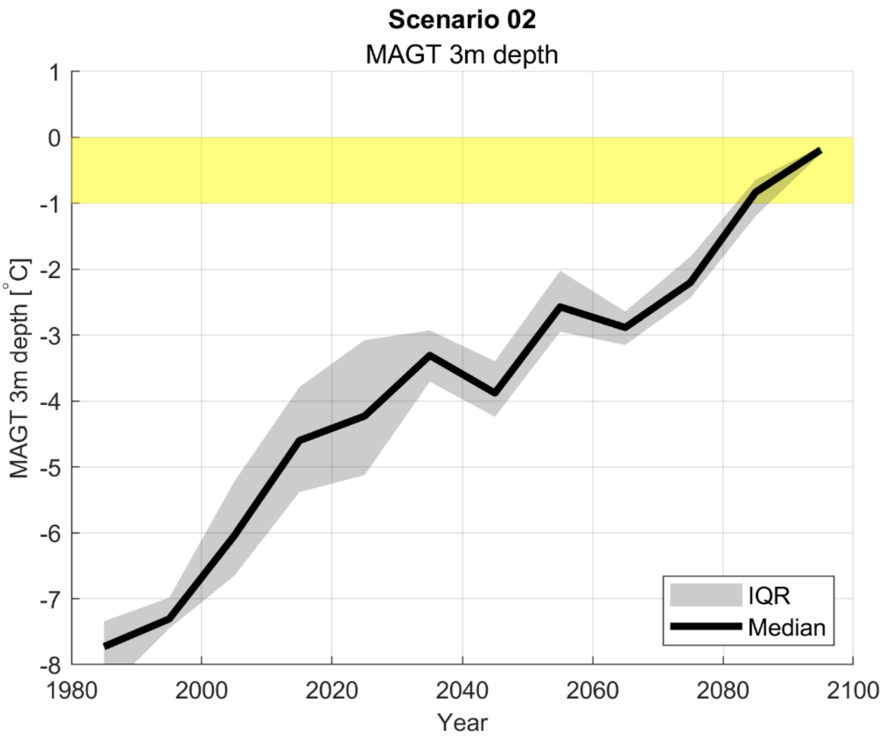

Figure A1 B-1. Adventdalen: MAGT in 3 m depth with median decadal values and decadal IQR for model scenario 02 (snowfall factor 0.1, silty soil, fairly drained).

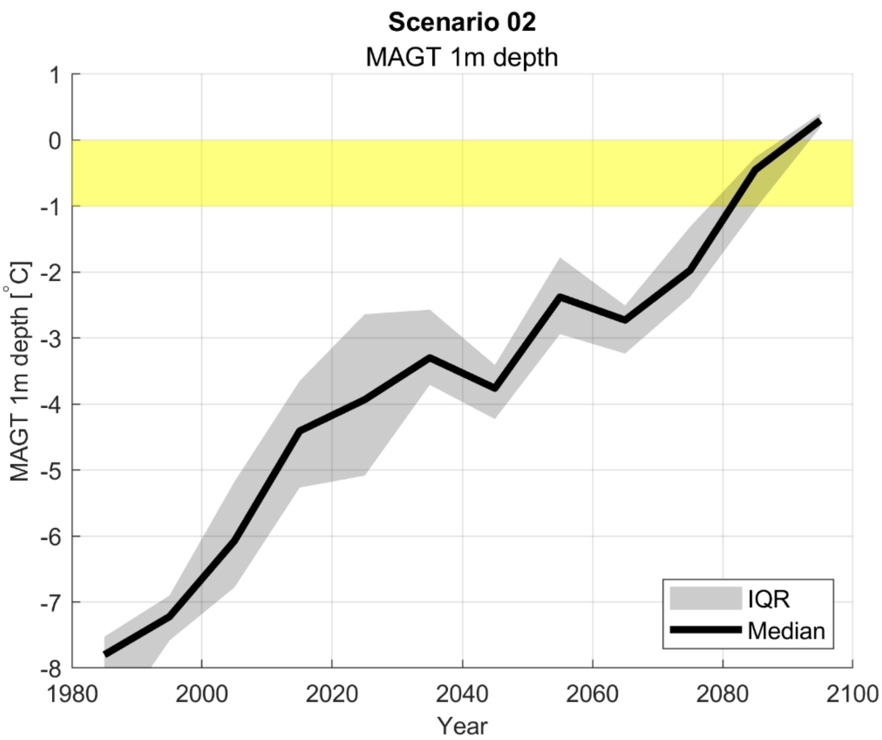

Figure A1 B-2. Adventdalen: MAGT in 1 m depth with median decadal values and decadal IQR for model scenario 02 (snowfall factor 0.1, silty soil, fairly drained).

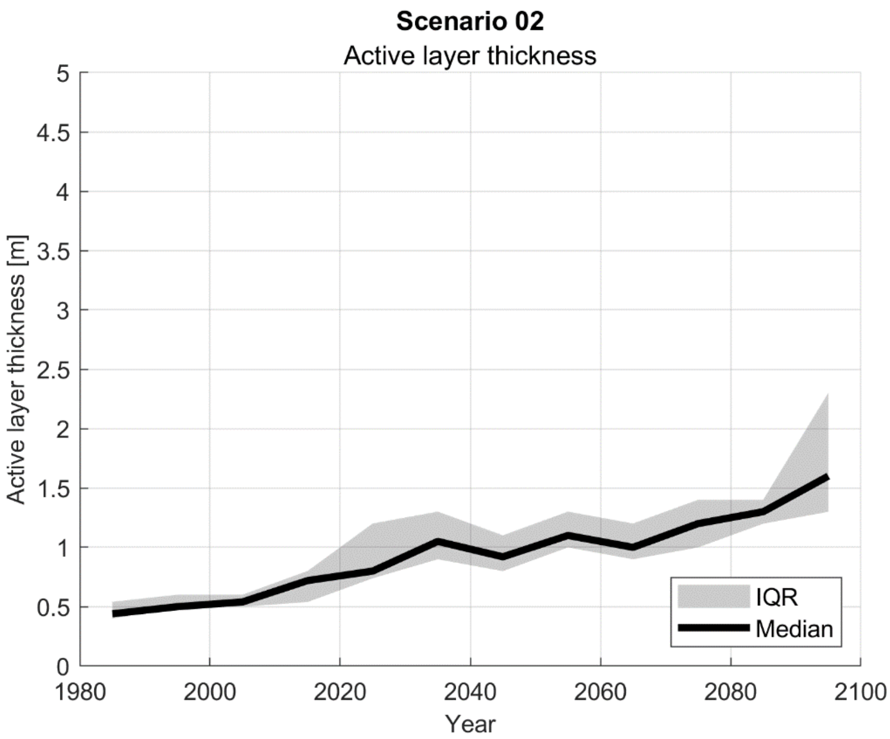

Figure A1 B-3. Adventdalen: ALT with median decadal values and decadal IQR for model scenario 02 (snowfall factor 0.1, silty soil, fairly drained).

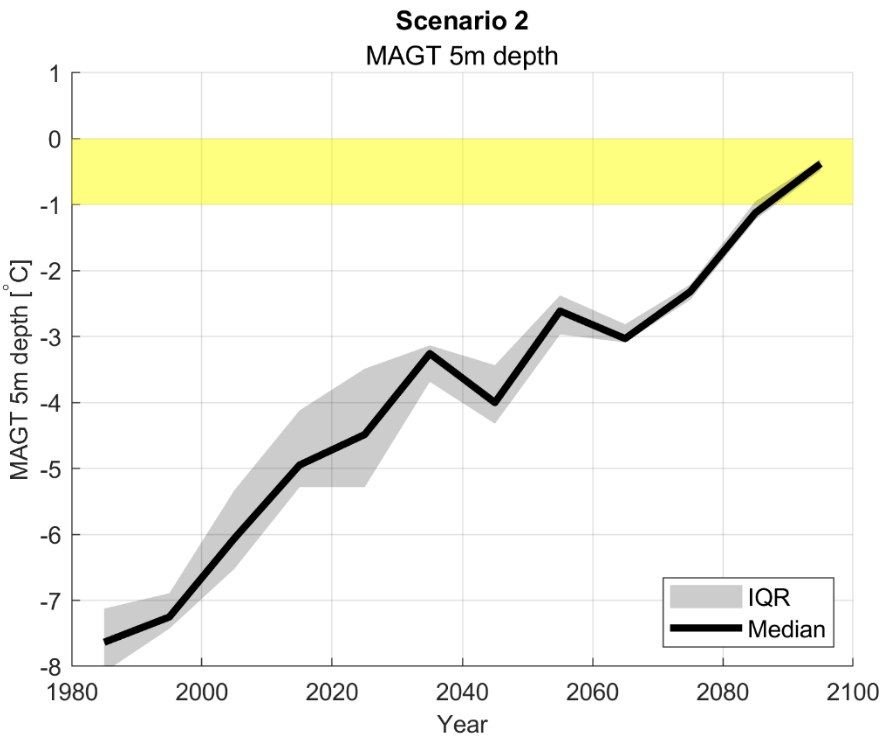

Figure A1 B-4. Adventdalen: MAGT in 5 m depth with median decadal values and decadal IQR for model scenario 02 (snowfall factor 0.1, silty soil, fairly drained).

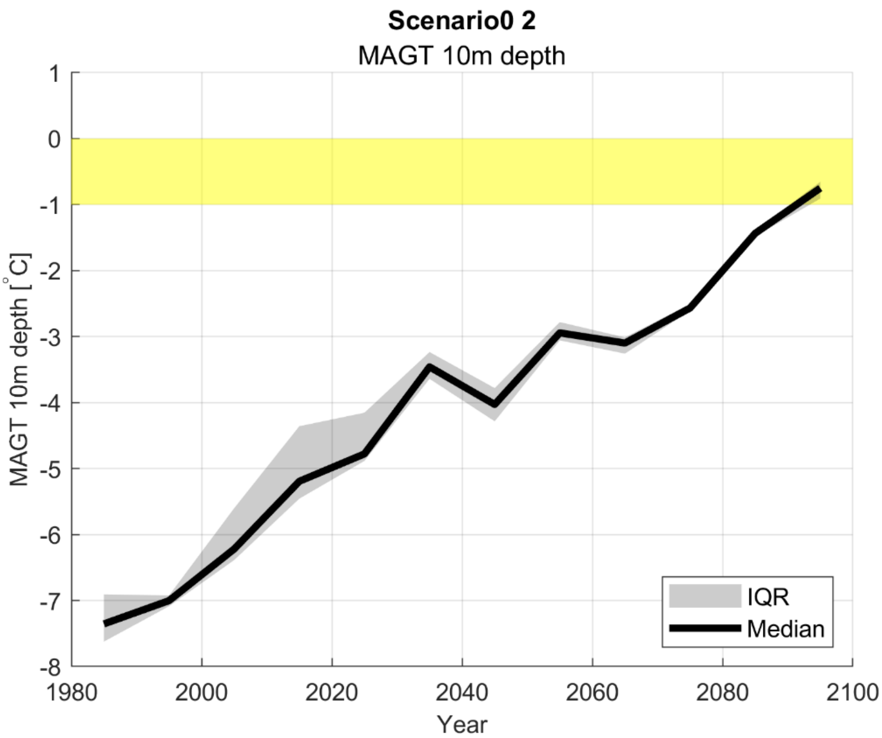

Figure A1 B-5. Adventdalen: MAGT in 10 m depth with median decadal values and decadal IQR for model scenario 02 (snowfall factor 0.1, silty soil, fairly drained).

Scenario 03: snowfall factor 0.1, organic layer, not drained

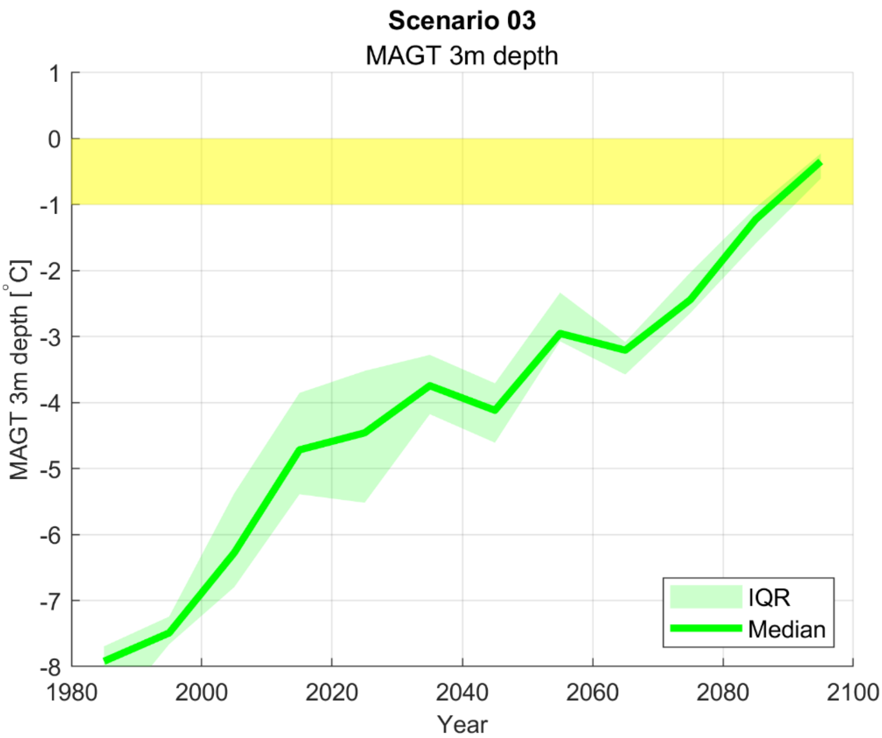

Figure A1 C-1. Adventdalen: MAGT in 3 m depth with median decadal values and decadal IQR for model scenario 03 (snowfall factor 0.1, organic layer, not drained).

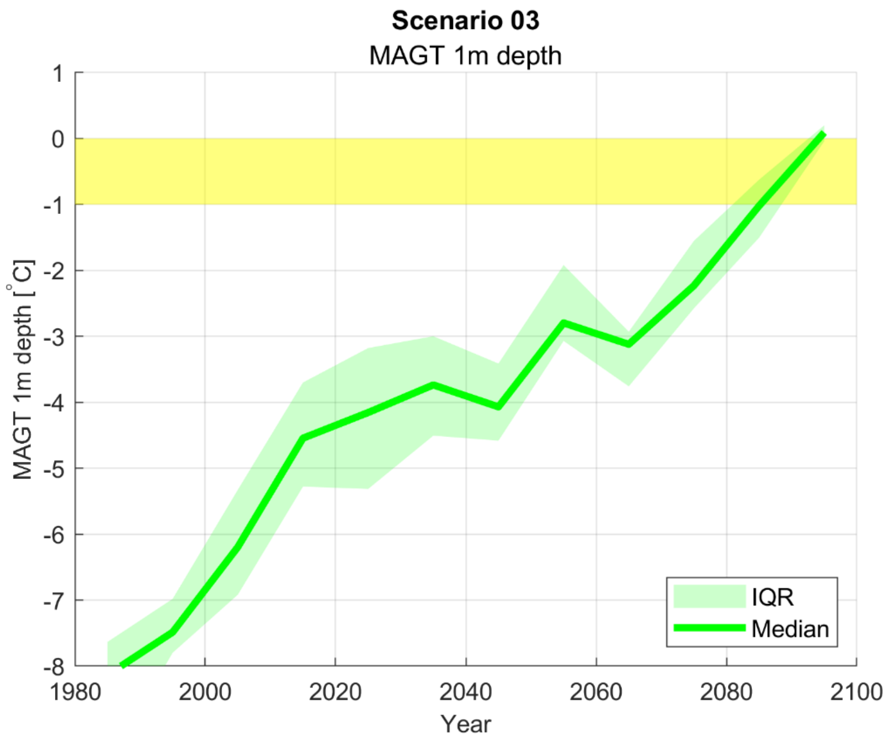

Figure A1 C-2. Adventdalen: MAGT in 1 m depth with median decadal values and decadal IQR for model scenario 03 (snowfall factor 0.1, organic layer, not drained).

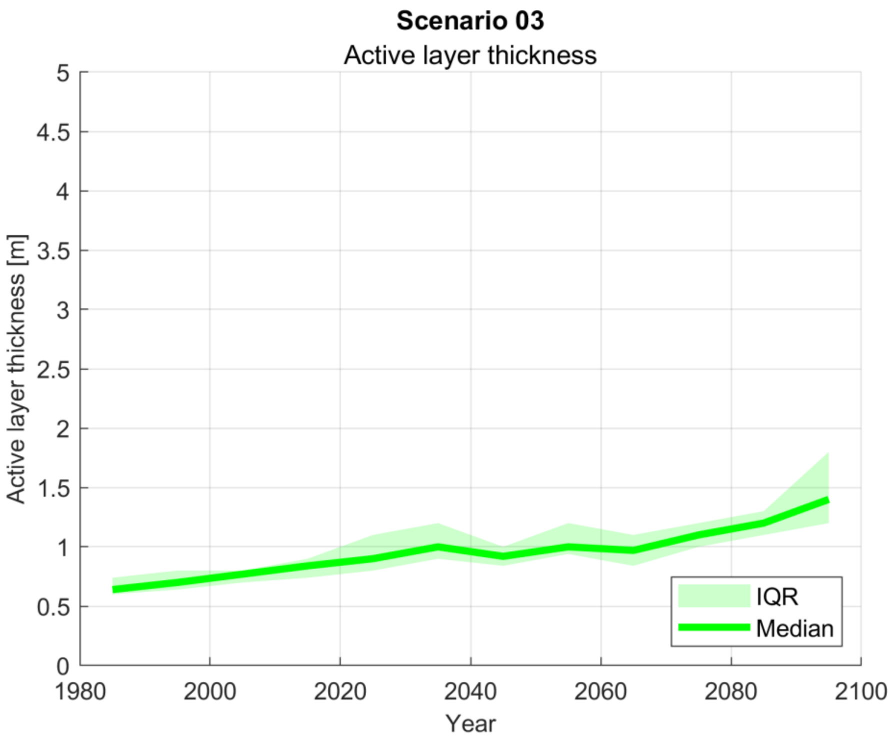

Figure A1 C-3. Adventdalen: ALT with median decadal values and decadal IQR for model scenario 03 (snowfall factor 0.1, organic layer, not drained).

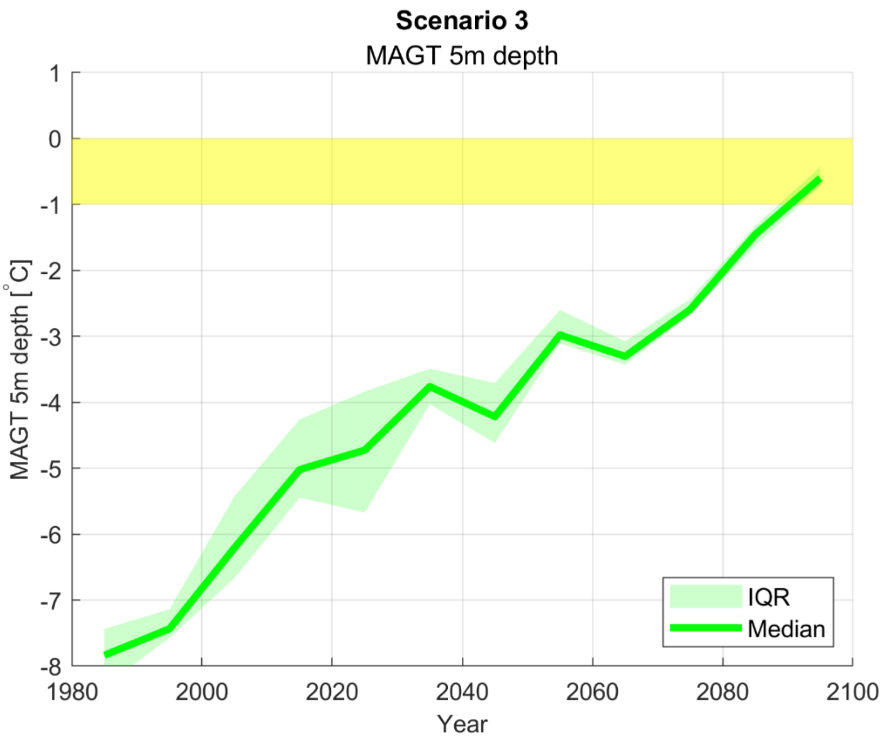

Figure A1 C-4. Adventdalen: MAGT in 5 m depth with median decadal values and decadal IQR for model scenario 03 (snowfall factor 0.1, organic layer, not drained).

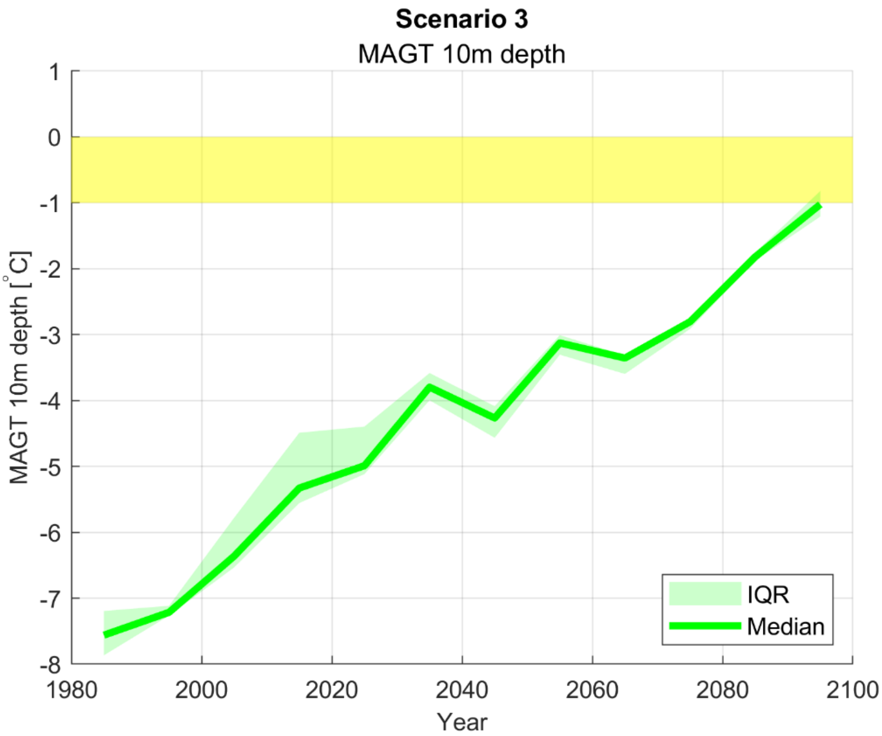

Figure A1 C-5. Adventdalen: MAGT in 10 m depth with median decadal values and decadal IQR for model scenario 03 (snowfall factor 0.1, organic layer, not drained).

Scenario 04: snowfall factor 0.5, blocky terrain, well drained

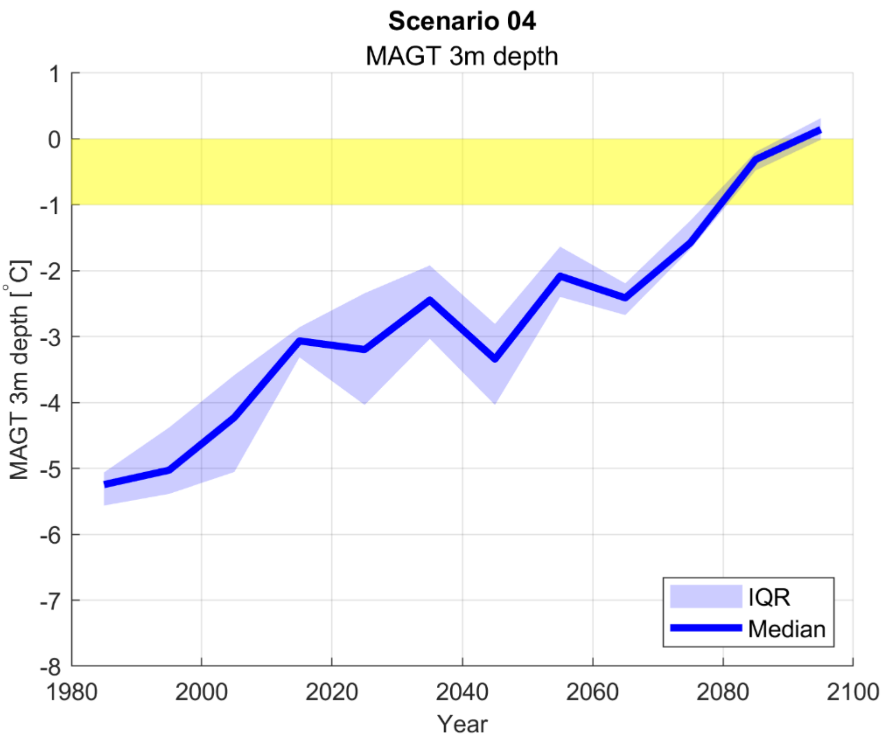

Figure A1 D-1. Adventdalen: MAGT in 3 m depth with median decadal values and decadal IQR for model scenario 04 (snowfall factor 0.5, blocky terrain, well drained).

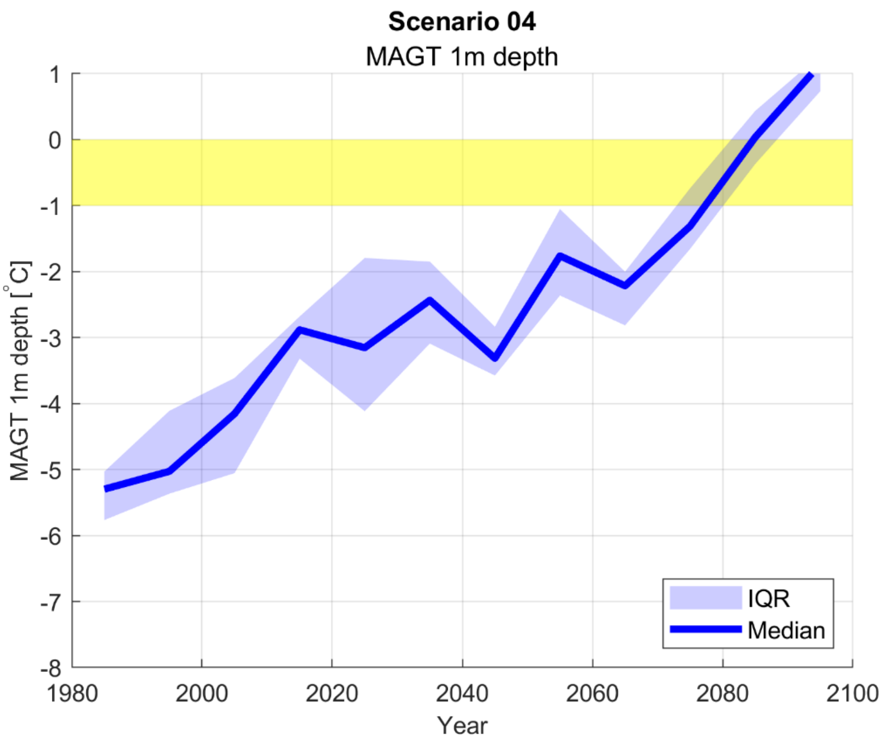

Figure A1 D-2. Adventdalen: MAGT in 1 m depth with median decadal values and decadal IQR for model scenario 04 (snowfall factor 0.5, blocky terrain, well drained).

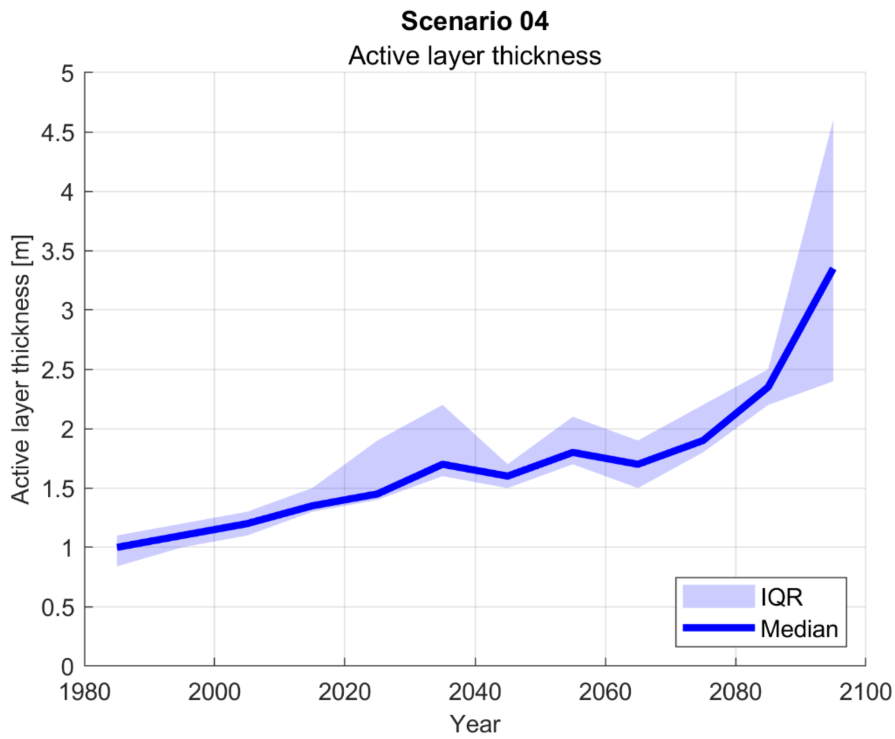

Figure A1 D-3. Adventdalen: ALT with median decadal values and decadal IQR for model scenario 04 (snowfall factor 0.5, blocky terrain, well drained).

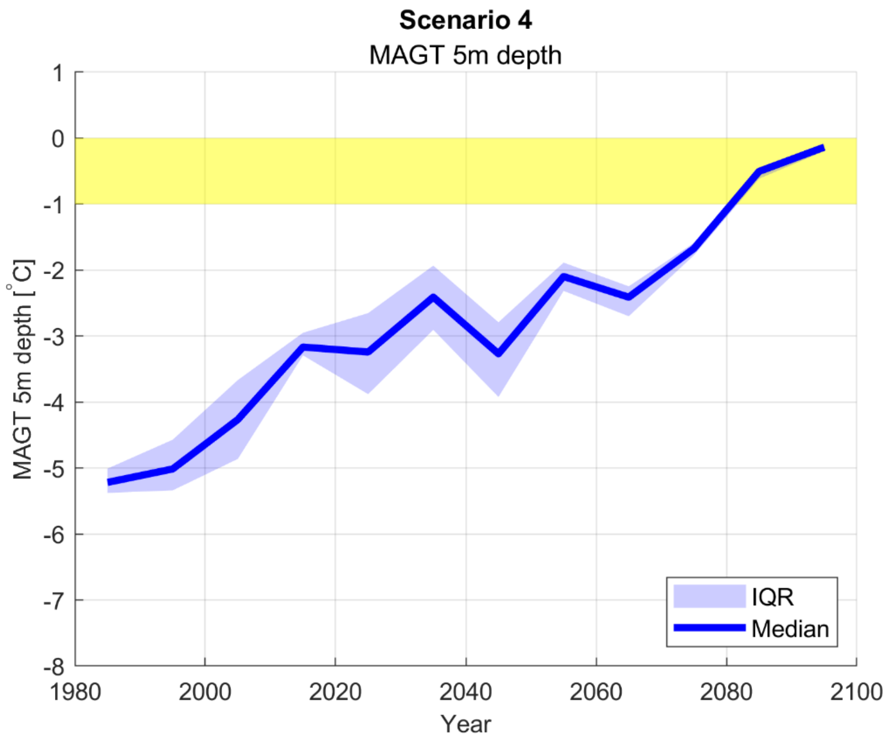

Figure A1 D-4. Adventdalen: MAGT in 5 m depth with median decadal values and decadal IQR for model scenario 04 (snowfall factor 0.5, blocky terrain, well drained).

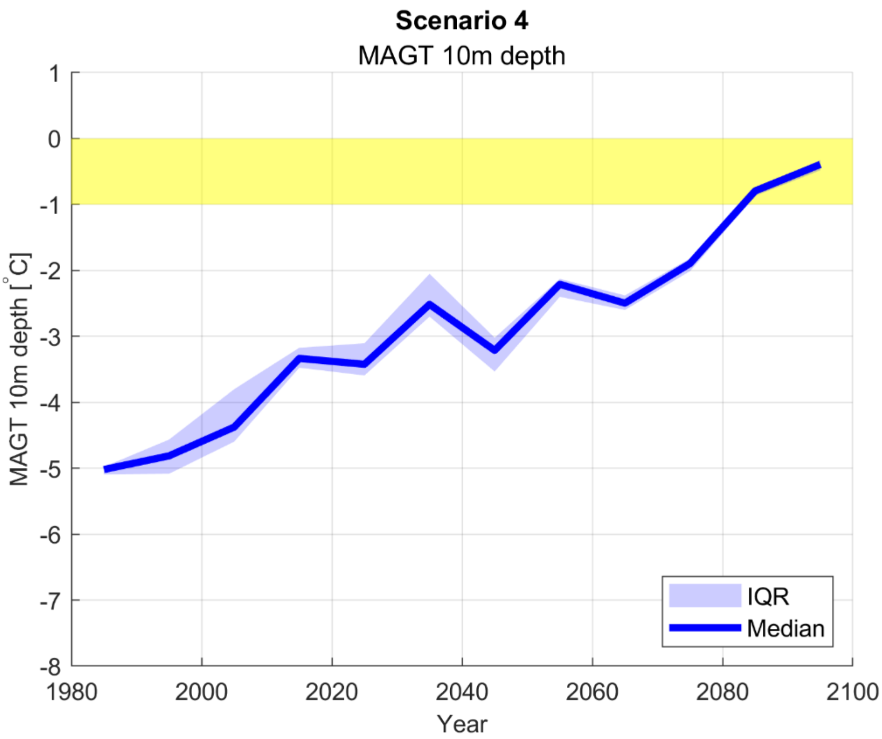

Figure A1 D-5. Adventdalen: MAGT in 10 m depth with median decadal values and decadal IQR for model scenario 04 (snowfall factor 0.5, blocky terrain, well drained).

Scenario 05: snowfall factor 0.5, silty soil, fairly drained

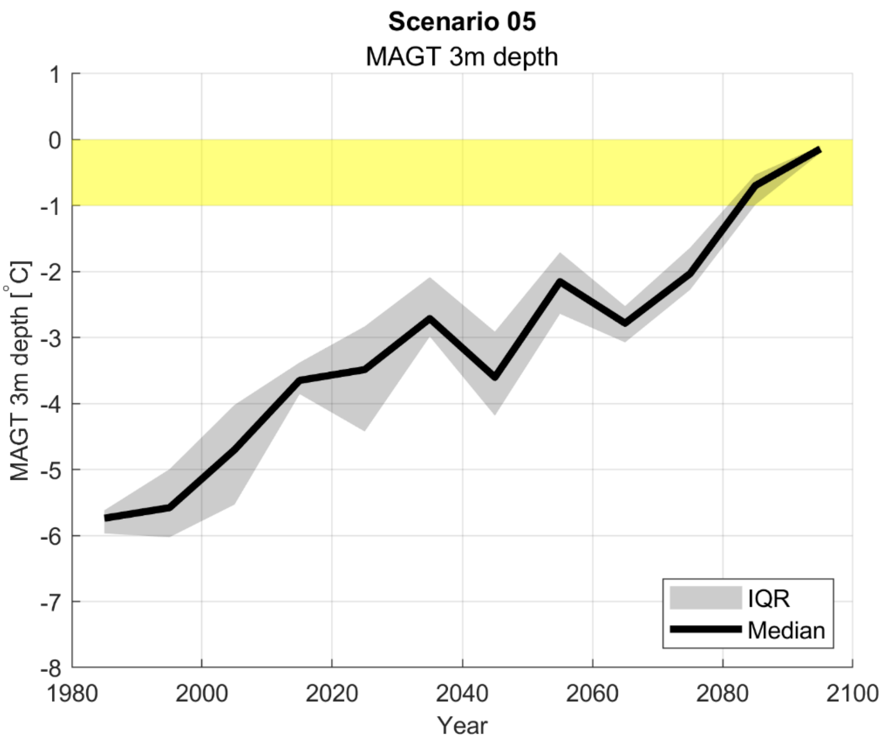

Figure A1 E-1. Adventdalen: MAGT in 3 m depth with median decadal values and decadal IQR for model scenario 05 (snowfall factor 0.5, silty soil, fairly drained).

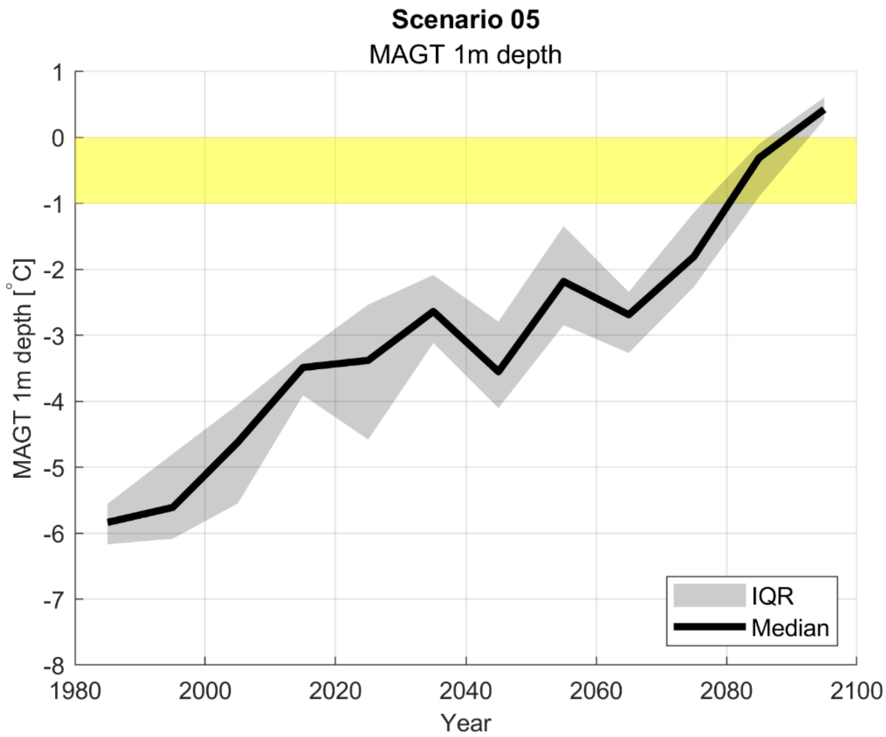

Figure A1 E-2. Adventdalen: MAGT in 1 m depth with median decadal values and decadal IQR for model scenario 05 (snowfall factor 0.5, silty soil, fairly drained).

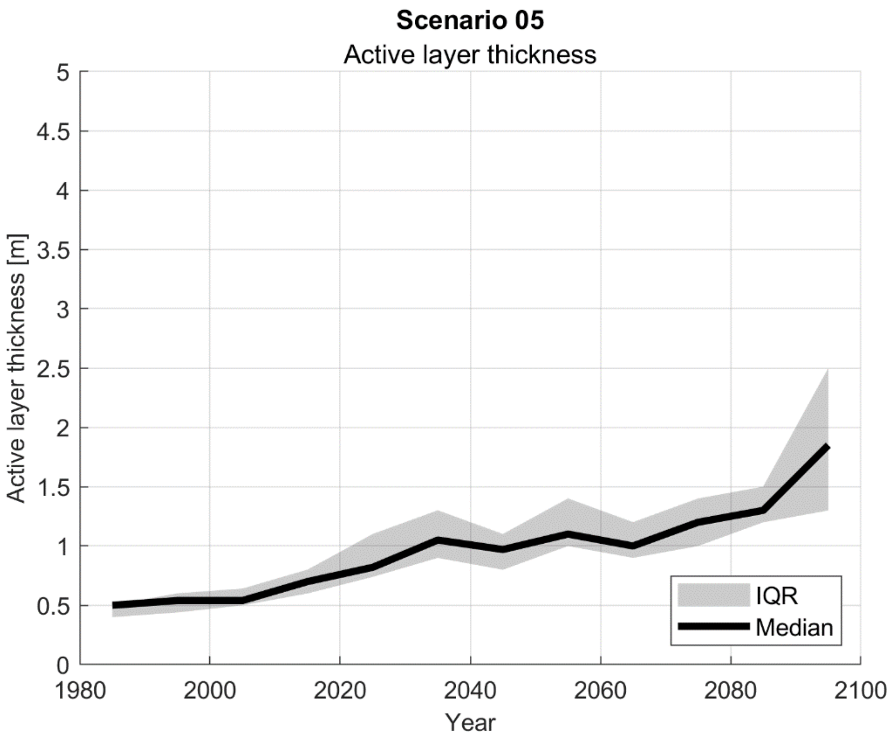

Figure A1 E-3. Adventdalen: ALT with median decadal values and decadal IQR for model scenario 05 (snowfall factor 0.5, silty soil, fairly drained).

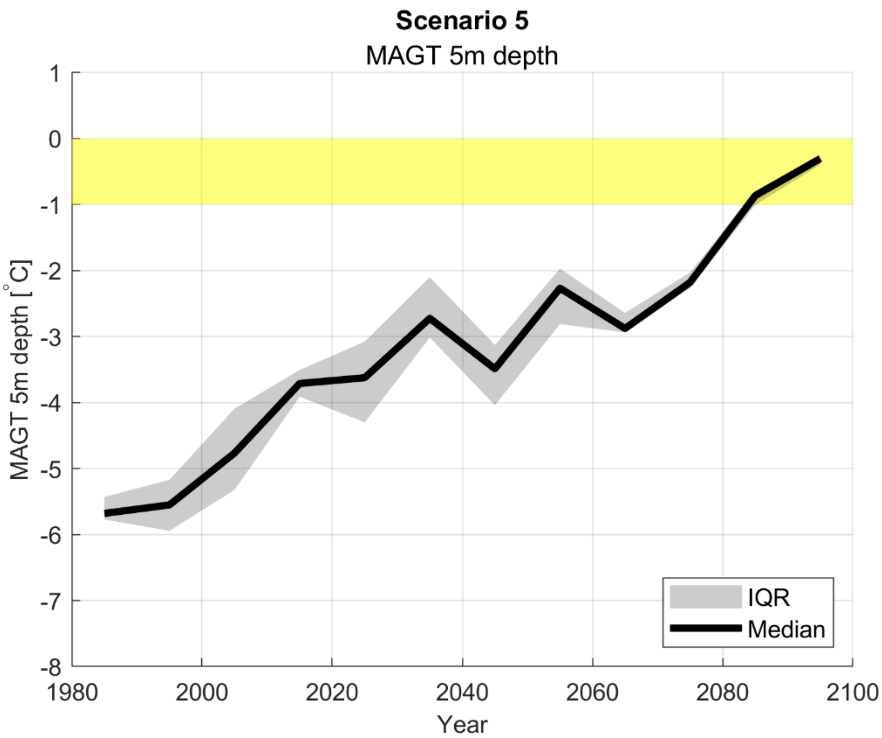

Figure A1 E-4. Adventdalen: MAGT in 5 m depth with median decadal values and decadal IQR for model scenario 05 (snowfall factor 0.5, silty soil, fairly drained).

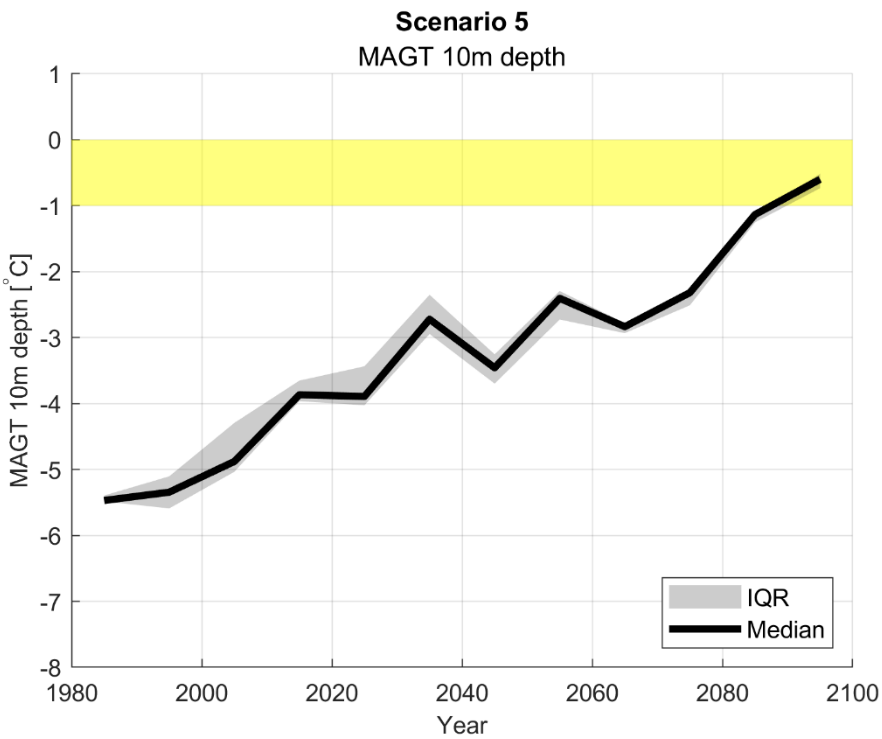

Figure A1 E-5. Adventdalen: MAGT in 10 m depth with median decadal values and decadal IQR for model scenario 05 (snowfall factor 0.5, silty soil, fairly drained).

Scenario 06: snowfall factor 0.5, organic layer, not drained

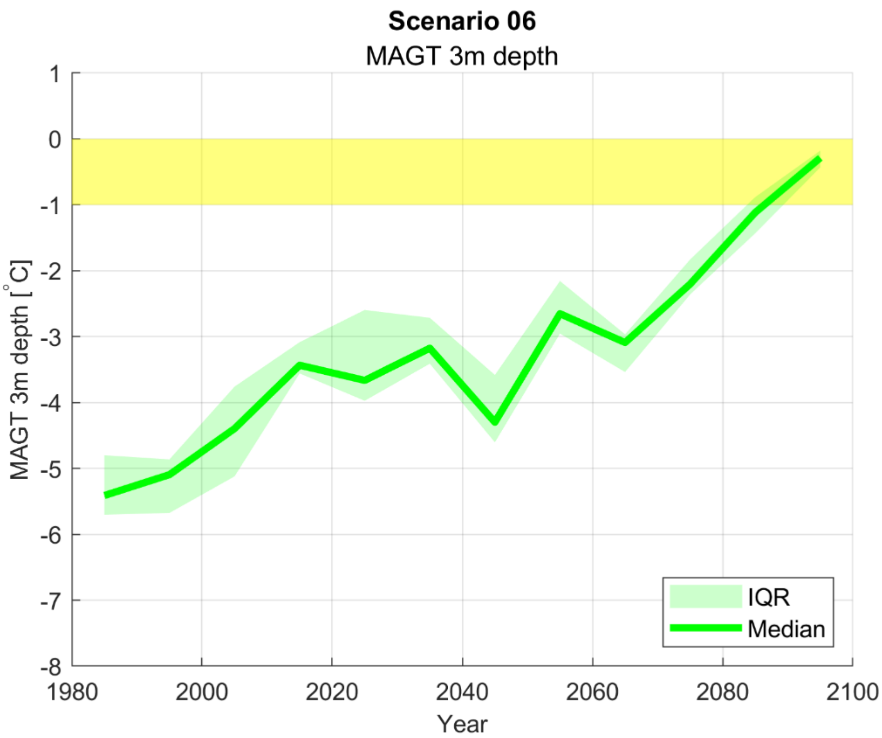

Figure A1 F-1. Adventdalen: MAGT in 3 m depth with median decadal values and decadal IQR for model scenario 06 (snowfall factor 0.5, organic layer, not drained).

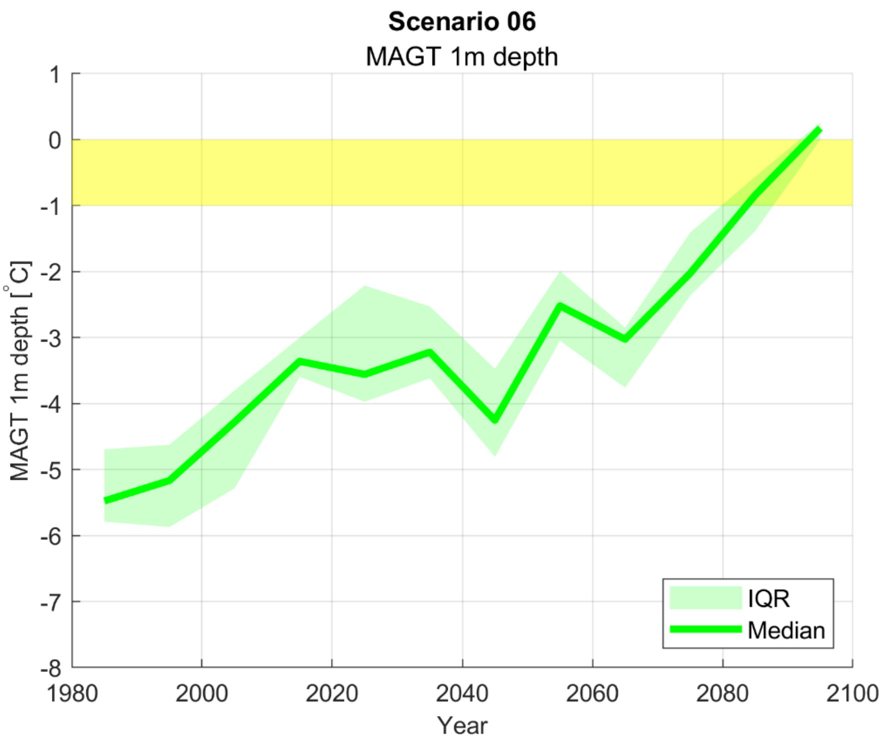

Figure A1 F-2. Adventdalen: MAGT in 1 m depth with median decadal values and decadal IQR for model scenario 06 (snowfall factor 0.5, organic layer, not drained).

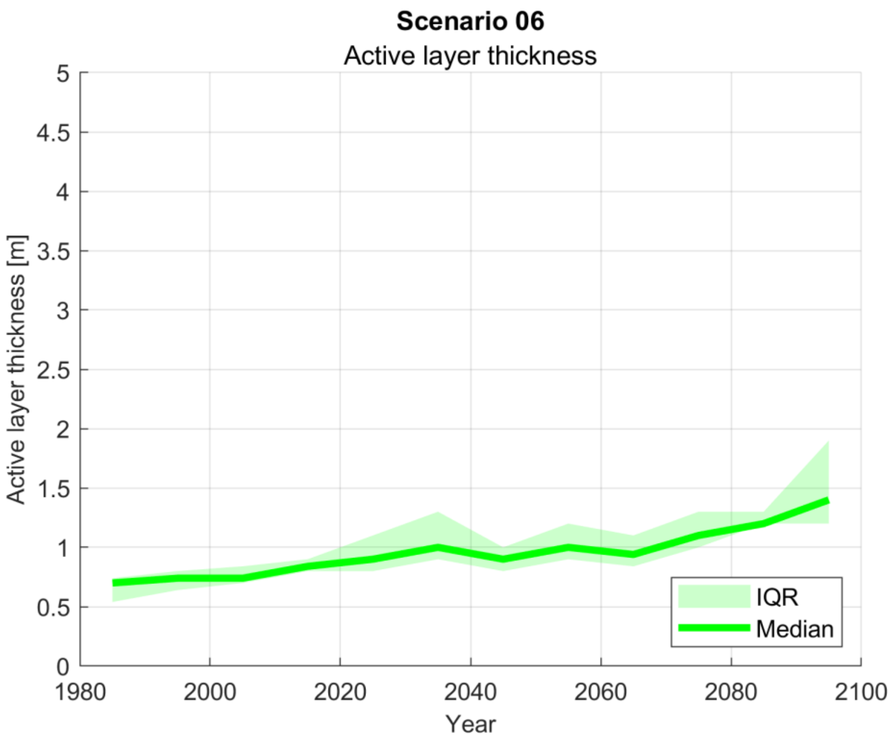

Figure A1 F-3. Adventdalen: ALT with median decadal values and decadal IQR for model scenario 06 (snowfall factor 0.5, organic layer, not drained).

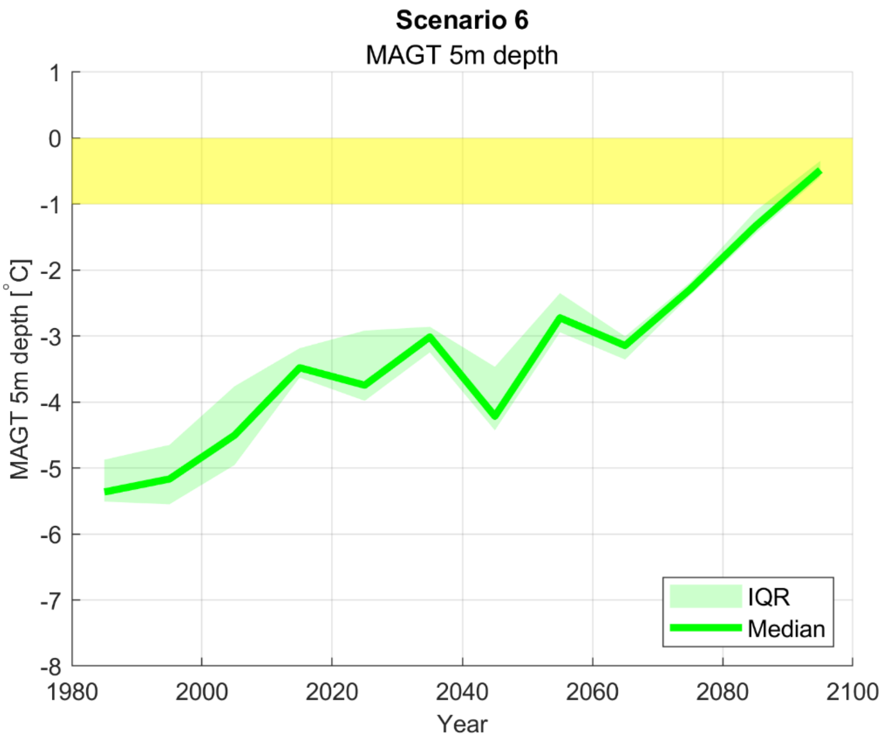

Figure A1 F-4. Adventdalen: MAGT in 5 m depth with median decadal values and decadal IQR for model scenario 06 (snowfall factor 0.5, organic layer, not drained).

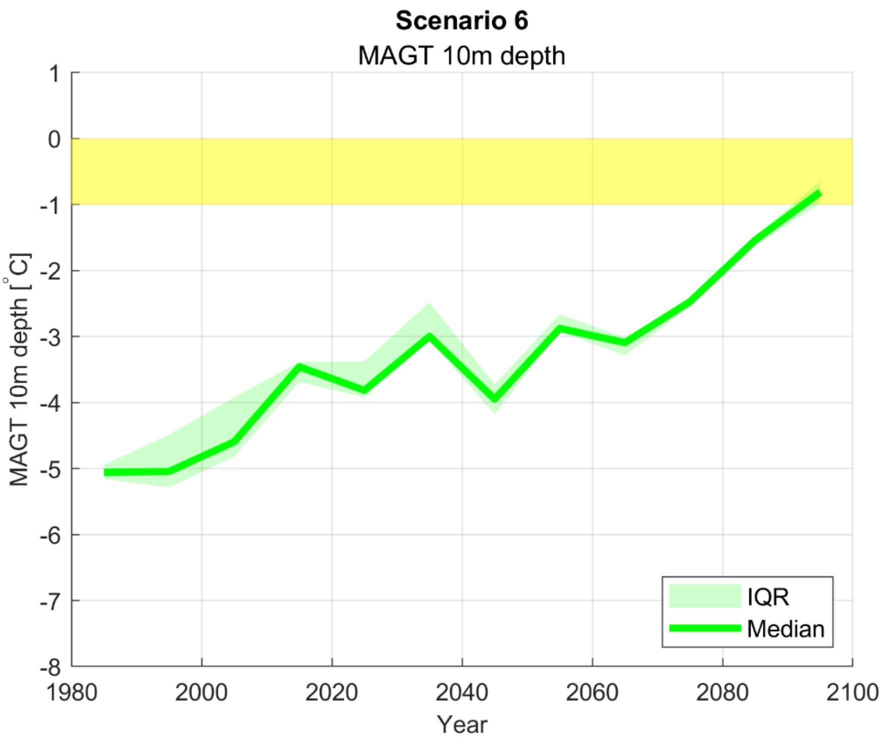

Figure A1 F-5. Adventdalen: MAGT in 10 m depth with median decadal values and decadal IQR for model scenario 06 (snowfall factor 0.5, organic layer, not drained).

Scenario 07: snowfall factor 1.0, blocky terrain, well drained

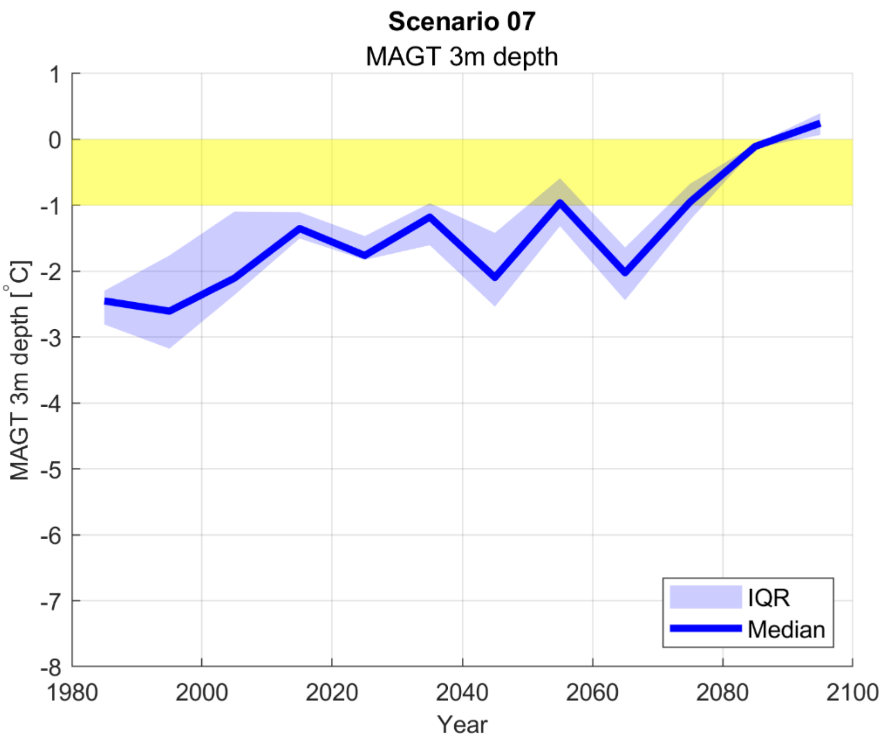

Figure A1 G-1. Adventdalen: MAGT in 3 m depth with median decadal values and decadal IQR for model scenario 07 (snowfall factor 1.0, blocky terrain, well drained).

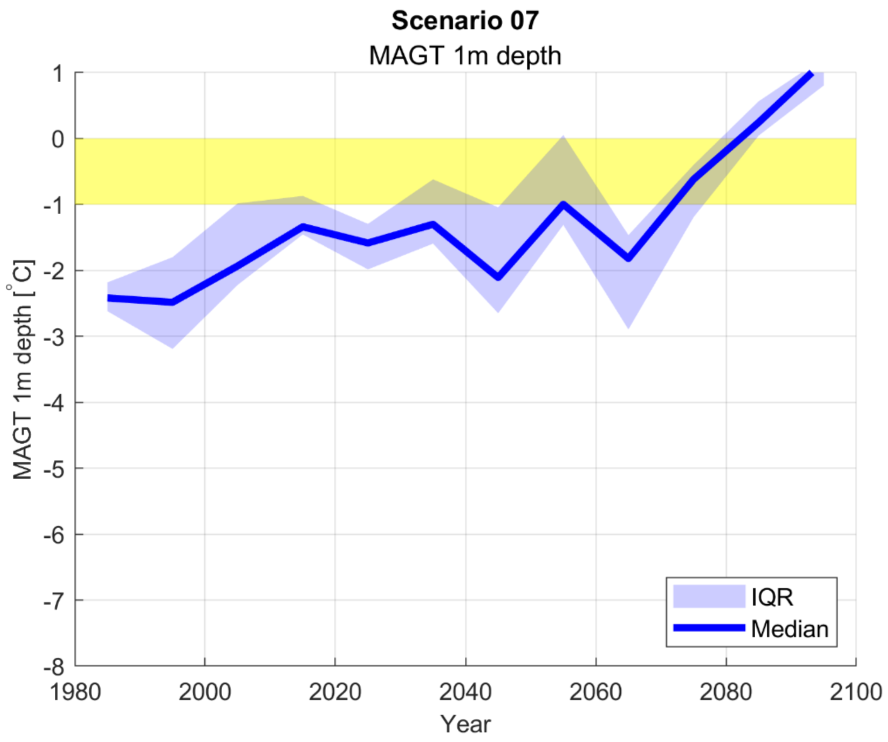

Figure A1 G-2. Adventdalen: MAGT in 1 m depth with median decadal values and decadal IQR for model scenario 07 (snowfall factor 1.0, blocky terrain, well drained).

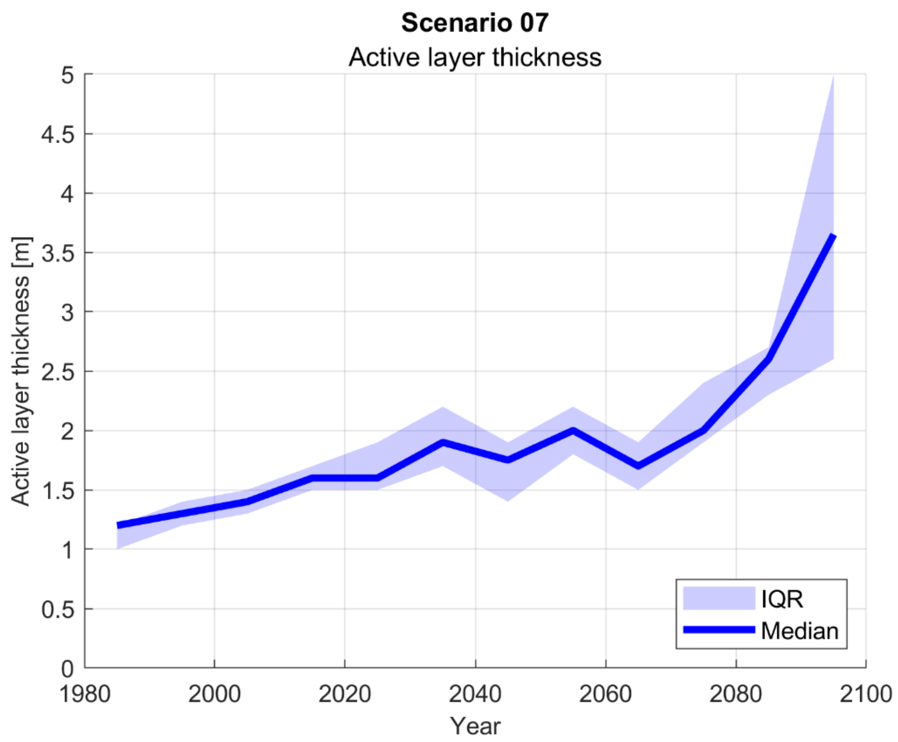

Figure A1 G-3. Adventdalen: ALT with median decadal values and decadal IQR for model scenario 07 (snowfall factor 1.0, blocky terrain, well drained).

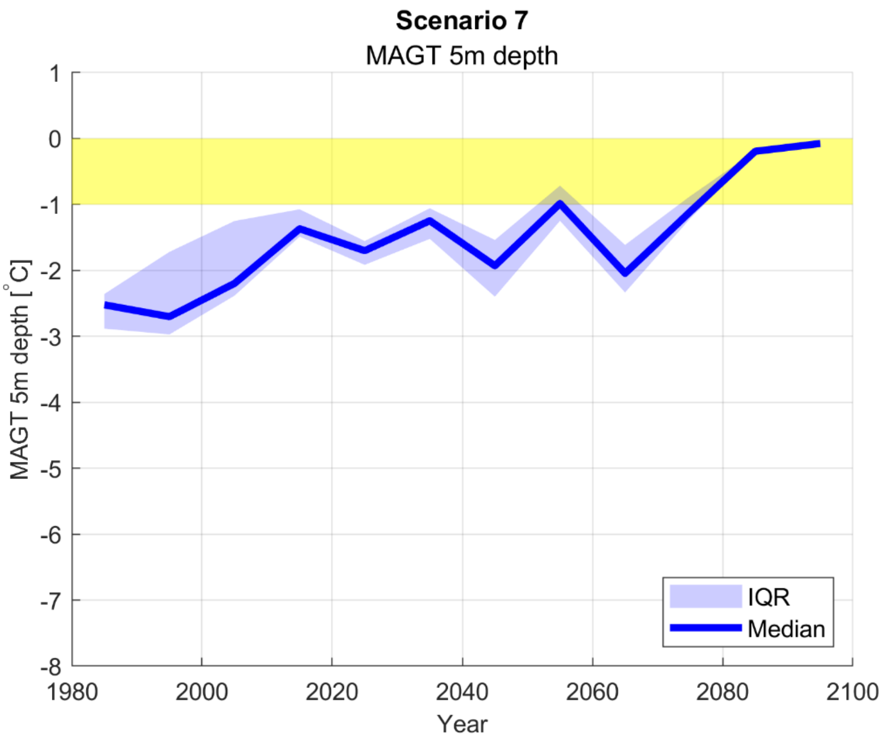

Figure A1 G-4. Adventdalen: MAGT in 5 m depth with median decadal values and decadal IQR for model scenario 07 (snowfall factor 1.0, blocky terrain, well drained).

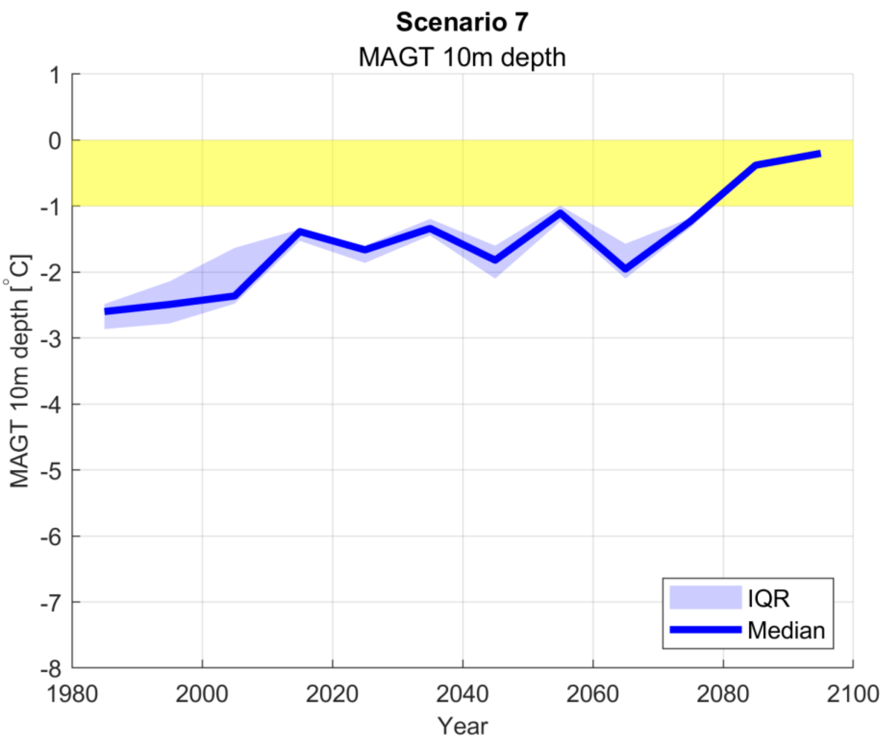

Figure A1 G-5. Adventdalen: MAGT in 10 m depth with median decadal values and decadal IQR for model scenario 07 (snowfall factor 1.0, blocky terrain, well drained).

Scenario 08: snowfall factor 1.0, silty soil, fairly drained

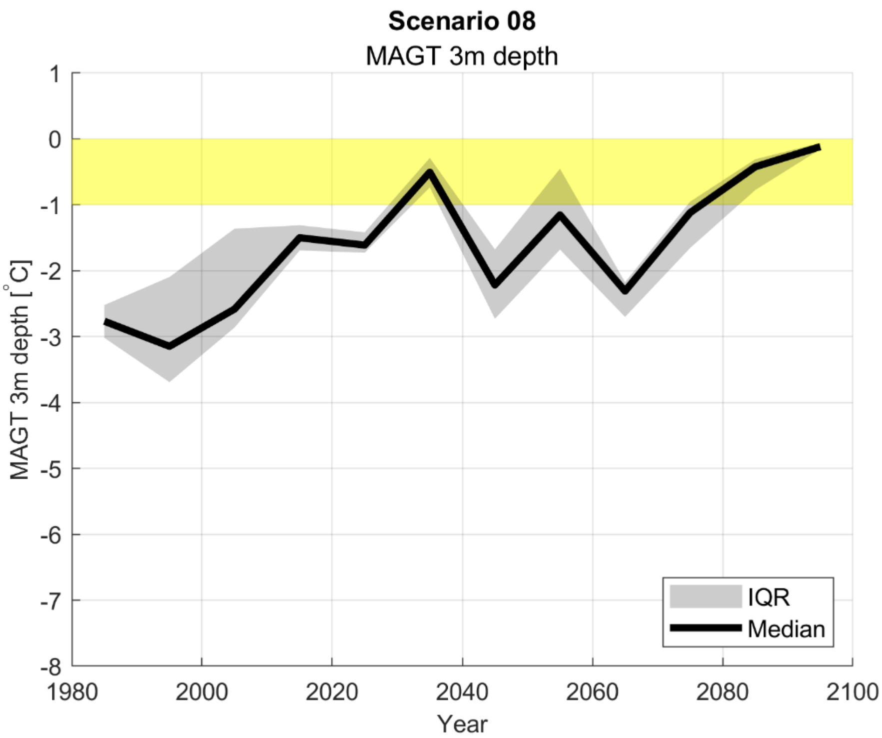

Figure A1 H-1. Adventdalen: MAGT in 3 m depth with median decadal values and decadal IQR for model scenario 08 (snowfall factor 1.0, silty soil, fairly drained).

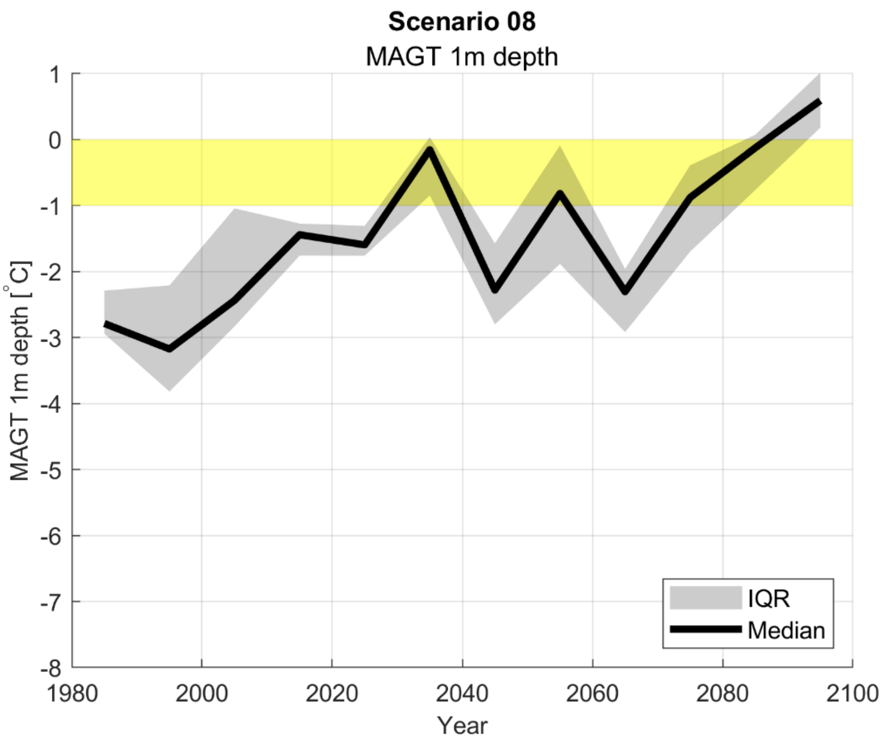

Figure A1 H-2. Adventdalen: MAGT in 1 m depth with median decadal values and decadal IQR for model scenario 08 (snowfall factor 1.0, silty soil, fairly drained).

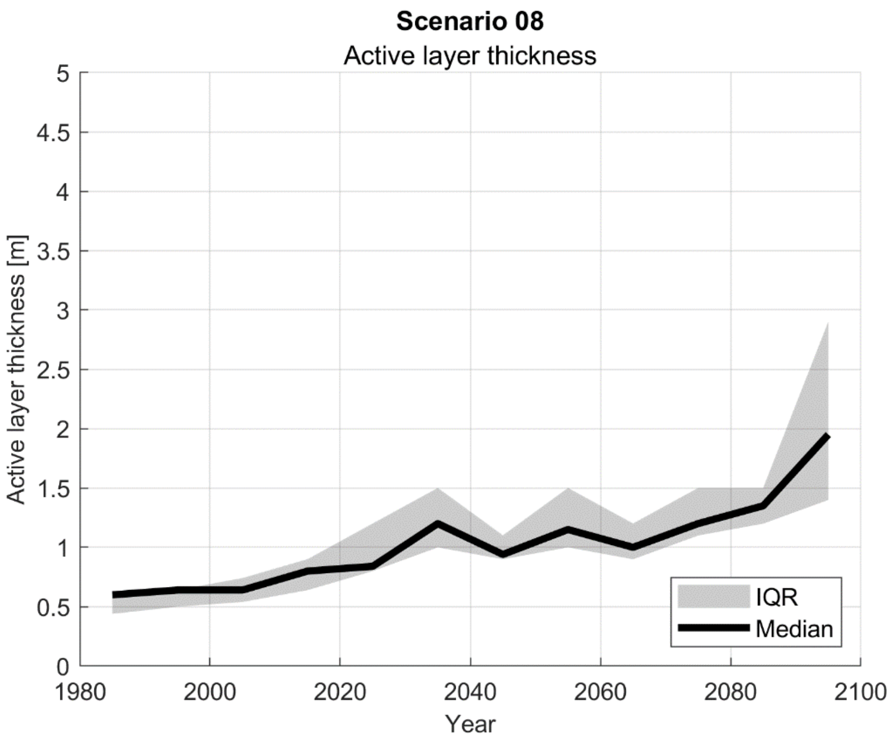

Figure A1 H-3. Adventdalen: ALT with median decadal values and decadal IQR for model scenario 08 (snowfall factor 1.0, silty soil, fairly drained).

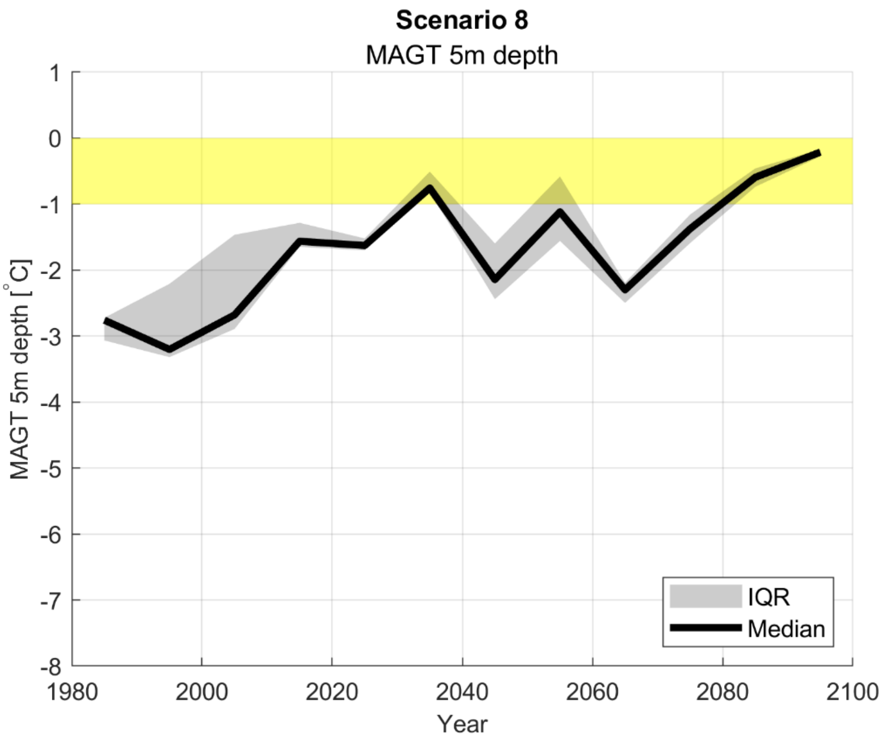

Figure A1 H-4. Adventdalen: MAGT in 5 m depth with median decadal values and decadal IQR for model scenario 08 (snowfall factor 1.0, silty soil, fairly drained).

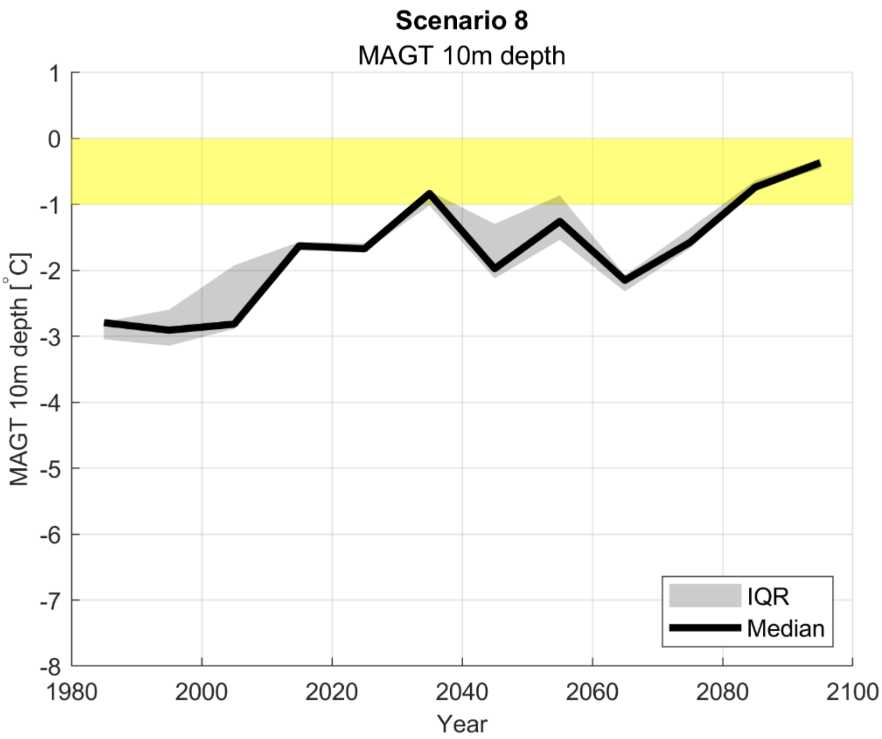

Figure A1 H-5. Adventdalen: MAGT in 10 m depth with median decadal values and decadal IQR for model scenario 08 (snowfall factor 1.0, silty soil, fairly drained).

Scenario 09: snowfall factor 1.0, organic layer, not drained

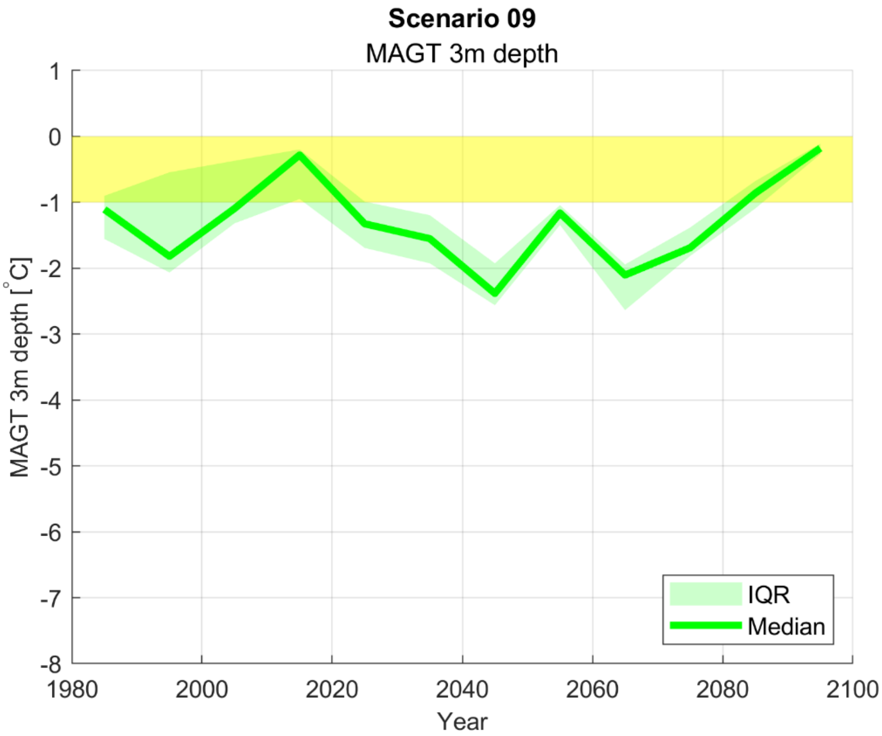

Figure A1 I-1. Adventdalen: MAGT in 3 m depth with median decadal values and decadal IQR for model scenario 09 (snowfall factor 1.0, organic layer, not drained).

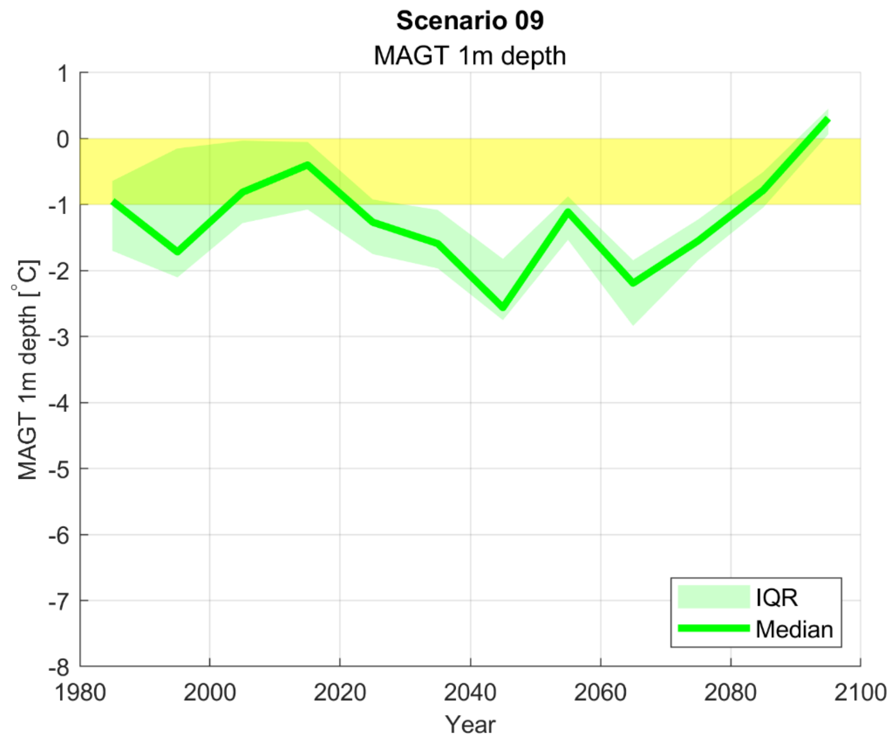

Figure A1 I-2. Adventdalen: MAGT in 1 m depth with median decadal values and decadal IQR for model scenario 09 (snowfall factor 1.0, organic layer, not drained).

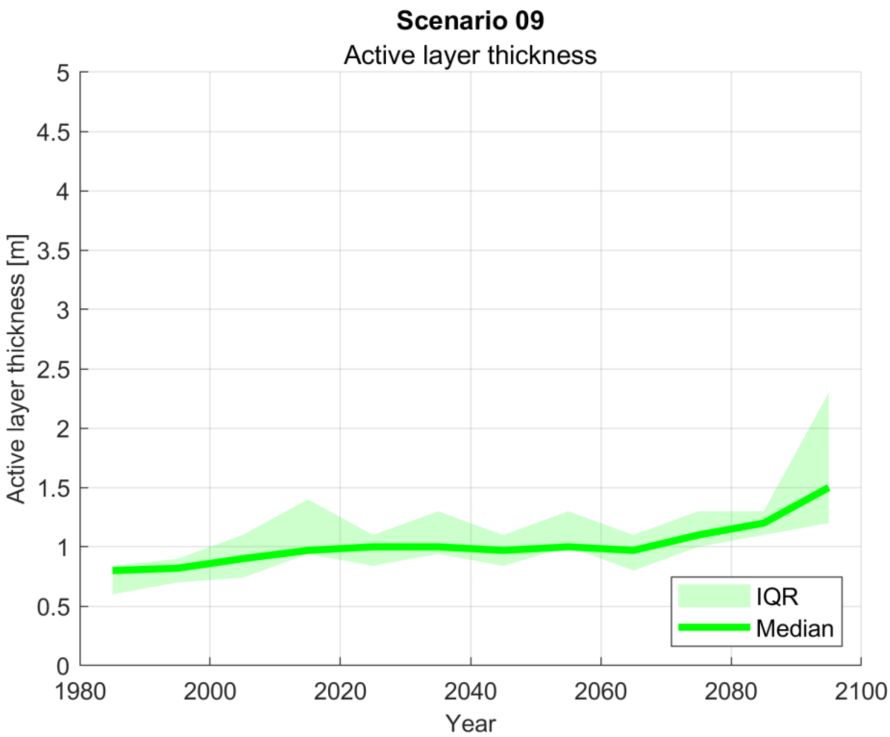

Figure A1 I-3. Adventdalen: ALT with median decadal values and decadal IQR for model scenario 09 (snowfall factor 1.0, organic layer, not drained).

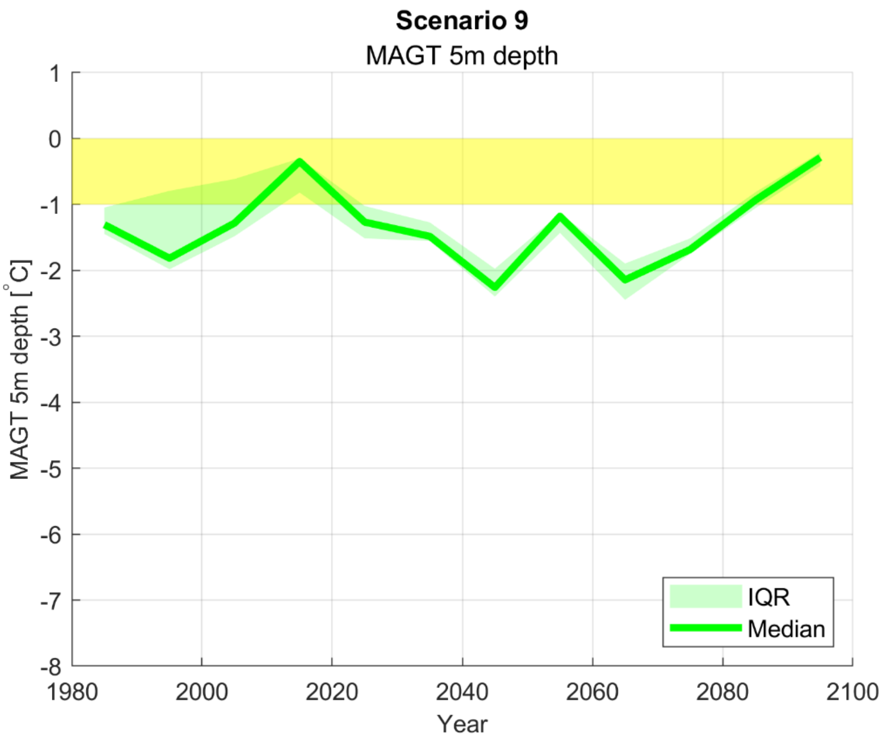

Figure A1 I-4. Adventdalen: MAGT in 5 m depth with median decadal values and decadal IQR for model scenario 09 (snowfall factor 1.0, organic layer, not drained).

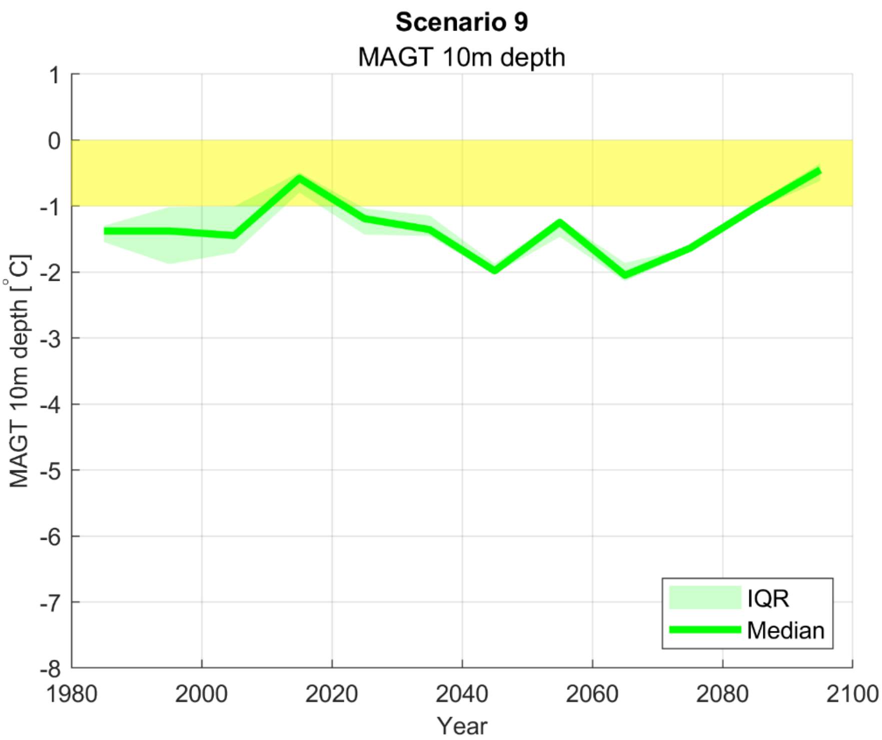

Figure A1 I-5. Adventdalen: MAGT in 10 m depth with median decadal values and decadal IQR for model scenario 09 (snowfall factor 1.0, organic layer, not drained).

Scenario 10: snowfall factor 1.5, blocky terrain, well drained

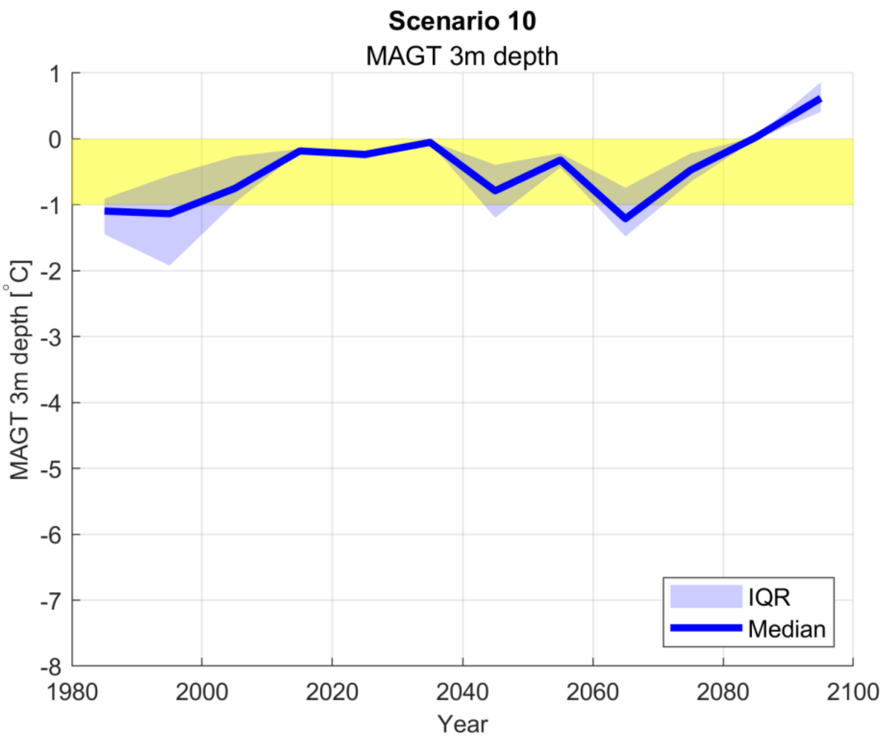

Figure A1 J-1. Adventdalen: MAGT in 3 m depth with median decadal values and decadal IQR for model scenario 10 (snowfall factor 1.5, blocky terrain, well drained).

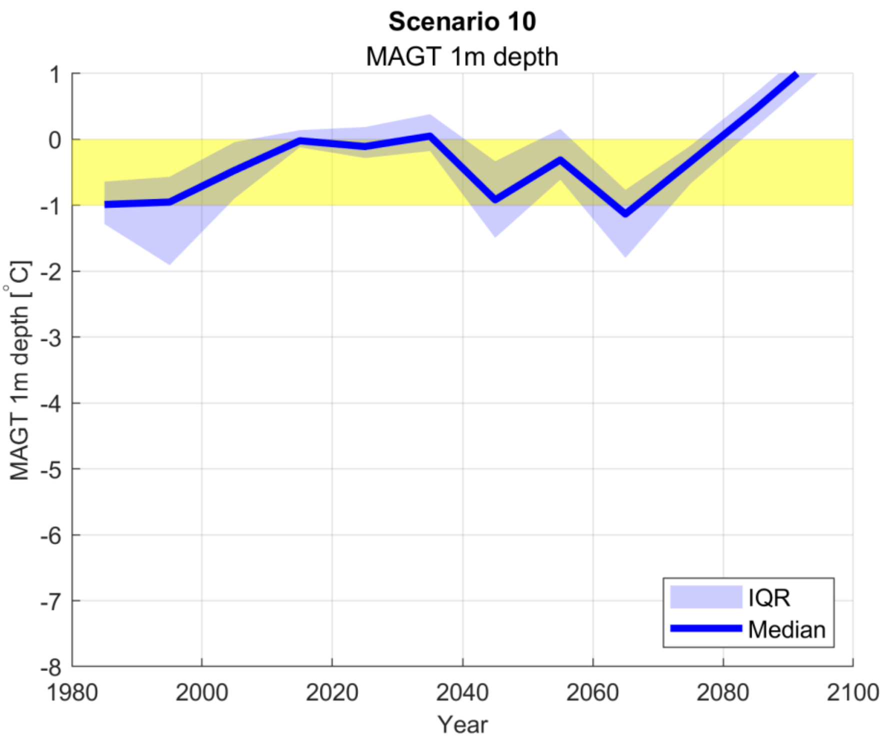

Figure A1 J-2. Adventdalen: MAGT in 1 m depth with median decadal values and decadal IQR for model scenario 10 (snowfall factor 1.5, blocky terrain, well drained).

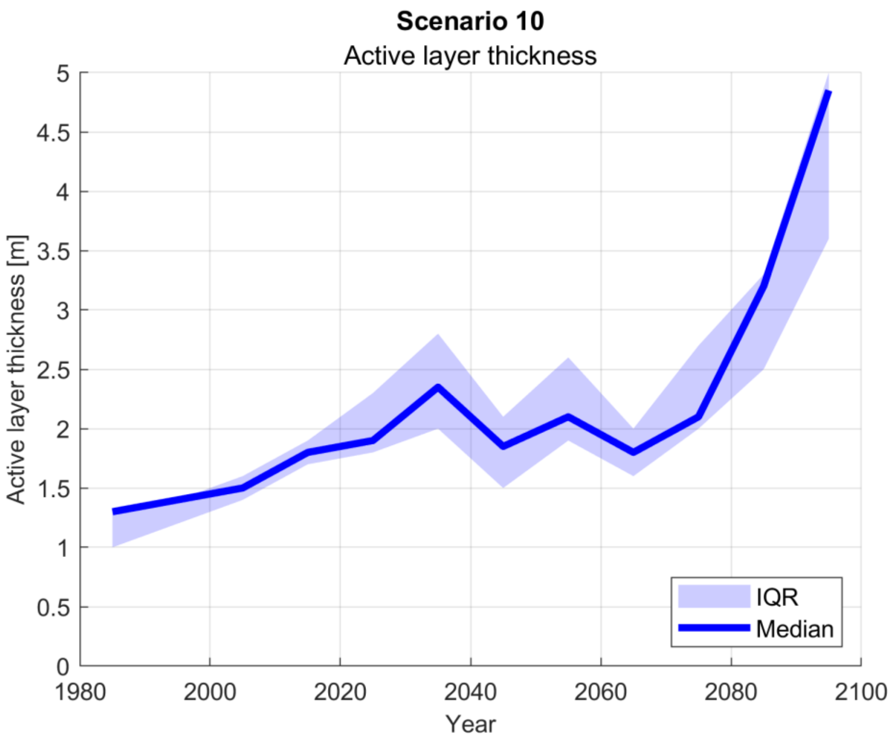

Figure A1 J-3. Adventdalen: ALT with median decadal values and decadal IQR for model scenario 10 (snowfall factor 1.5, blocky terrain, well drained).

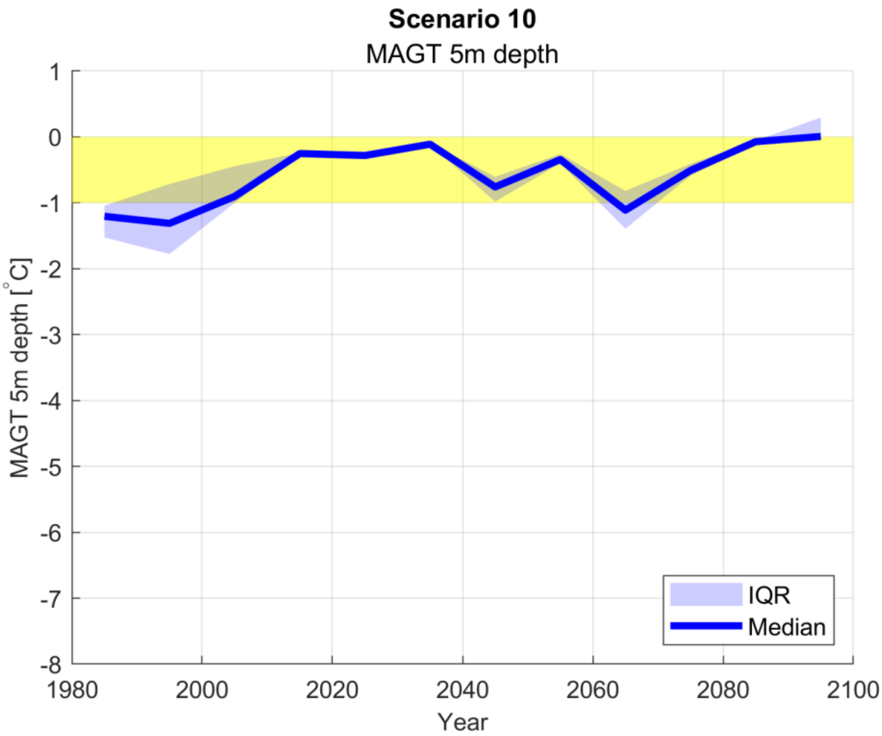

Figure A1 J-4. Adventdalen: MAGT in 5 m depth with median decadal values and decadal IQR for model scenario 10 (snowfall factor 1.5, blocky terrain, well drained).

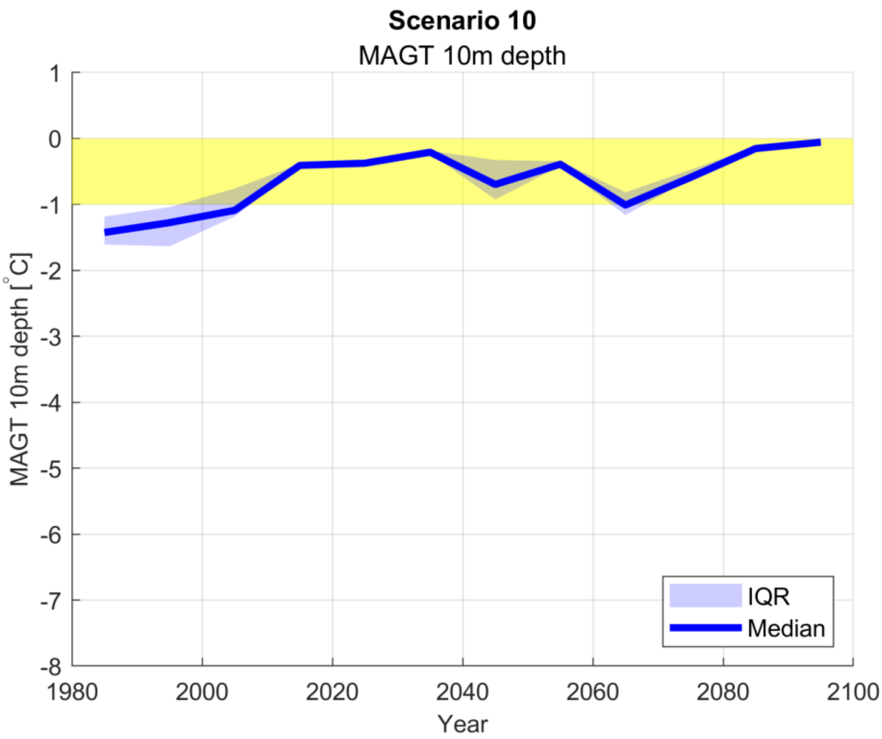

Figure A1 J-5. Adventdalen: MAGT in 10 m depth with median decadal values and decadal IQR for model scenario 10 (snowfall factor 1.5, blocky terrain, well drained).

Scenario 11: snowfall factor 1.5, silty soil, fairly drained

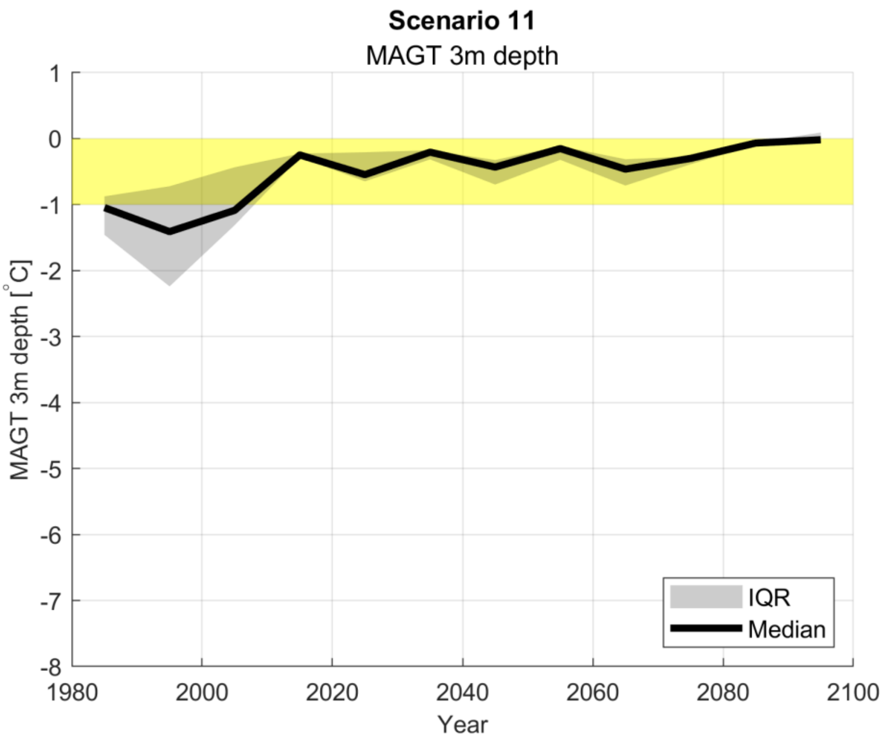

Figure A1 K-1. Adventdalen: MAGT in 3 m depth with median decadal values and decadal IQR for model scenario 11 (snowfall factor 1.5, silty soil, fairly drained).

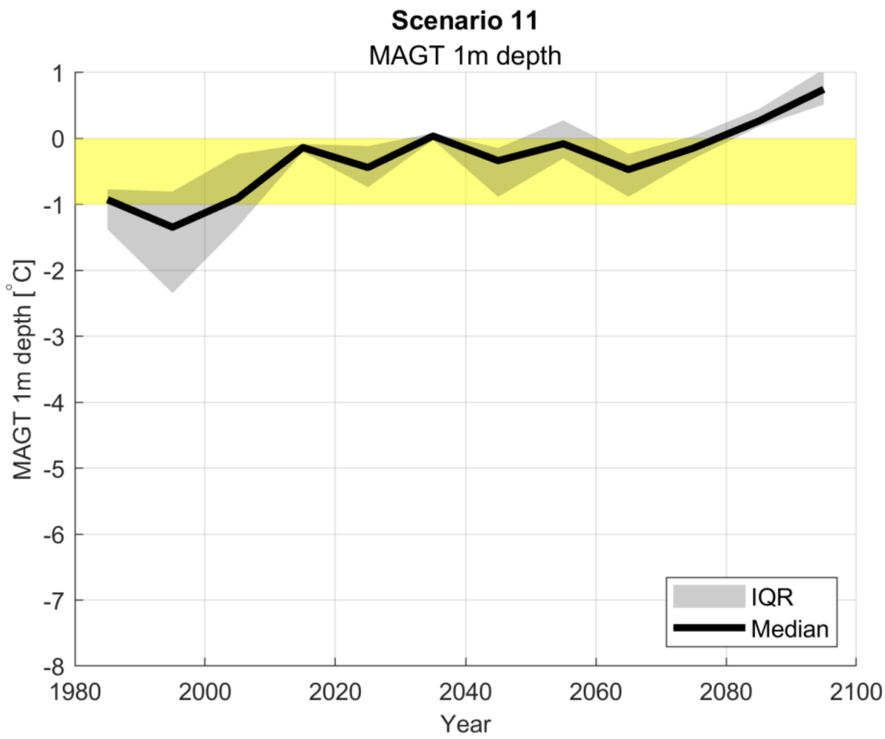

Figure A1 K-2. Adventdalen: MAGT in 1 m depth with median decadal values and decadal IQR for model scenario 11 (snowfall factor 1.5, silty soil, fairly drained).

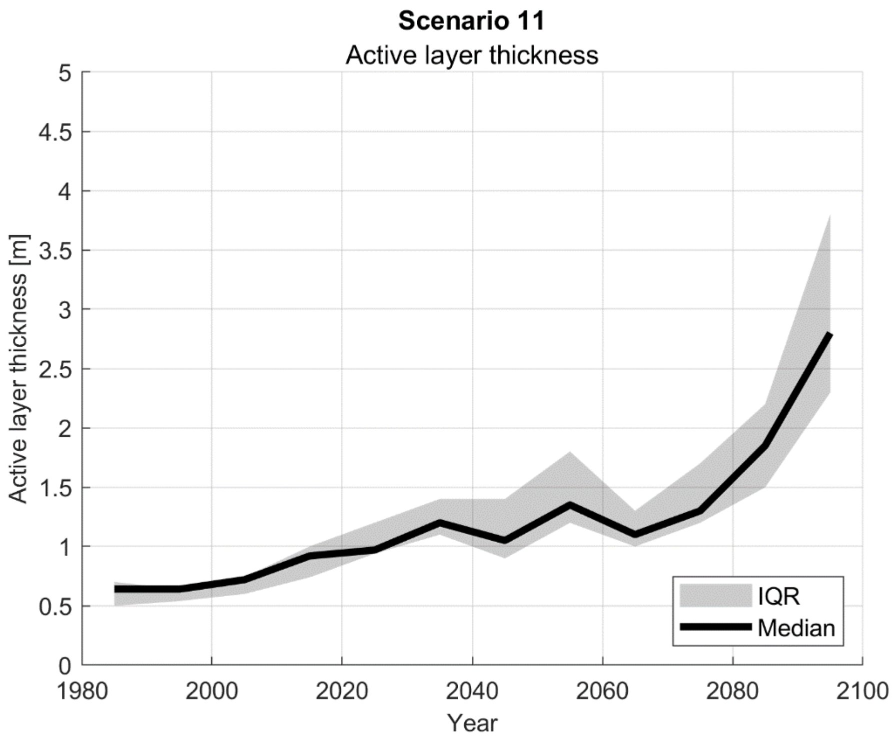

Figure A1 K-3. Adventdalen: ALT with median decadal values and decadal IQR for model scenario 11 (snowfall factor 1.5, silty soil, fairly drained).

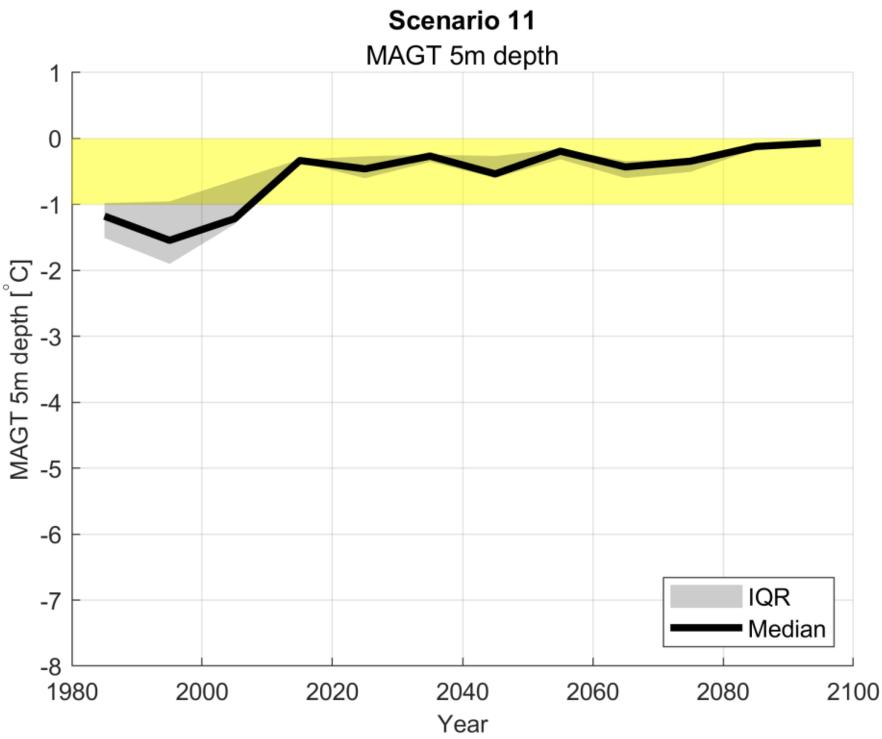

Figure A1 K-4. Adventdalen: MAGT in 5 m depth with median decadal values and decadal IQR for model scenario 11 (snowfall factor 1.5, silty soil, fairly drained).

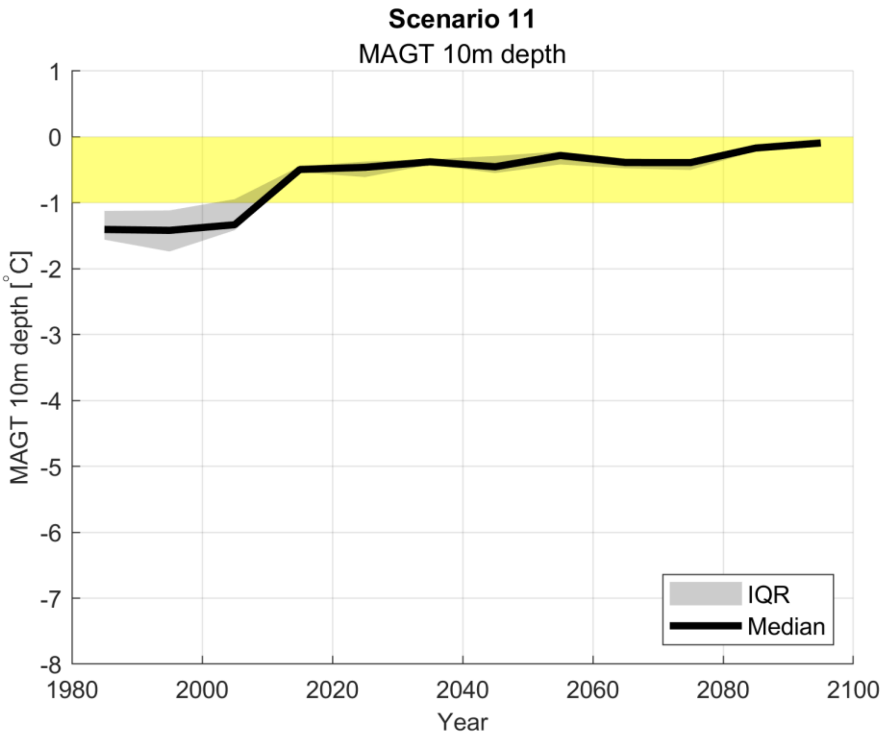

Figure A1 K-5. Adventdalen: MAGT in 10 m depth with median decadal values and decadal IQR for model scenario 11 (snowfall factor 1.5, silty soil, fairly drained).

Scenario 12: snowfall factor 1.5, organic layer, not drained

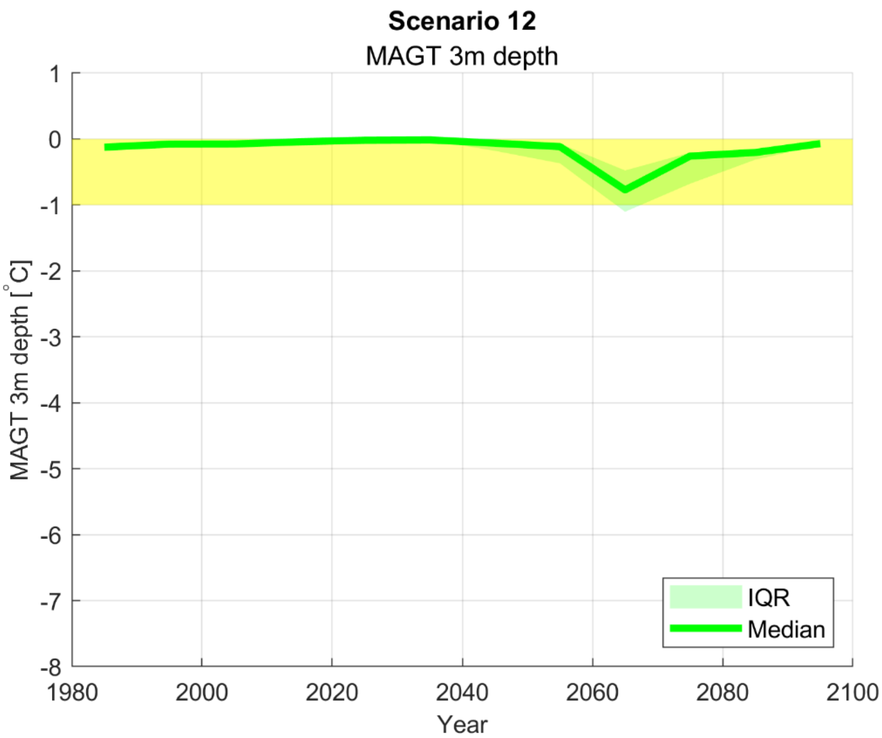

Figure A1 L-1. Adventdalen: MAGT in 3 m depth with median decadal values and decadal IQR for model scenario 12 (snowfall factor 1.5, organic layer, not drained).

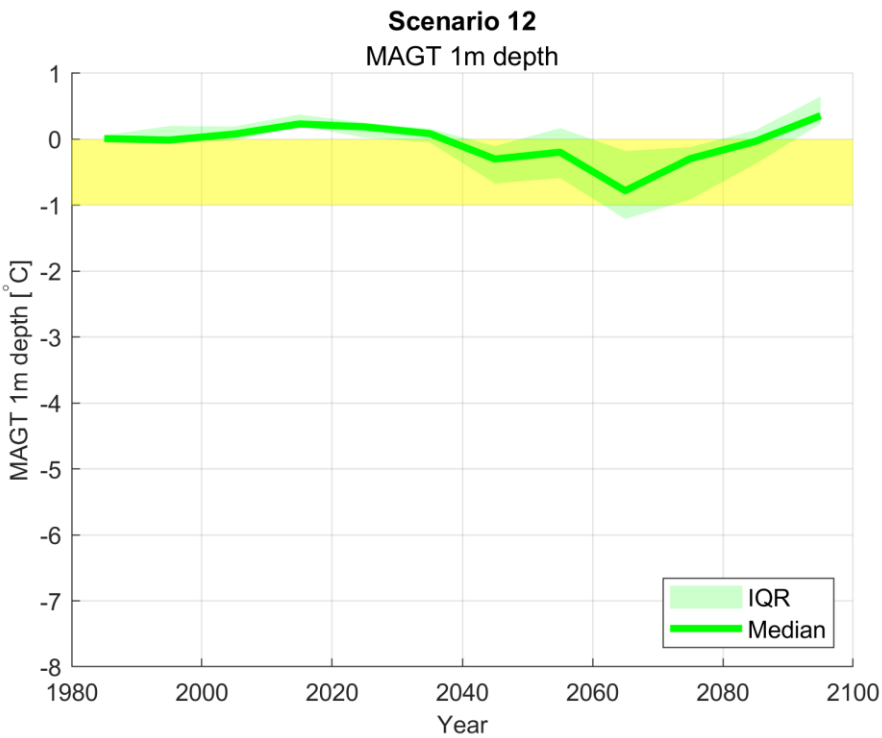

Figure A1 L-2. Adventdalen: MAGT in 1 m depth with median decadal values and decadal IQR for model scenario 12 (snowfall factor 1.5, organic layer, not drained).

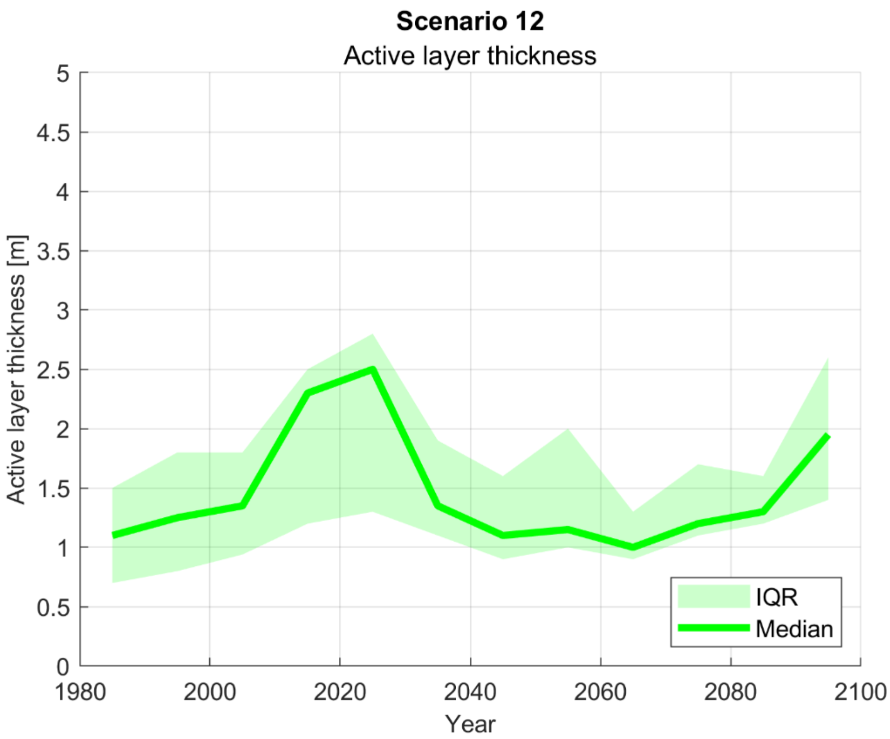

Figure A1 L-3. Adventdalen: ALT with median decadal values and decadal IQR for model scenario 12 (snowfall factor 1.5, organic layer, not drained).

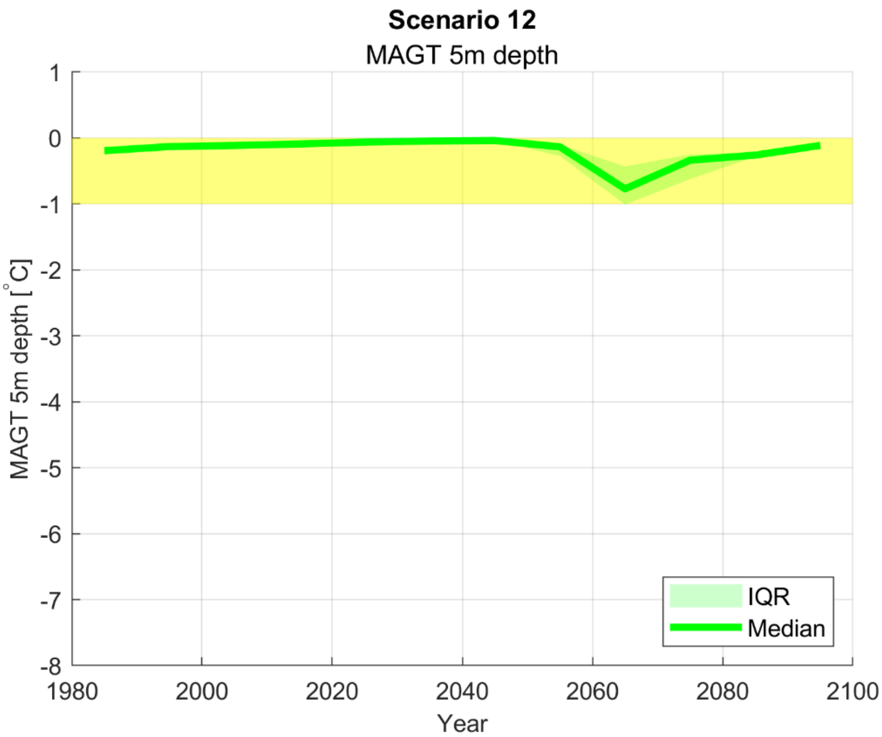

Figure A1 L-4. Adventdalen: MAGT in 5 m depth with median decadal values and decadal IQR for model scenario 12 (snowfall factor 1.5, organic layer, not drained).

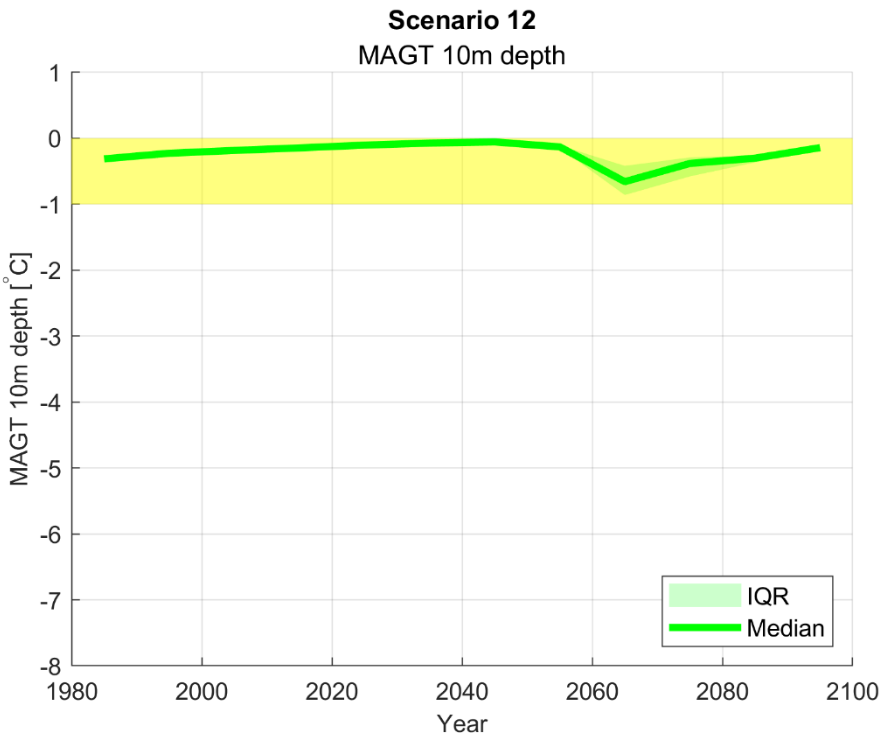

Figure A1 L-5. Adventdalen: MAGT in 10 m depth with median decadal values and decadal IQR for model scenario 12 (snowfall factor 1.5, organic layer, not drained).

Appendix 2. Data for Ny-Ålesund

Scenario 13: snowfall factor 0.5, silty soil, fairly drained

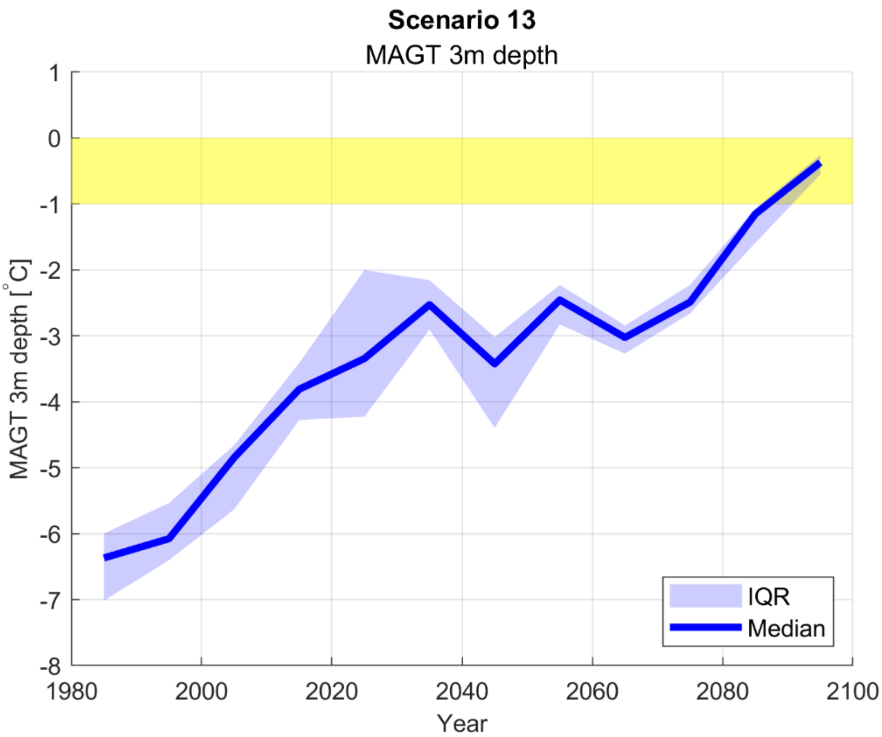

Figure A2 A-5. Ny-Ålesund: MAGT in 3 m depth with median decadal values and decadal IQR for model scenario 13 (snowfall factor 0.5, silty soil, fairly drained).

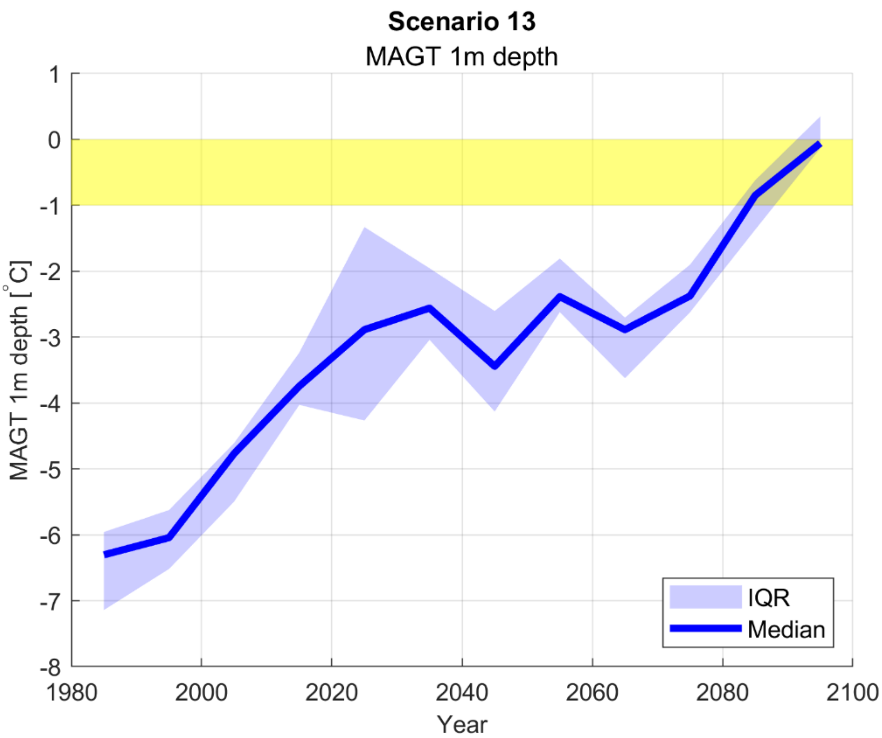

Figure A2 A-2. Ny-Ålesund: MAGT in 1 m depth with median decadal values and decadal IQR for model scenario 13 (snowfall factor 0.5, silty soil, fairly drained).

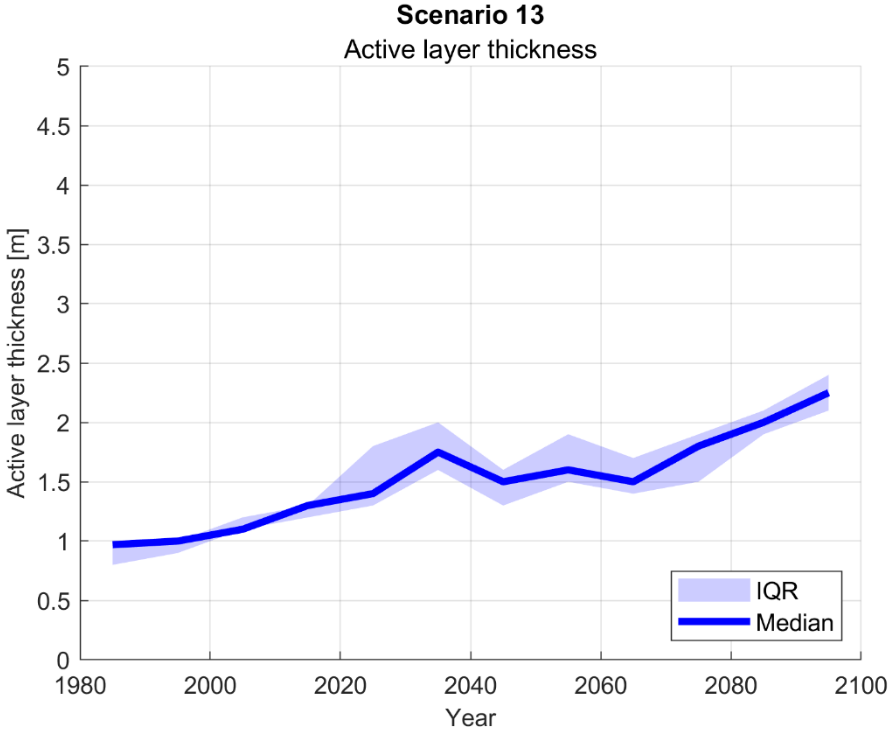

Figure A2 A-3. Ny-Ålesund: ALT with median decadal values and decadal IQR for model scenario 13 (snowfall factor 0.5, silty soil, fairly drained).

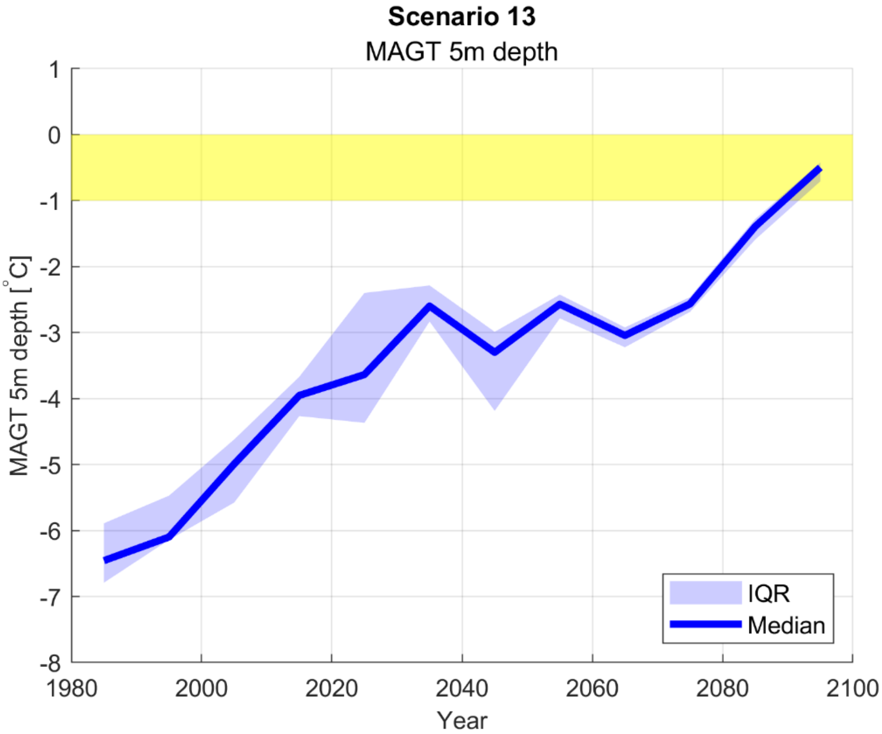

Figure A2 A-4. Ny-Ålesund: MAGT in 5 m depth with median decadal values and decadal IQR for model scenario 13 (snowfall factor 0.5, silty soil, fairly drained).

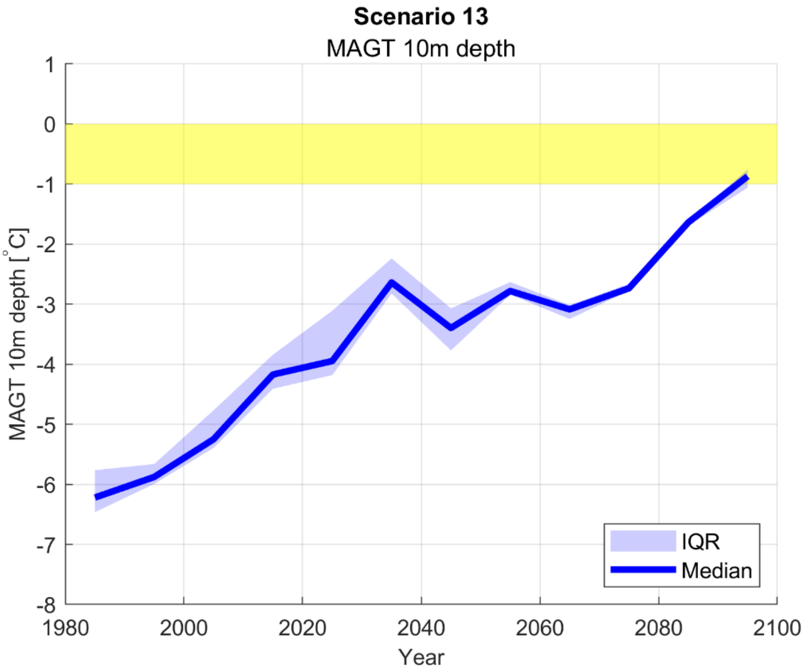

Figure A2 A-5. Ny-Ålesund: MAGT in 10 m depth with median decadal values and decadal IQR for model scenario 13 (snowfall factor 0.5, silty soil, fairly drained).

Scenario 14: snowfall factor 0.5, silty soil, fairly drained

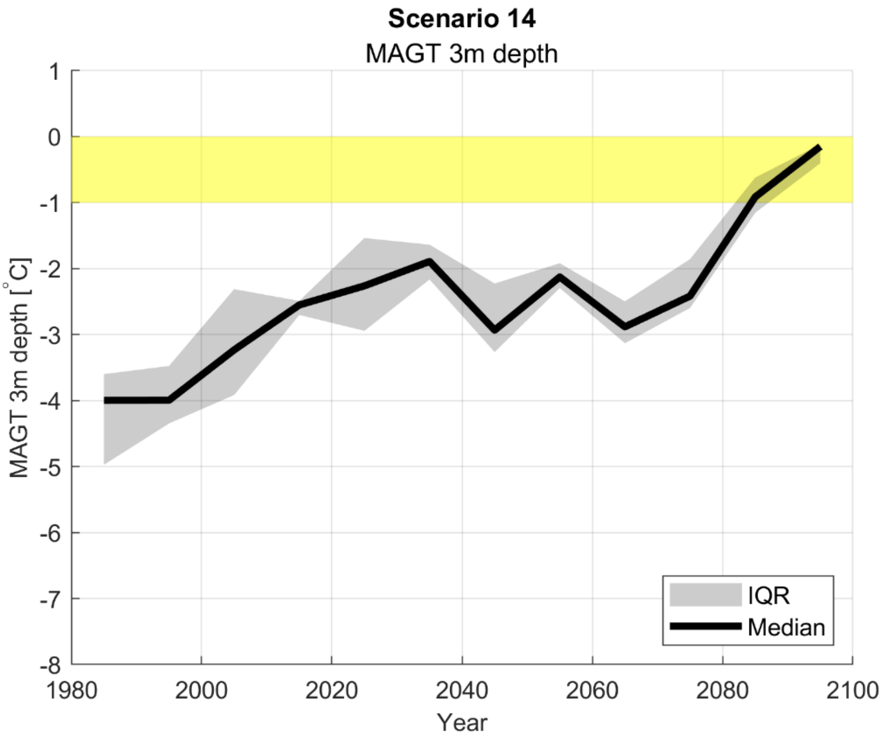

Figure A2 B-1. Ny-Ålesund: MAGT in 3 m depth with median decadal values and decadal IQR for model scenario 14 (snowfall factor 1.0, silty soil, fairly drained).

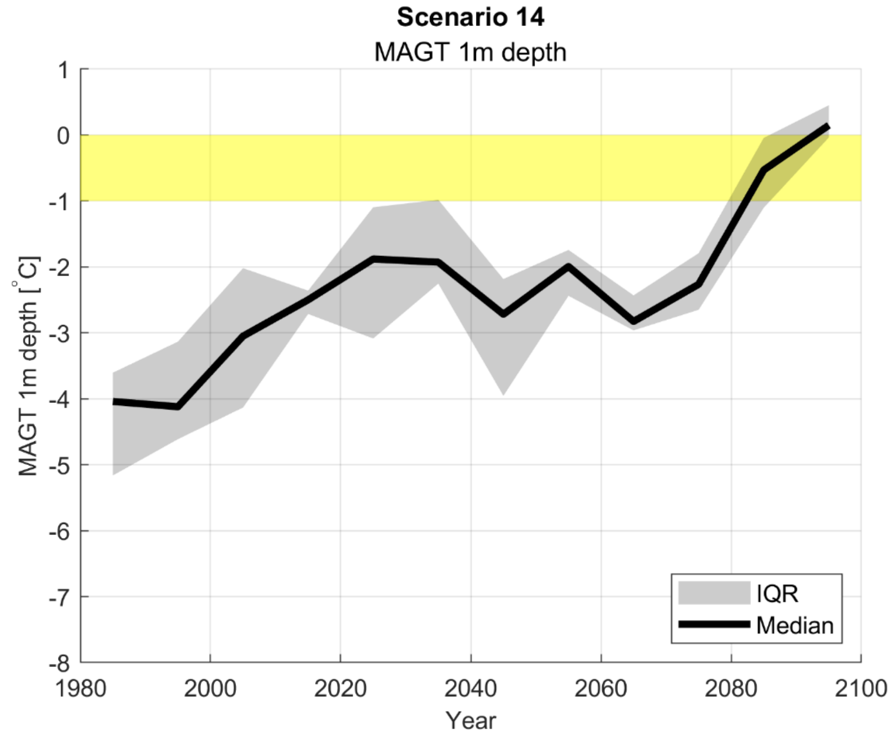

Figure A2 B-2. Ny-Ålesund: MAGT in 1 m depth with median decadal values and decadal IQR for model scenario 14 (snowfall factor 1.0, silty soil, fairly drained).

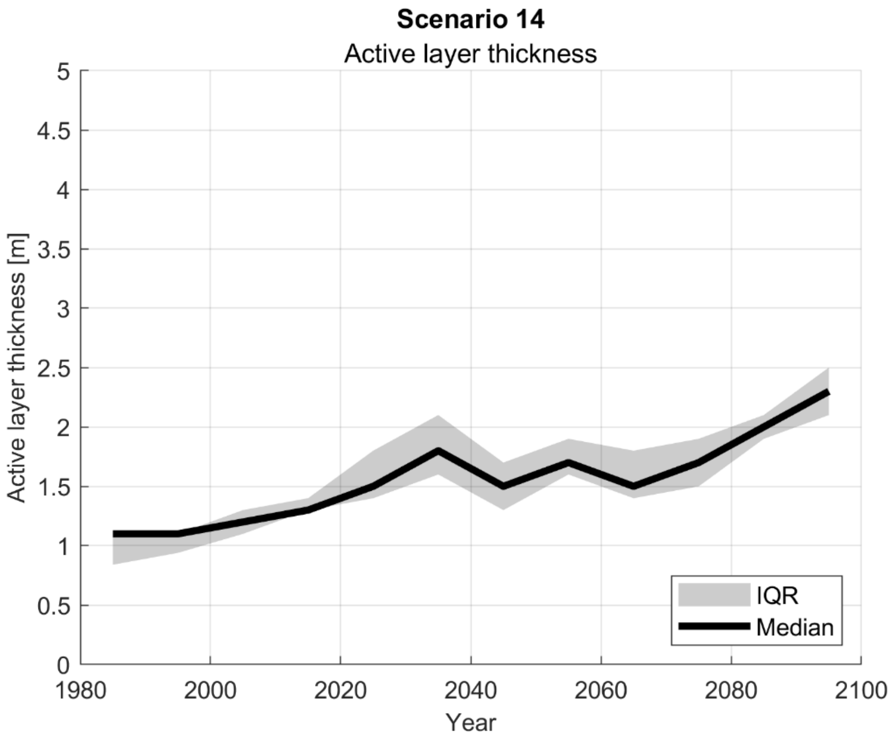

Figure A2 B-3. Ny-Ålesund: ALT with median decadal values and decadal IQR for model scenario 14 (snowfall factor 1.0, silty soil, fairly drained).

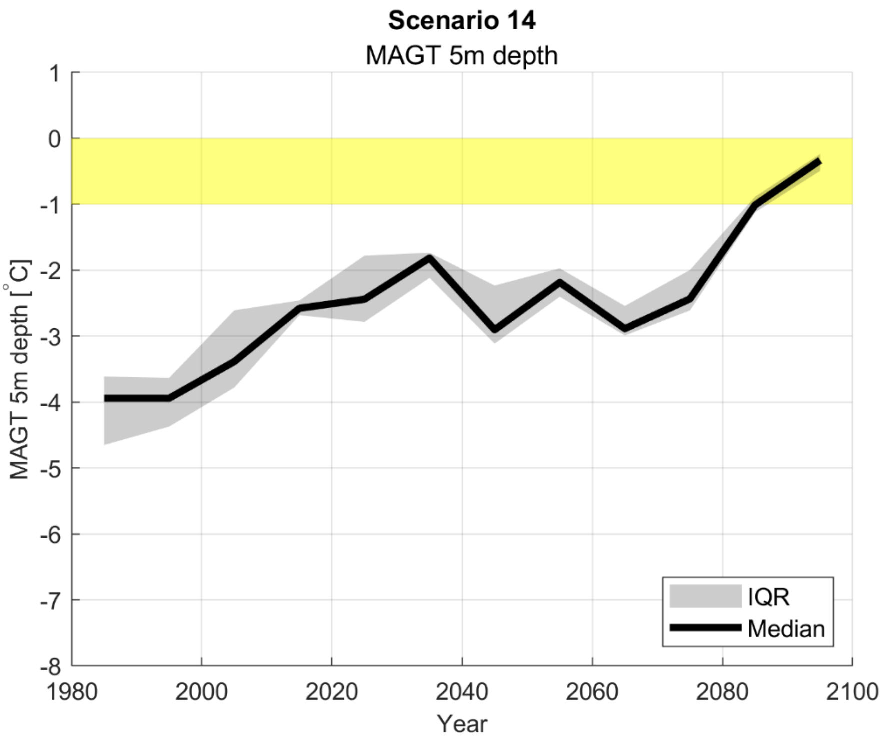

Figure A2 B-4. Ny-Ålesund: MAGT in 5 m depth with median decadal values and decadal IQR for model scenario 14 (snowfall factor 1.0, silty soil, fairly drained).

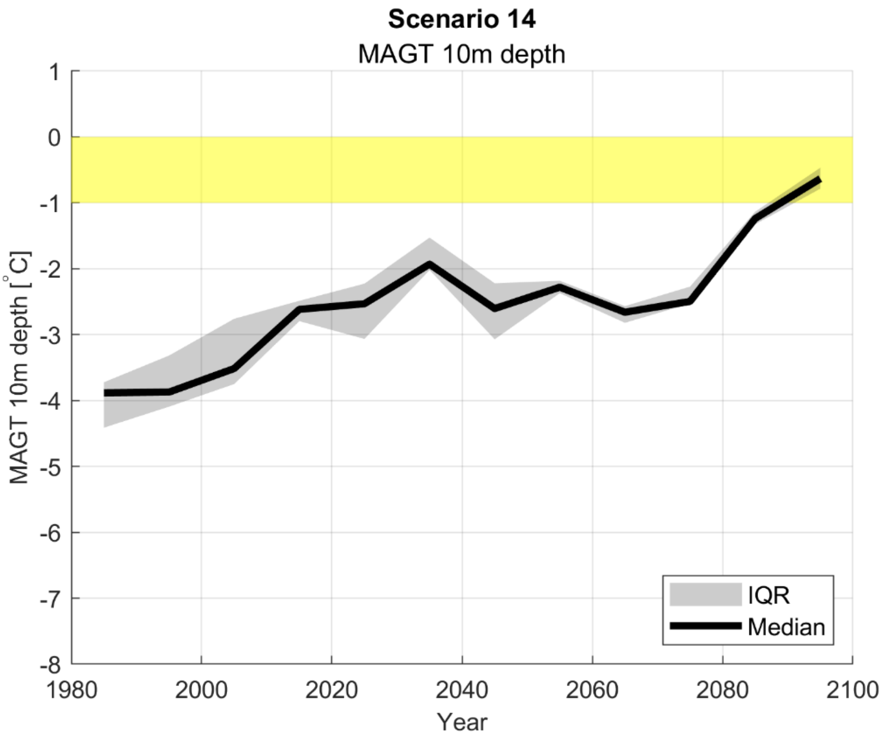

Figure A2 B-5. Ny-Ålesund: MAGT in 10 m depth with median decadal values and decadal IQR for model scenario 14 (snowfall factor 1.0, silty soil, fairly drained).

Scenario 15: snowfall factor 1.5, silty soil, fairly drained

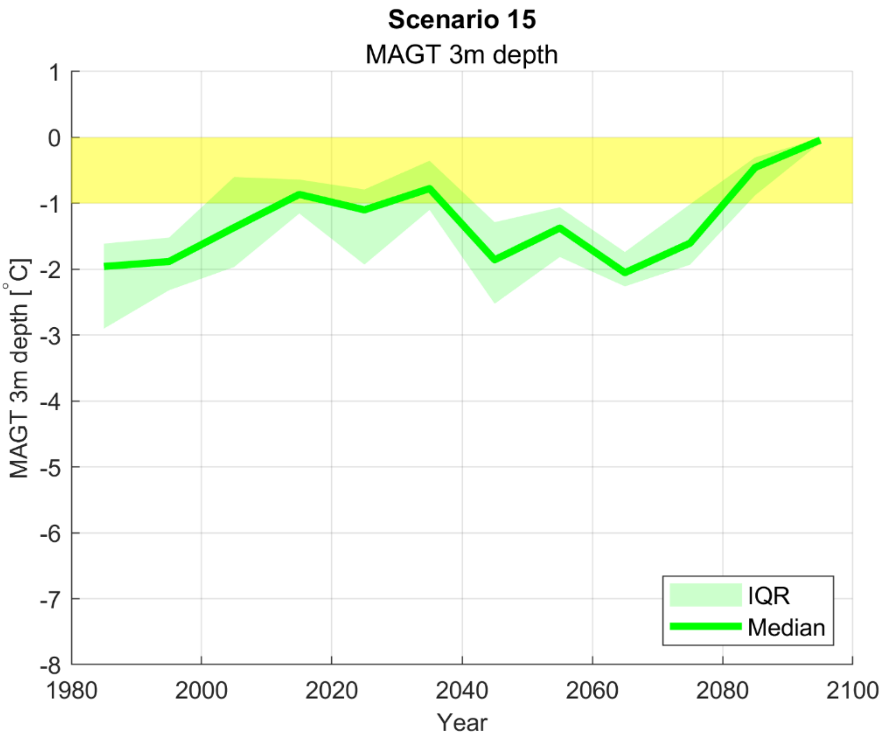

Figure A2 C-1. Ny-Ålesund: MAGT in 3 m depth with median decadal values and decadal IQR for model scenario 15 (snowfall factor 1.5, silty soil, fairly drained).

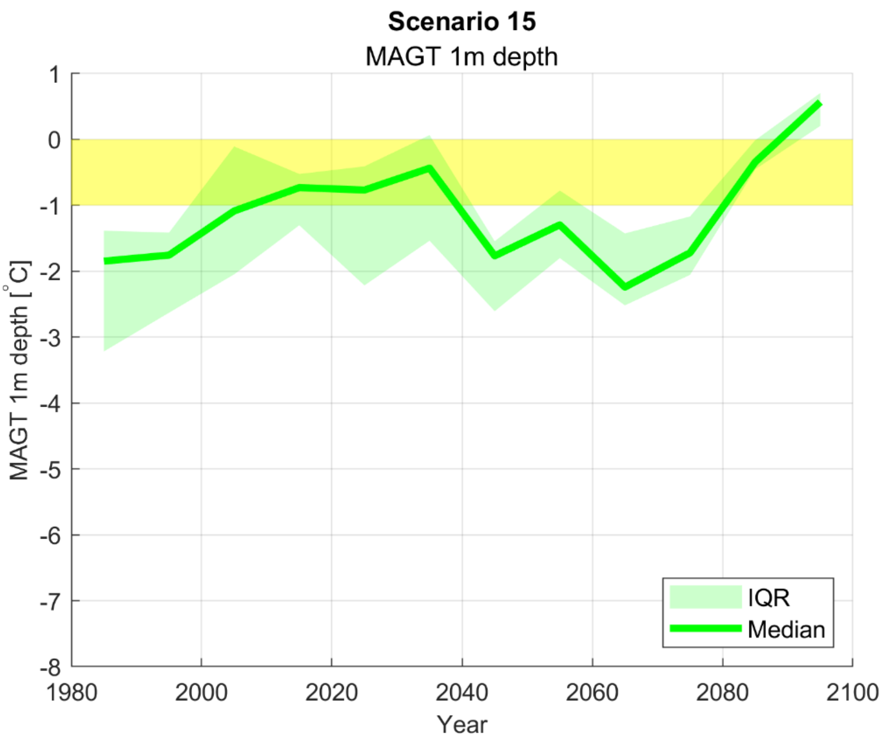

Figure A2 C-2. Ny-Ålesund: MAGT in 1 m depth with median decadal values and decadal IQR for model scenario 15 (snowfall factor 1.5, silty soil, fairly drained).

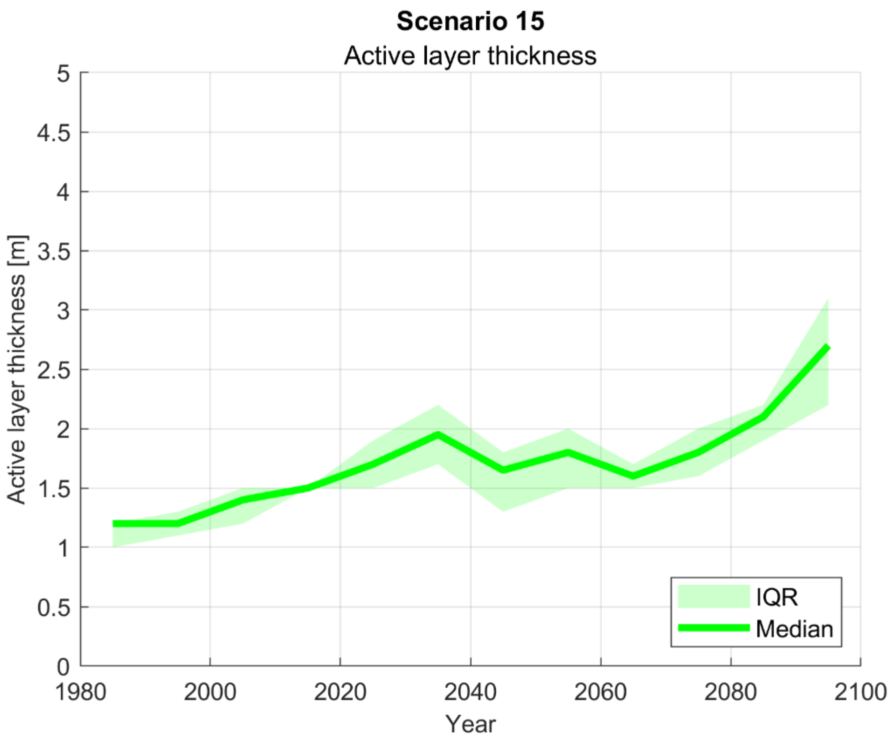

Figure A2 C-3. Ny-Ålesund: ALT with median decadal values and decadal IQR for model scenario 15 (snowfall factor 1.5, silty soil, fairly drained).

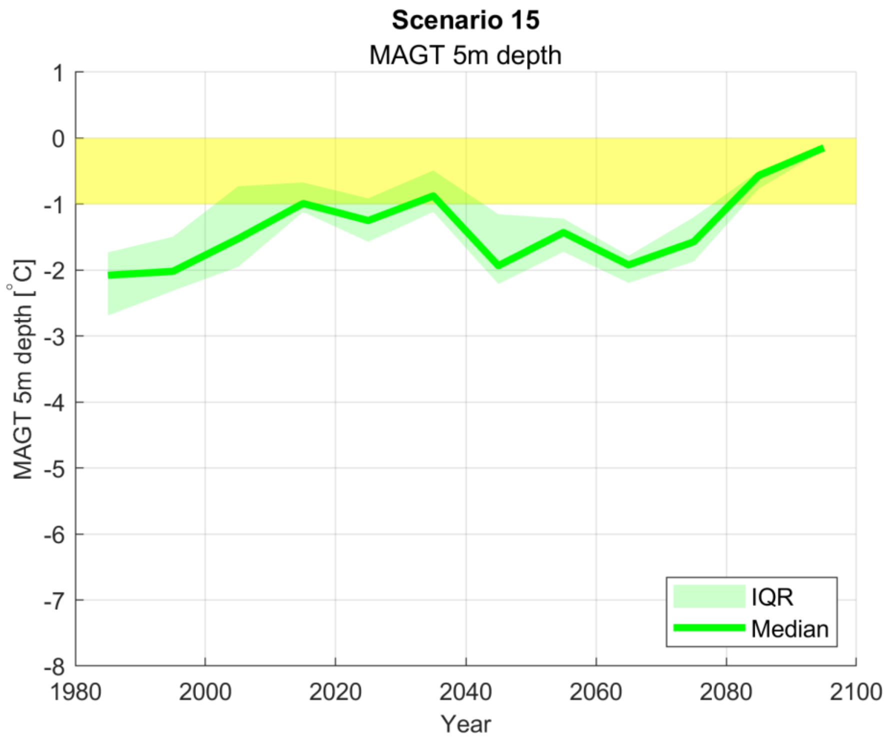

Figure A2 C-4. Ny-Ålesund: MAGT in 5 m depth with median decadal values and decadal IQR for model scenario 15 (snowfall factor 1.5, silty soil, fairly drained).

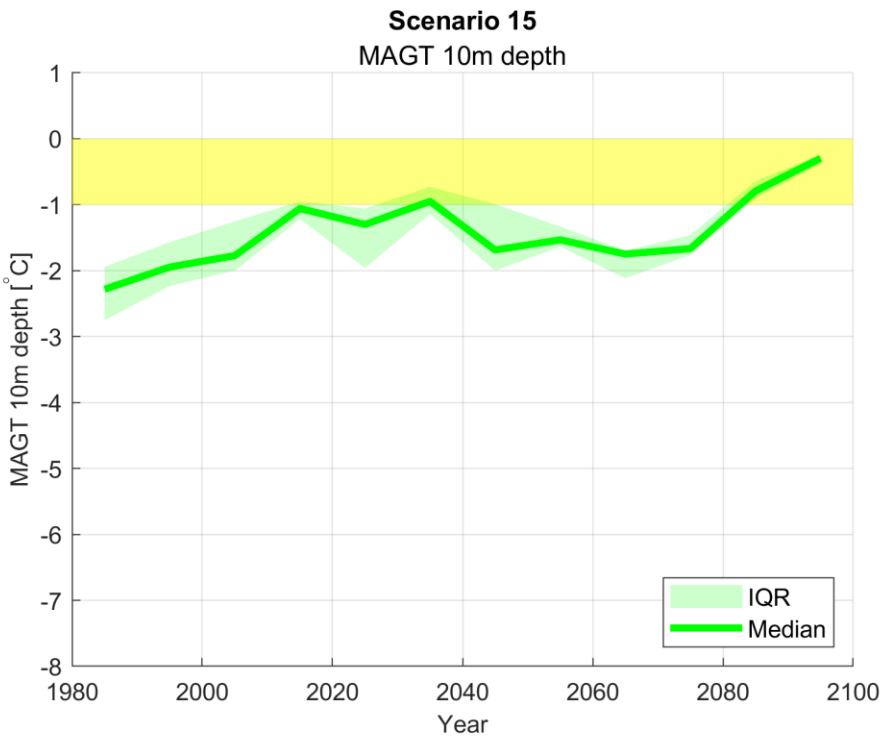

Figure A2 C-5. Ny-Ålesund: MAGT in 10 m depth with median decadal values and decadal IQR for model scenario 15 (snowfall factor 1.5, silty soil, fairly drained).