Supplement of The Cryosphere, 15, 2491–2509, 2021
https://doi.org/10.5194/tc-15-2491-2021-supplement

The Cryosphere
Open Access

Supplement of

Surface temperatures and their influence on the permafrost thermal regime in high-Arctic rock walls on Svalbard

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Supplement 1: Sensitivity analysis to model parameters

To analyse the sensitivity of our model results to different input parameters, we performed five additional sets of simulations. We varied the parameters roughness length, mineral fraction (which is equal to one minus porosity) and albedo of the rock surface for which we could not obtain reliable values. Furthermore, we analysed the parameter exposition as it can change in the rock wall because of small ledges and corners at the surface. To account for uncertainties in changes of seawater temperature, we performed model runs with an increase of 1.0 °C and 2.0 °C in seawater temperature until 2100 for the RCP4.5 scenario.

We found the strongest deviations from the reference simulation when varying the roughness length. Changes in the range of a few millimetre (± 0.005 m) result in only small deviations in modelled MARST (< 0.1 °C), while an increase in the range of decimetres (+ 0.1 m) can lead to over 0.5 °C lower MARST. These findings emphasize that the roughness length is a crucial factor for the calculation of RST, highlighting the role as a fitting parameter.

When varying the mineral fraction up to 0.1, the modelled MARST changed insignificantly (< 0.1 °C), suggesting that the calculation of RST is robust against variations in the mineral fraction. This finding is especially important as the exact value of the mineral fraction for the rock walls was not known in this study.

Varying the exposition of the slope up to 10° had almost no effect on the modelled MARST (< 0.1 °C). The insignificant deviations can be explained by the high latitude of the field site and the prevalent polar night and polar day conditions.

We also analysed the sensitivity of the model results against changes of the rock surface albedo, as the albedo of carbonates can vary in different field conditions and the exact value was not known. Changes up to 0.02 did not substantially affect the modelled MARST (< 0.1 °C). However, reducing the rock surface albedo by 0.1 resulted in clearly lower modelled MARST (up to 0.26 °C).

Future simulations of the RCP4.5 scenario show an increase in modelled MARST of up to 0.1 °C and 0.14 °C for an increase in seawater temperature until 2100 by 1.0 °C and 2.0 °C, respectively. Hanssen-Bauer et al. (2019) states that the surface waters around Svalbard will increase by 1.0 °C in 50 years from now in the RCP4.5 scenario, but regional deviations are likely. However, the sensitivity analysis shows that MARST of the coastal cliffs in our field site will only be affected to a slight extent.

To conclude, the results of the sensitivity analysis found that the parameters were in most cases robust against variations, with roughness length and rock surface albedo being the most sensitive parameters.

Supplement 2: Simulations with snow cover

The measured RST data indicate temporarily occurring snow cover in some rock walls. As RW01 shows the most pronounced and regularly occurring dampening of the temperature signal, additional model runs were performed for this rock wall. Figure S2.1 displays a comparison of measured RST in RW01, a model run without snow cover (*no snow scenario*), a model run taking the maximum snowfall into account (*snow scenario, max*) and a model run restricting snow depth to a maximum of 20 cm (*snow scenario, 20 cm*) to account for the limited accumulation capacity of the steep rock wall. The simulations considering the snow cover were performed with CryoGrid 3, following the model approach of Magnin et al. (2017).

In January to mid of February, both snow scenarios overestimate the snow cover, leading to up to 10 °C higher RST, while the *no snow scenario* matches the measured data significantly better. This leads to the assumption that RW01 was not covered by snow in early winter despite the occurring snowfall. In March and April, both snow scenarios represent the measured data better than the *no snow scenario*. This is especially true for the *snow scenario, max*, which implies a thicker snow cover than expected for the vertical rock wall. In May and June, the measured data in RW01 still indicates the presence of a snow cover, while both snow scenarios underestimates the influence of snow in the rock wall. Consequently, the measurements suggest that the rock wall RW01 had a significantly thicker snow cover than calculated from the snowfall produced by the forcing data.

This leads to the conclusion that our model is able to represent snow cover and calculate a dampening of the temperature signal in general. However, the snowfall provided by the forcing data leads to high errors and cannot represent the conditions under snow cover in the rock wall. This can be explained by the fact that the snow cover in the rock wall does not directly correlate with the snowfall of the forcing data. Instead, it is likely that a snowdrift builds up from the foot of the rock wall in winter until it eventually covers the temperature logger. Therefore, both snow scenarios overestimate the snow cover in early winter, when the snow at the foot of the rock wall does not reach the temperature logger yet, and underestimates the snow cover in late spring and early summer, when the massive snow drift needs more time for melting than. As our model can only represent snow cover produced by the snowfall of the forcing data, but not the effect of snowdrift in complex terrain, we excluded periods with snow cover from the analysis in this study and focussed on measurement sites, which were found to be largely snow-free.

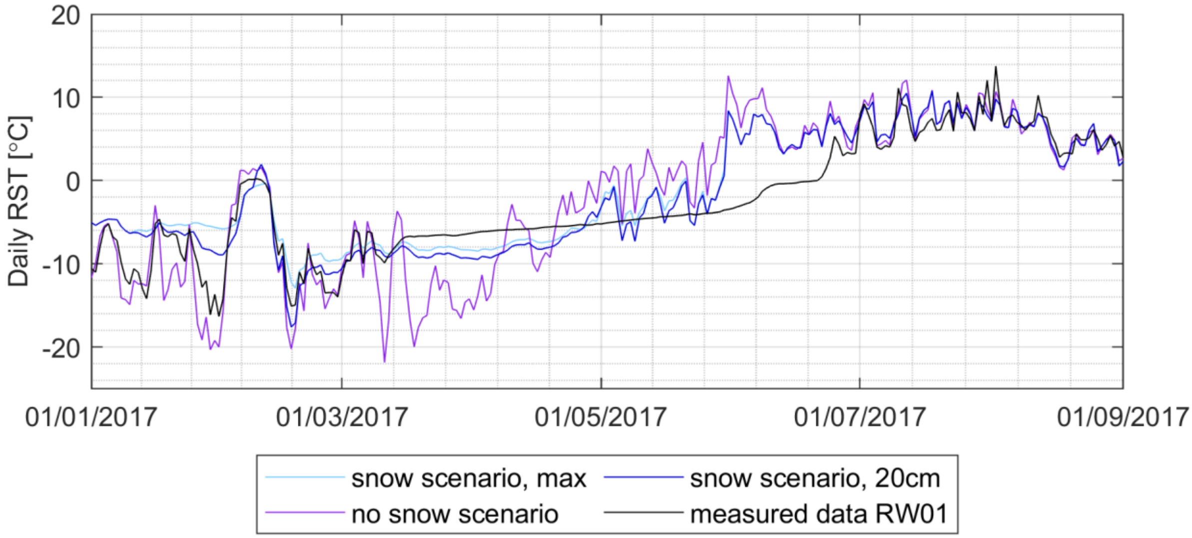

Figure S2.1: Comparison of measured daily RST in RW01 to a simulation without snow cover (*no snow scenario*), a model run taking the maximum snowfall into account (*snow scenario, max*) and a model run limiting snow depths to a maximum of 20 cm (*snow scenario, 20 cm*). The *no snow scenario* shows no dampening of the temperature signal, while both snow scenarios represent the snow cover well in late winter, but show an overestimation in early winter and an underestimation in late spring.

Future snow conditions will be characterized by a reduction of days with snow cover all over Svalbard. The snow water equivalent will be highly dependent on the emission scenario: Simulations of RCP4.5 show that snow water equivalent will be the same or slightly more, while simulations of RCP8.5 indicate a reduced maximum snow water equivalent of 50 % or more (Hanssen-Bauer et al., 2019). While the development of a snow cover in the analysed rock walls and its influence on RST is highly uncertain, we compare two future runs for RCP4.5 with no snow accumulation in the rock wall and snow accumulation to a maximum of 20 cm in the rock wall, respectively (Figure S2.2). In the simulations, the snow cover reduces MARST by 0.25 °C to 1.21 °C. The lowering of MARST by the snow cover is due to the albedo increase in spring, which cools the surface by reflecting short-wave radiation. However, these results must be regarded as a rough approximation, as snowdrift and not snowfall seems to be the main driver of snow cover in these rock walls. As in most cases no significant snow cover could be detected in our measurement data, MARST might be closer to the scenario neglecting the snow cover, but might be reduced at sites where snowdrifts influence RST.

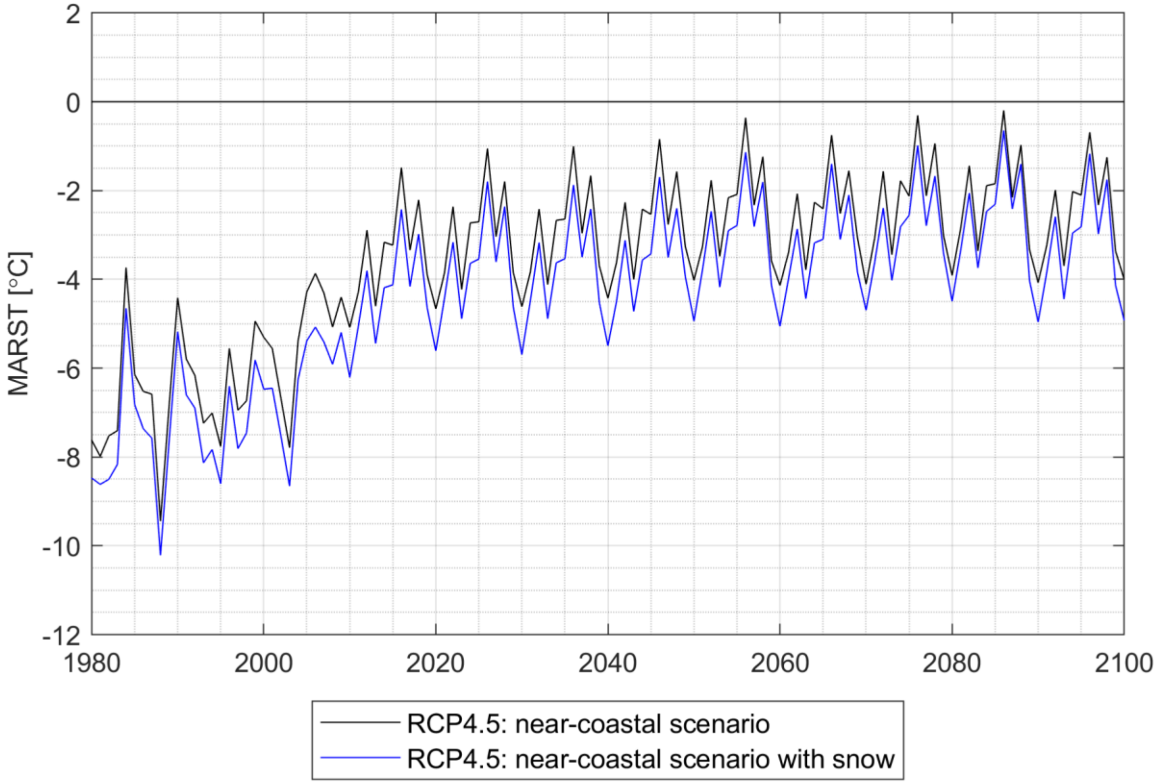

Figure S2.2: MARST of past and future simulations of the *near-coastal scenario* with RCP4.5 comparing two model runs neglecting the snow cover and taking potential snow cover up to 20 cm into account.

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Supplement 3: Full time series of measurement data and model results

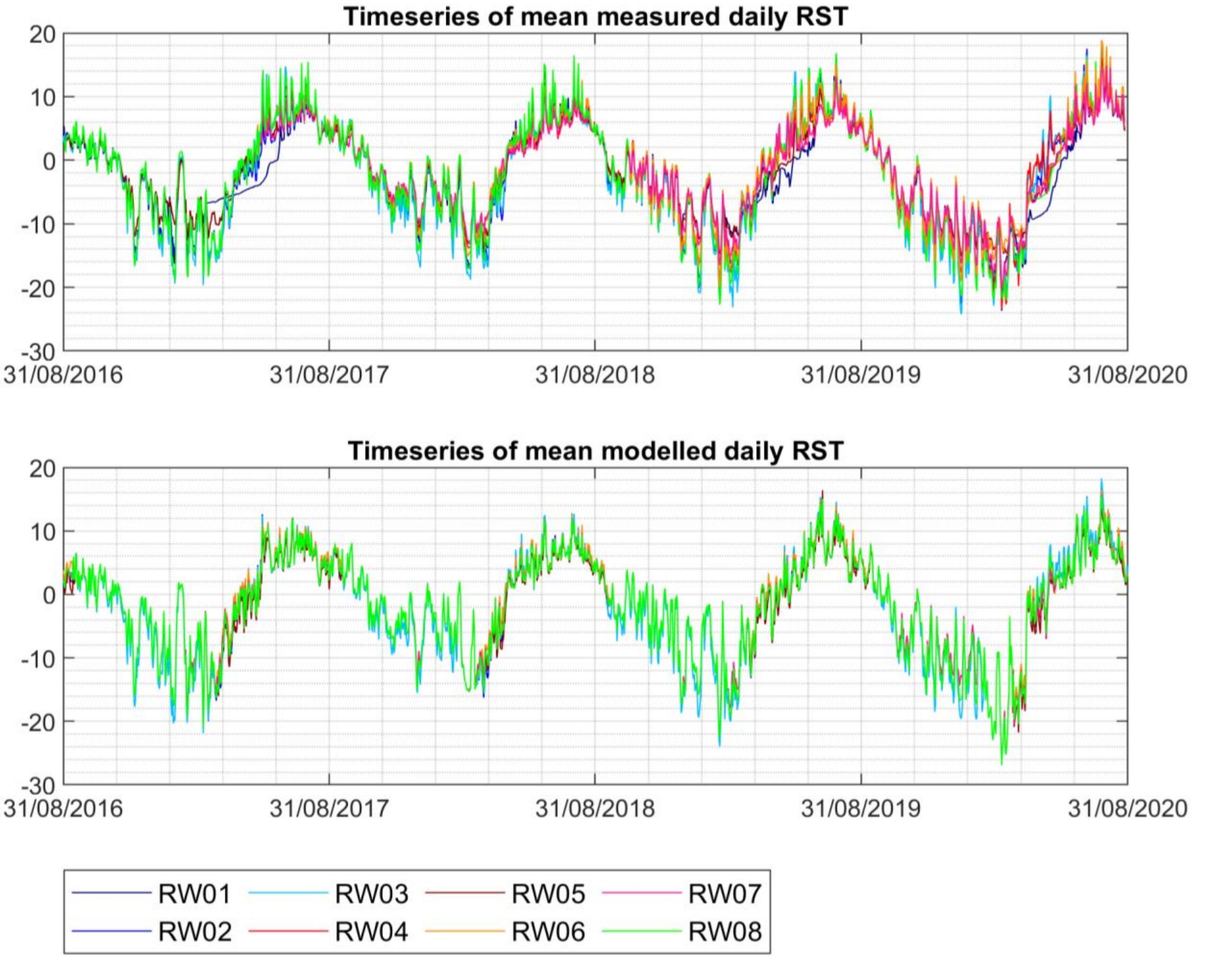

Figure S3.1: Time series of measurement data and model results ranging from 27.08.2016 to 31.08.2020 and including all rock walls RW01 to RW08.

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