Response to Referee #2

We would like to thank the reviewer for evaluating our manuscript and for the comments, which helped to improve it. We provide answers to the comments below as well as changes in the manuscript.

The comments of the reviewer are written in **bold**, the extracts of the manuscript in *italics* with changes highlighted in *blue*.

General comments:

This manuscript presents a four-year time series of eight temperature loggers at rock cliffs in the surroundings of Ny-Ålesund. The authors use the model CryoGrid 3 in order to discuss the measurements and resolve the influence of the different components on the energy balance on the observations. In addition, the model is combined with three different representative concentration pathways in order to predict the evolution of rock cliff temperature and active layer thickness throughout the next century. The measurements advance our knowledge of the energy balance at rock cliffs in the Arctic, and the model is useful for their discussion. However, I have some concerns regarding the manuscript. In my opinion, the temperature measurements are not up to the state of art, and the modelling work is promising but could be largely integrated with more simulations: adding the two parts is still not sufficient for a publication.

We appreciate that the reviewer acknowledges the advance in knowledge provided by our work. From his text we understand that his main concerns are the way the temperature measurements were performed, as well as the modelling work that could be enhanced by more simulations. To account for these points, we explain our sampling strategy and included clarifications, as well as new model runs in our revised manuscript. Please find the answers to the specific points below.

Regarding the measurements: I could not find any information about the calibration of the temperature loggers. This is a major point of concern and strongly weakens all the sequent results and discussion. Additionally, I don't understand why the measurements have been performed with an accuracy of only 0.5 °C. In general, I would like to have an explanation of the sampling strategy, which is to my knowledge not up to the state of art in this field.

We have experience with a wide range of measurement tools, including GeoPrecision (Magnin et al., 2019), Onset Hobo, Campbell and fully self-designed equipment. For this study in coastal cliffs of Ny-Ålesund, we chose to apply iButtons for several reasons:

1. All installations of instruments in the surroundings of Ny-Ålesund have to follow the land owner's (KingsBay AS) regulations and land management plan, including minimal disturbance of the local environment. The coastal cliffs are under the influence of strong coastal erosion. Volumes of several cubic meters detach every year from localized spots, and smaller volumes have likely detached in the vicinity of our logger sites. If measurement equipment was taken down by such events, it would land directly on the tidal beaches, where seals, sea birds and reindeer regularly

rest and forage, and eventually enter the marine ecosystem. As iButtons are the most miniaturized and non-invasive tools, they clearly were the preferable method for this study.

2. Due to the rock type and the strong coastal erosion, parts of the rock walls are highly fractured, resulting in safety concerns when installing the temperature loggers. Placing iButtons in cracks takes minimal time and thus strongly reduces the exposure to risk, especially since natural rockfalls seem to occur mostly in spring, while we conducted our fieldwork in late summer. The "normal" equipment used to measure near-surface temperatures in rockwalls, for example in the European Alps, requires drilling holes to place the temperature sensor and mount the loggers. Vibrations from drilling would put additional stress on the rockwalls, thus increasing the risk for the operator, especially when installing the loggers from the foot of the wall. For this reason, we did not use equipment that requires drilling for this study, and will not do so in the future for these and similar sites.

Our measurements provide the very first temperature measurements of rock walls in the surroundings of Ny-Ålesund and to our knowledge in such a coastal high Arctic setting. We are of the opinion that a range of different systems are suitable to conduct measurements of rock near-surface temperatures, and that the most suitable system should be selected to fit the particular conditions of the study site. What ultimately matters is that the uncertainty of the measurements is low enough, so that the conclusions of the study can be secured in the light of this uncertainty. We have therefore made an effort to provide improved uncertainty calculations which not only relies on the manufacturer's accuracy of the loggers (point 1 below), but also takes the effect of the placement in the walls into account (point 2 below).

1. The manufacturer provides an accuracy of 0.5 °C for the iButtons. Similar to an ice-bath, this accuracy can be verified for the freezing point of water, if melting snow conditions can be identified in the time series, with temperatures remaining stable near 0 °C for longer periods. Due to the lack of a snow cover for most sites, we were not able not identify such episodes for most sites. However, we found one clear occasion where temperatures (RW01 in fig. 03) were found to be between -0.125 °C and 0.042 °C, which is well inside the given accuracy. This also corresponds to our experience from previous studies using iButtons, where we rarely detected iButtons, which featured an error of more than 0.25°C during melt conditions. For this reason, we did not calibrate the iButtons prior to deployment, as in previous work (e.g. Gisnås et al., 2014).
2. For each rockwall site, at least one backup iButton sensor was installed to mitigate the risk of equipment loss and failure (see above). These backup loggers were generally placed within 10 cm of the main sensor in exactly the same aspect, but in different cracks or different (e.g. wider/narrower/differently shaped) parts of the same crack. These data were not used in the original manuscript. For the revised manuscript, we have now used these duplicate measurements to evaluate the combined uncertainty of the sensor+logger system and the effect of the placement in the walls.

For all rock wall sites, the differences in MARST between the adjacent temperature loggers were found to be less than 0.1 °C for annual averages, while we base our conclusions on differences in MARST between different rock wall sites on the order of 1.0 °C (table 5). Furthermore, seasonal RST showed differences of less than 0.2 °C between adjacent temperature loggers. For winter season RST, we base our conclusions on temperature differences between different rock wall sites of 1.5 °C to 2.2 °C (table 5). We therefore conclude that our conclusions relating to the in-situ measurements are well supported in the light of the measurement uncertainty.

References:
Magnin, F., Etzelmüller, B., Westermann, S., Isaksen, K., Hilger, P., & Hermanns, R. L. (2019): Permafrost distribution in steep rock slopes in Norway: measurements, statistical modelling and implications for geomorphological processes. Earth Surface Dynamics, 7(4), 1019-1040.
Gisnås, K., Westermann, S., Schuler, T. V., Litherland, T., Isaksen, K., Boike, J., & Etzelmüller, B. (2014): A statistical approach to represent small-scale variability of permafrost temperatures due to snow cover. The Cryosphere, 8(6), 2063-2074.

The following changes were done in the manuscript:

Line 115-120: The temperature sensors were placed in deep cracks in the rock wall so that both sides of the iButton are in direct thermal contact with the rock surface and the sensor is protected from sunlight (Fig. 2c). At each measurement site, we installed at least one more iButton, generally placed within 10 cm of the main sensor in exactly the same aspect, but often in different cracks or different parts of the same crack. We used these duplicate measurements to evaluate the combined uncertainty of the sensor/logger system and the placement in the rock walls. For all sites, the differences between the two sensors were found to be less than 0.1 °C for annual averages, while seasonal averages showed differences of less than 0.2 °C.

Regarding the modelling: a sensitivity study to the many model parameters would be beneficial to the conclusions of the paper and could, with a proper set up, provide interesting insights in the investigated processes. In the modeling in general, and in particular for the future scenarios, the quantification of the uncertainty (related to the climate scenarios and their propagation in the modelling) is required.

We agree with the reviewer that the quality of our manuscript can benefit from a sensitivity study. We performed five additional sets of simulations, varying the parameters roughness length, mineral fraction, albedo of the rock surface, exposition of the slope as well as increasing seawater temperature for the future simulation. We included this analysis as a supplement in our manuscript:

Supplement, Line 1-33: ***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.

Due to the limits of the temperature time series and the current state of the modelling, I suggest to restructure the manuscript in order to provide a more thorough study. Personally, I suggest to focus the manuscript on the modelling part: use the observations for model calibration and then use this to perform a more complete series of synthetic experiments to investigate the energy balance in different conditions. Therefore, I consider the manuscript promising and potentially suited for publication, but I suggest some major revisions prior to publication. A short list of specific comments (not exhaustive) is listed below.

We have provided a thorough assessment of the uncertainty of our measurements, which shows that our conclusions are well supported by our measurements. In particular, they convincingly show the influence of sea ice cover, which is a key finding of our study. As the in-situ data set from such a high-latitude location is unique, we would like to keep the measurements as a prominent part of our manuscript.

We followed the suggestion of the reviewer to perform additional model runs with several sensitivity studies that we included in the supplement. Hereby, we set our focus on the parameters roughness length, porosity and albedo of the rock surface, for which the values were poorly constrained. Furthermore, we analysed the influence of varying exposition of the slope and increasing seawater temperature. All results can be found in the supplement.

Specific comments:

Abstract: I suggest to focus the abstract (according to the comments above) having in mind the novelty and the scope of the manuscript.

Abstract: The abstract could benefit from a more quantitative description of the main results.

Following the comment of the reviewer, we highlight the novelty of the manuscript in the abstract and point out that these are one of the first measurements of RST in steep rock walls in the high Arctic. We made the following changes in our manuscript:

Line 16-17: This study presents one of the first comprehensive datasets of rock surface temperature measurements of steep rock walls in the high Arctic, comparing coastal and near-coastal settings.

Furthermore, we agree with the reviewer that the manuscript could benefit from a more quantitative description of the main results. Therefore, we made the following changes in the manuscript:

Line 19-26: Our measurements comprise four years of rock surface temperature data from summer 2016 to summer 2020. Mean annual rock surface temperatures ranged from -0.6 °C in a coastal rock wall in 2017/18 to -4.3 °C in a near-coastal rock wall in 2019/20. Our measurements and model results indicate that rock surface temperatures at coastal cliffs are up to 1.5 °C higher than near-coastal rock walls when the fjord is ice-free in winter season, resulting from additional energy input due to higher air temperatures at the coast and radiative warming by relatively warm seawater. An ice layer on the fjord counteracts this effect, leading to similar rock surface temperatures as in near-coastal settings. Our results include a simulated surface energy balance with short-wave radiation as the dominant energy source during spring and winter with net average seasonal values of up to 100 W/m^2, and long-wave radiation being the main energy loss with net seasonal averages between 16 W/m^2 and 39 W/m^2.

Line 1: The manuscript investigates rock temperatures, which have an impact on many topics also beyond rock wall instabilities (ecology, biology…). I suggest to extent the rationale to clarify the potential influence of the study.

We added in the introduction that degradation of mountain permafrost can impact the local ecology and that the thermal state of the ground is also an important parameter for landscape development. Furthermore, we included the impact on coastal erosion and local ecology, which is important at our field site due to breeding seabirds. We made the following changes in our manuscript:

Line 34-35: As a response to climate change, degradation of mountain permafrost can impact local ecology (Jin et al., 2020), play an important role in landscape development (Etzelmüller and Frauenfelder, 2009) and contribute to slope destabilization…

Line 40-42: However, permafrost dynamics in steep rock walls in the high Arctic are poorly understood, despite the impact on coastal erosion (Ødegård and Sollid, 1993) and local ecology such as breeding seabirds (Yuan et al., 2010).

Figure 2: Please show the location of the loggers on the images. The quality of the figure is not high, I guess this can be improved in the revised manuscript.

We followed the suggestion of the reviewer and marked the location of the loggers in the images. Furthermore, we changed the resolution of the images to a higher quality and exported it to a resolution of 330 dpi following the guidelines of The Cryosphere.

You can find the following changes in the manuscript:

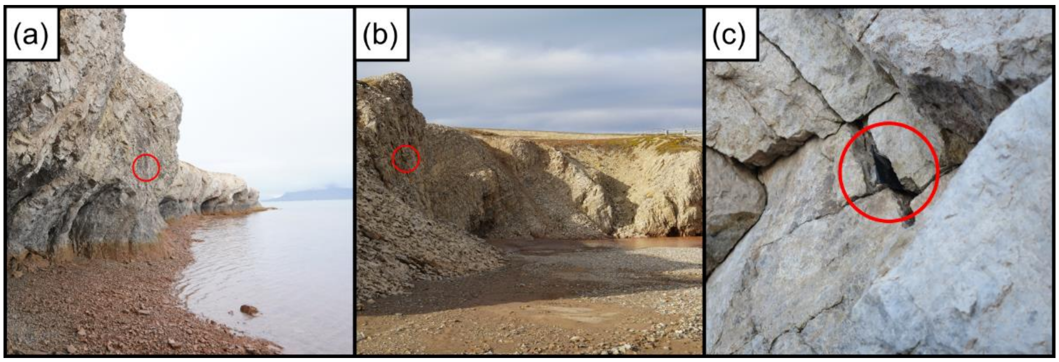

Figure 1: Locations of rock wall loggers used in this study: (a) coastal cliffs at the open fjord next to Ny-Ålesund airport (tidal zone visible in bottom). The position of RW06 is marked with a red circle; (b) near-coastal rock walls in the canyon of Bayelva. The position of RW01 is marked with a red circle; (c) close-up of a rock wall logger location: marking tape is visible, while the logger is located about 5 cm inside the crack in thermal contact with the rock.

Line 121: If there are any important overlapping methodological points with other papers it would be helpful to explain this more explicitly.

We understand that more clarification is needed in this paragraph. Therefore, we made the following changes in the manuscript:

Line 134-137: As a consequence, movement of air parcels at a vertical wall would be parallel to the surface rather than perpendicular. Therefore, we assumed in all model calculations, that the near-surface wind profile follow a neutral atmospheric stratification. To do so, we applied the same approach as performed by Magnin et al. (2017), who used CryoGrid 3 to simulate rock wall and permafrost temperatures at the Aiguille de Midi, France.

Figure 3 (and 5 later): It would be beneficial to show – maybe in the Appendix – the entire time series of the measurements (and of the modelling results for Fig. 5).

We included a figure in the supplement to the manuscript, showing the entire time series:

Supplement, Line 89-92: ***Supplement 3: Time series of measurement data and model results***

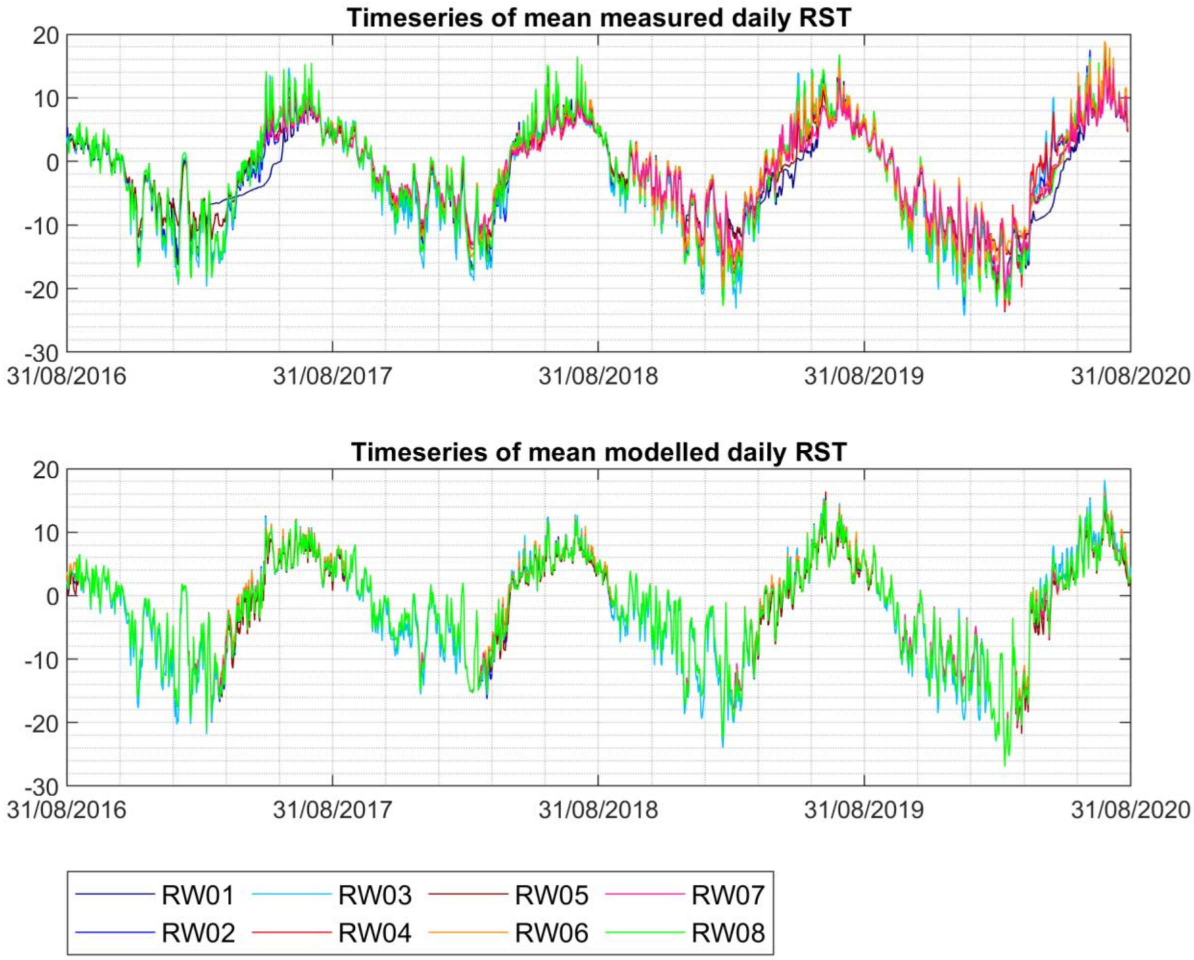

Figure S3.1: Time series of measurement data and model results ranging from 27.08.2016 to 31.08.2020 and including all rock walls RW01 to RW08.

Line 161: what about rock joints? The bedrock is limestone – heavily fractured – as mentioned in the manuscript and shown in the figures.

The latent heat fluxes are determined by the water which is available for evaporation. Rock joints might act as pathways for the water, but do not play an important role in storing water close to the surface, where it can be evaporated. Therefore, the latent heat fluxes are mainly driven by evaporation, when the rock surface is wet from rainwater and a water bucket approach can sufficiently represent this process.

However, the influence of rock joints cannot be neglected completely. Therefore, we adapted the volumetric water content in our model and assumed a higher value than the literature gives for fresh rock samples without cracks. As this might lead to uncertainties in determining the volumetric water content, we included this parameter in our sensitivity study. The results are robust against deviations in the volumetric water content.

We made the following changes in the manuscript:

Line 194-199: We considered the bedrock to have a volumetric mineral content of 97 % and a volumetric water content of 3 %, which implied saturated conditions during the entire simulation. The assumed porosity was selected higher than measurements of 0.5 % of fresh carbonate samples without cracks in the Ny-Ålesund region (Park et al., 2020), with the goal to account for the fractured nature of the rock walls. Due to the high uncertainty of this value, a sensitivity study was performed for the volumetric mineral and water content.

Supplement, line 14-16: 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.

Table 2: this could include the references directly in the table.

We thank the reviewer for this suggestion and added a column in table 2 to show the references. Furthermore, we added the references in the text.

Line 194-199: We considered the bedrock to have a volumetric mineral content of 97 % and a volumetric water content of 3 %, which implied saturated conditions during the entire simulation. The assumed porosity was selected higher than measurements of 0.5 % of fresh carbonate samples without cracks in the Ny-Ålesund region (Park et al., 2020), with the goal to account for the fractured nature of the rock walls. Due to the high uncertainty of this value, a sensitivity study was performed for the volumetric mineral and water content.

Line 204-209: We set the albedo for the horizontal ground surface to 0.15 (Westermann et al., 2009) and for water surfaces to 0.1, which is in the range of the surface ocean albedo for the typical high solar zenith angles in Svalbard (Li et al., 2006; Robertson et al., 2006). The albedo for ice and snow was set to a relatively low value of 0.55, as the highest influence of reflected short-wave radiation was expected for spring, when snowmelt decreases the albedo. This is in line with the reported decrease in albedo from 0.8 to 0.5 in Westermann et al. (2009). All values can be found in Table 2 and a sensitivity study for selected parameters is provided in the supplement.

Table 1: Model parameters assumed in the simulations.

Parameter		Value	Unit	Reference
Albedo rock wall	α	0.30	[-]	Blumthaler and Ambach (1988)
Albedo ground	α_g	0.15	[-]	Westermann et al. (2009)
Albedo open water	α_w	0.1	[-]	Li et al. (2006)
Albedo melting snow / ice	α_s	0.55	[-]	Westermann et al. (2009)
Emissivity	ε	0.97	[-]	Bussieres (2002)
Roughness length	z_0	0.018	[m]	-
Mineral fraction	$mineral$	0.97	[-]	modified after Park et al. (2020)
Water and ice fraction	$waterIce$	0.03	[-]	modified after Park et al. (2020)
Water bucket depth	d	0.001	[m]	-

Line 226: is the sea temperature constant throughout the entire simulation for all three scenarios?

Hanssen-Bauer et al. (2019) states that the surface waters around Svalbard will increase by 1 °C in fifty years from now for the RCP4.5 scenario. However, stronger warming is expected in areas further south and other areas might even cool about 1 °C (Hanssen-Bauer et al., 2019). Therefore, it is difficult to assess the expected sea temperature increase in Kongsfjorden and the sea temperature is constant for all three scenarios.

Nevertheless, we want to account for the comment of the reviewer. We ran additional simulations for the RCP4.5 scenario with a sea temperature increase of 1 °C and 2 °C until 2100, respectively. Slight differences in MARST of up to 0.14 °C are expected at the end of the century.

We included the findings in the supplement:

Supplement, Line 5-7: 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.

Supplement, Line 26-30: 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 study shows that MARST of the coastal cliffs in our field site will only be affected to a slight extent.

Line 319 and Figure 6: what happens in summer? A short explanation would complete the paragraph and in case could also lead to an extension of the figure.

This paragraph analyzes the factors leading to different rock surface temperatures when sea ice is present. During our measurement period from 2016 – 2020, sea ice appeared only in the months given in figure 6, a comparison between conditions with sea ice and without sea ice is not possible for summer months.

To avoid possible misunderstanding, we made the following changes in the manuscript:

Line 349-352: Between December and February, air temperature and the lack of radiative heating are the dominant factors, while reflected short-wave radiation plays no role. In March and April, the influence of reflected short-wave radiation increases as polar night conditions end. As no sea ice occurred after April in the measurement period 2016 to 2020, no analysis could be performed for late spring and early summer season.

Line 476: this paragraph has no connection with the rest of the manuscript, I suggest to avoid it. Possibly it could be mentioned as an outlook.

We follow the suggestion of the reviewer and deleted the chapter 5.5. Instead, we included a significantly shorter paragraph in 5.4 to account for the main message of the deleted chapter.

Line 516-522: Our model results indicate a significant warming of permafrost temperatures and a deepening of ALT in the 21st century, a trend that can lead to destabilization of rock slopes (Krautblatter et al., 2013). Besides, loss of sea ice and correlated longer duration of open-water season can enhance coastal erosion (Barnhart et al., 2014). In this study, the thermal regime of relatively low coastal cliffs is investigated. Indeed, similar processes can also affect much higher cliffs. Failures of coastal rock slopes can impact the water body and trigger displacement waves along shorelines, as happened in Paatuut / Greenland in 2000 (Dahl-Jensen et al., 2004; Hermanns et al., 2006). Due to permafrost degradation, rock slope failures in the high Arctic might become more likely in future, which should be taken into account for risk assessment of settlements and infrastructure.