Reply to Dr. Daniel Remias (Reviewer#1)

April 14, 2020
Dr. Yukihiko Onuma
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Dear Dr. Remias,

We would appreciate very much a number of valuable comments. Please see enclosed our responses to the all your comments as well as the revised marked-up manuscript entitled as "Temporal changes in snow albedo, including the possible effects of red algal growth, in northwest Greenland, simulated with a physically based snow albedo model" by Yukihiko Onuma et al. [Paper # tc-2019-263] submitted to the journal The Cryosphere. Our responses (**blue text**) to each your comment (**black text**) were described on the following pages. We also described major revised sentences based on your suggestion (revised part: yellow marker), after our response.

Best regards,
Yukihiko Onuma and co-authors

General Comments:

This study links field observations of arctic snow packs at Greenland with phenomena influencing the surface albedo and thus alterations of melting rates with a mathematical model proposed by the authors. The model is intended to explain the role, respectively to forecast the consequences of different surface concentrations mineral dust, black carbon and organic impurities (mainly snow algae) on the seasonal melting rates.

The questions of this work are of very high ecological relevance, taking global warming into account, and in this special case the fate of the Greenland Ice Sheet. Several important studies recently dealt with albedo changes of bare glacier ice, however partly neglecting the role of decreased albedo of snow on these glaciers, which will lead to earlier exposure of the glacier surfaces in the ablation zone during the melting season.

The proposed model is feasible and a first good step for performing simulation of scenarios. As for every model, improvements will likely follow to make it more robust, and satellite data generally needs more accurate supplementation of field data acquired in situ. In general, false positive results have to be excluded. In the case of this work, one distinct glacier has been sampled during one season.

We also consider that it is important to understand albedo, including the effect of snow algal blooming, changes of snow on glaciers in Greenland Ice sheet. In order to quantify the snow albedo reduction caused by snow algae using a physically based snow albedo model, we think that the detailed time series observations, including the measurements of snow impurity concentrations, snow physical properties and meteorological conditions, are required first. Of course, observation to quantify snow biological properties should be needed to establish and validate the model. Please see our responses to your comments below.

Major Comments:

1. My review will focus on biological aspects; I am not a specialist for albedo or mathematical simulations. The main issue of this manuscript is that the authors will have to consider the biology of algae causing red snow worldwide in more detail, and as a consequence, the model of snow algae "growth on snow surfaces" (which does practically not take place) has to be modified.

As you pointed out, we should consider the biological aspect (morphology, cell size, pigment and cell movement etc.) more in order to reproduce red snow worldwide using our model of snow algae "growth on snow surfaces". We added the explanation about current status and issues of the model in this manuscript (Lines from 336 to 343 and from 382 to 385).

Lines from 328 to 343 in the revised manuscript:

Although our field observations ended on day 215, snow algal abundance could further increase until the end of the melting season. In order to infer temporal changes in snow albedo for the whole melting season, we calculated snow albedo using the PBSAM and a snow algae model proposed by Onuma et al. (2018). Temporal changes in abundance of *S. nivaloides* on surface snow of Qaanaaq Glacier can simply be expressed by a differential logistic growth equation. Microbial growth was therefore calculated as follows (Onuma et al., 2018):

$$X = \frac{K}{1+\frac{K-X_0}{X_0}e^{\mu(t_0-t)}} \text{ , } t = d - d_f \qquad (4)$$

where X and X_0 are population densities of microbes at t and t_0, respectively, and μ is the growth rate of microbes in t^{-1}. K is the carrying capacity of algae in the snow surface and t_0 is the day of the first appearance of algae on the snow surface. t represents the number of the days during which the snow surface temperature was above 0°C, because snow algal growth mainly occurs on the melting snow surface. Although this model assumes algal growth on the snow surface, the algal cells observed in the surface snow were mostly cyst stage, which does not divide and thus not activity increase their population. The algae may divide at the subsurface or deeper layers in the snowpack. Therefore, the increase of algal cells at snow surface may due to not only their growth but also to accumulation at the surface as snow melt. However, their actual life cycle is still uncertain on this glacier. In this study, we use this model, which may include growth and/or accumulation of the algal cells but can reasonably reconstruct the observation of their seasonal change on the snow surface of the study site (Onuma et al., 2018).

Lines from 381 to 385 in the revised manuscript:

Unfortunately, we have only the validation data in the study site (MD, BC and OC concentrations and snow physical properties in surface and subsurface snow layers). The detailed time series observation, including analysis of cell size, pigment composition, algal community, should be conducted in other sites to evaluate our albedo model. Moreover, the detailed spatial measurements of algal cell abundance and snow albedo would also be needed because patchy distribution of red snow often appear on oligotrophic polar and alpine snow.

2. Regarding terminology, “red algae” and “bloomings” should be avoided throughout the manuscript, and correctly “red snow algae” or better “blooms of red snow” should be used. Consequently, the title could be altered to i.e. “Temporal changes in snow albedo, including the possible effect of algae causing red snow, simulated with a physically based model”

Following your advice, we avoided “red algae” and “bloomings” in the manuscript, so we used “red snow algae” and “blooms of red snow” instead. In addition, our title has been altered to “Temporal changes in snow albedo, including the possible effect of red snow algae, simulated with a physically based snow albedo model" based on your suggestion.

3. The globally most common algal species causing the well-known red snow phenomenon, also at Greenland, has been described recently as Sanguina nivaloides, and consequently "Chlamydomonas nivalis" should be avoided from now on. The according reference to be incorporated: Procházková et al. 2019 (https://doi.org/10.1093/femsec/fiz064). Likewise, the newest, updated general review for snow algae can be included: Hoham & Remias (https://doi.org/10.1111/jpy.12952; succeeding Hoham & Duval 2001). In these references, the authors can learn that the spherical red cysts which are abundant on snow surfaces, do not cleave at the surface during the melting season. Cell division takes place only early in the season when the population has not yet reached the still white surface, but the bottom snow is already water logged after the end of winter. This has a significant consequence for the proposed "snow algae growth factor": it does not exist! But from where comes the evident increase of seasonal cell concentration of such blooms? The only explanation in my mind is, given that the algae population stays about the same during snowmelt (except that cell diameter will increase to a certain extend), that the volume of snow decreases due to melting (and partly sublimation). Thus, the cell numbers per snow volume increase only passively in the case of red cysts. For creating a model regarding the albedo issues caused by snow algae, the theory can be kept but renamed to i.e. "accumulation model".

We modified the observed algal species in this study to *Sanguina nivaloides* from *Chlamydomonas nivalis* in the manuscript. Also, we referred to the following papers to review the latest biological study in the introduction of the manuscript. We agree that the algal cyst observed in our samples does not increase by cell division. In addition, the increment of cell concentration caused by the decrease of snow volume is would occur as you mentioned. We reported that the red cyst concentration of *Sanguina nivaloides* gradually increased with snow melting on the surface snow in the study site (Onuma et al., 2018). Snowpit observation conducted in the study site showed that the depth of snow was 110 cm when the snow algae first appeared on the snow surface. The snow temperature in the bottom layer (the thickness of 100-110 cm) was -1.7°C, indicating that there was no liquid water at the layer and thus algal growth at the layer seems to be impossible. In addition, algal cell was not contained in any snow samples collected from the snowpit except the samples at the surface. Nevertheless, the algal cell concentration gradually increased from 30 June to 3 August. Based on these results, we would conclude that the algae grew at the surface snow layers. Of course, we could rarely observe vegetative cells in the snow, thus it is necessary to study further their life cycle on this glacier. Also, it would be possible accumulate and remove of algal cells at the surface. Therefore, we refer the model as "snow algae model", which include both of algal growth and accumulation in this study. Based on your comments, we have renamed "algal growth model" to "snow algae model" in the whole of the manuscript. Accordingly, we described that the detailed assumption and current issue of snow algae model (Lines from 328 to 343).

Reference:

Hoham, R. W. and Remias, D.: SNOW AND GLACIAL ALGAE: A REVIEW., J. Phycol., doi: 10.1111/jpy.12952, 2020.

Procházková, L., Leya, T., Křížková, H. and Nedbalová, L.: Sanguina nivaloides and Sanguina aurantia gen. et spp. nov. (Chlorophyta): the taxonomy, phylogeny, biogeography and ecology of two newly recognised algae causing red and orange snow., *FEMS Microbiol. Ecol.*, 95:fiz064, doi: 10.1093/femsec/fiz064, 2019.

4. In this manuscript, the "typical" cell concentration per red snow volume is mentioned several times. But what is typical? First of all, it depends on the location of the ecosystem. Coastal snow fields are usually affected by local nutrient input and may have striking blood red coloration, whereas oligotrophic alpine and polar snow has much lower abundances, causing a more pink snow.

We agree with you. Typical cell concentration for red snow depends on the location of the ecosystem. We think that the study site (Qaanaaq Glacier) fall into the category of oligotrophic polar snow. The information of the location (oligotrophic polar and alpine snow) for definition of "typical red snow" has been added in the manuscript (Line 319). In addition, the range of the typical algal cell concentration in this study has been modified (Line 320). Accordingly, the results in Figures 6 and 7 and the sentences in from Discussion 4.5 to Discussion 4.8 have been modified.

Lines from 317 to 322 in the revised manuscript:

This is probably due to the lower cell concentrations at the study site, which was $4.9 \pm 1.7 \times 10^4$ cells L^{-1} (mean ± SD) on day 215, when compared with those of typical red snow appeared on oligotrophic polar or alpine snow, which range from 3.2×10^6 to 2.0×10^8 cells L^{-1} (Thomas and Duval, 1995; Takeuchi and Koshima, 2004; Takeuchi et al., 2006; Stibal et al., 2007; Takeuchi, 2013; Lutz et al., 2014; ; Tanaka et al., 2016; Onuma et al., 2018; Procházková et al., 2018). In fact, visible red snow was not seen on day 215 at the study site.

5. Moreover, the concentration of the organic impurities on the snow surface can also be influenced

by meteorological events like precipitation, and the authors should discuss this aspect.

The precipitation event should be discussed to reveal a factor affecting temporal changes in algal abundance. However, we believe that the discussion would be outside the scope of our paper because snow algal abundance did not significantly affect the surface albedo during the period. The OC and algal cell concentrations ranged from 3.2×10^{-2} to 1.3×10^{-1} mg L^{-1} and 0 to 1.3×10^{-4} cells L^{-1} in the surface snow from day 168 to day 209, respectively, indicating that the concentrations are pretty lower than that of typical red snow in oligotrophic polar snow. The discussion about the temporal changes in the lower algal cell concentration may lead to confuse the issue (i.e. contribution of red snow blooming to snow albedo). Therefore, we did not add the discussion to the manuscript in this time although precipitation event is an important factor to discuss temporal changes in snow algal abundance.

6. Melting surface snow has temperatures about 0.5 to 1 C in all studies I know. Therefore, why were calculations performed simulating an elevated snow temperature of +1.5C? This should be physically impossible, and thus I suggest removing this hypothetical data from the manuscript, and likewise change fig. 7.

In our simulation, snow temperature becomes 0°C when the temperature exceeds 0°C by warming test. Our explanation in the manuscript was insufficient about that, so the explanation has been described (Lines from 445 to 446).

Lines from 443 to 446 in the revised manuscript:

The simulation was conducted for 30 days, starting after day 215. The temporal changes in surface snow temperature under different assumptions were used as input variables for the snow algae model. The range of the surface snow temperature was within plus or minus 1.5°C. In the model simulation, snow temperature becomes 0°C when the temperature exceeds 0°C by warming test.

Detail comments:

1. Line 16: use Sanguina nivaloides instead of Chlamydomonas nivalis throughoutge'

The species name has been corrected in the whole of the manuscript.

2. Line 27: Why should this albedo model only be valid for snow covers in Greenland? Could it be applied elsewhere?

The albedo model was established on the basis of the observation in Qaanaaq Glacier. Unfortunately, we have only the validation data in the study site (snow impurity concentrations and snow physical properties in surface and subsurface snow layers). However, we plan to apply the model to the other site (for example, Alaskan glacier and Svalbard). The current issue and future plan have been described in the manuscript (Lines from 381 to 385).

3. Line 41: visible is from 400 to 700 nm

The word has been corrected (Line 42).

4. Line 47: "of" instead "in" the Greenland Ice Sheet

The word has been corrected (Line 48).

5. Line 50: insert "algae" to the list in brackets

The word has been inserted (Line 52).

6. Line 52: insert "in" after "might be present"

Following another reviewer's comment, "on" has been inserted after "present" (Line 52).

7. Line 57: Start sentence with "The …"

The word has been inserted (Line 58).

8. Line 67: reference Yallop et al. 2012 is about glacier algae, not about snow algae

The reference has been removed (Line 69).

9. Line 68: delete "and ice" for snow algae.

The word has been deleted (Line 70).

10. Line 70: give reference Hoham & Remias instead of Hoham & Duval

The reference has been replaced with Hoham & Remias (Line 71).

11. Lnie 71: use Sanguina nivaloides instead of Chlamydomonas nivalis and include reference Procházková et al 2019

The sentence has been modified as suggested. In addition, the reference has been included in the sentence (Lines from 72 to 75).

Lines from 70 to 75 in the revised manuscript:

Blooms of snow algae occur on thawing snow surfaces and change the color of snow to red or green (Thomas and Duval, 1995; Takeuchi et al., 2006; Hoham and Remias, 2020). Red colored snow results from a bloom of snow algae, which are typically *Sanguina (S.) nivaloides* (renamed recently from *Chlamydomonas nivalis*), and can be observed widely in polar and alpine snow fields (Hoham and Duval, 2001; Segawa et al., 2005; Takeuchi, 2013; Hisakawa et al., 2015; Lutz et al., 2016; Tanaka et al., 2016; Ganey et al., 2017; Segawa et al., 2018; Procházková et al., 2019).

12. Line 74: "algal blooms have" instead of "algal blooming has"

The words have been corrected (Line 76).

13. Line 78: "cellular pigment composition", delete "in cell"

The words have been corrected (Line 80).

14. Line 84 & 93: reformulate as explained earlier: the algal abundance on surface is not due to growth but due to concentration. E.g. "accumulation model"

As we mentioned at Major comment 3, our model considers both effects of algal growth and accumulation to reproduce algal cell abundance. We have modified the sentence (Lines from 86 to 87).

Lines from 85 to 87 in the revised manuscript:

In addition, temporal changes in algal abundance were not used at the model calculation. Snow algal abundance can change significantly because of their growth, accumulation and removal of their cells over time (Müller et al., 2001; Takeuchi, 2013; Onuma et al., 2016; 2018). Therefore, snow albedo simulations should incorporate a numerical model of snow algae.

15. Line 191: The mean cell radius was 11.4 µm – based on algae from the study site? Please state. Elsewhere in the manuscript, a different cell size number based on an older study of Onuma et al. was given.

Yes, the size was measured using the cells observed in the study site. Onuma et al. (2018) showed that the mean cell size at the study sites (Sites A and B in the previous study), but we showed that the mean cell size at Site B only in this study. The explanation has been added to the manuscript (Line198).

16. Line 237: the decrease of OC on days 197 and 209 should be discussed, and please consider meteorological events like precipitation as a causer?

As we answered at Major comment 5, we did not add the discussion to the manuscript in this time because we believe that the discussion would be outside the scope of our paper.

17. Lines 240 – 245: The correlation between OC concentration and snow algae abundance appears

to be obvious. Still, despite high significance, other organisms can also contribute to OC like bacteria, and in this habitat most likely, yeast-like fungi. This should be at least briefly discussed (e.g. line 285: the formula is not a proof that snow algae are the main constitute of OC in snow – though this is apparent for this study). Since fungal blooms depend on the snow algae, there could be a stable correlation as well.

Although we could not quantify the abundance of fungi, we have quantified the abundance of *Chroococcaceae cyanobacterium* during the observational period. The abundance ranged from 0 to 9.7×10^5 cells m^{-2} from day 168 to day 215, so it possibly contributes to OC concentration. However, the cell size was very smaller (2.3 ± 0.6 μm in radius) compared with that of red cyst of *Sanguina nivaloides*. Therefore, we assumed that the effect of the cyanobacteria can be neglected to obtain the relationship between the red cyst abundance of *Sanguina nivaloides* and the concentration of OC. As you pointed out, we should discuss the contribution of bacteria and fungi to OC concentration. The discussion has been described (Lines from 299 to 304).

Lines from 297 to 304 in the revised manuscript:

Indeed, *S. nivaloides* was the dominant species in snowpack at the study site throughout the summer season of 2014 (Onuma et al., 2018). However, significant amounts of OC were detected in snow samples without cells of *S. nivaloides*, indicating that these snow samples contained organic matter originated from the other organisms (for example, bacteria and yeast-like fungi) and atmospheric OC aerosol. The intercept of 0.0826 of equation (3) can be interpreted as to be contributed from the other organisms and the atmospheric OC aerosol. In fact, Chroococcaceae cyanobacterium, which is a cyanobacteria found commonly on glaciers and snowpacks in Greenland, was observed on the surface snow of the study site from mid-June to early August in 2014 (Onuma et al., 2018). However, their effect was neglected in the present study because the concentration was much smaller than the abundance of *S. nivaloides* at the study site.

18. Line 285: "constituent" instead of "constitution"

The word has been corrected (line 295).

19. Line 289: please explain/hypothesise how algae-free snow contains significant amount of OC at a remote place of Northwestern Greenland. Long-distance deposition?

Following the previous your comment (Detail comments 17), we reconsidered the reason for the intercept of 0.0826 of equation (3) in the manuscript. Probably, the contribution of cyanobacteria abundances is included in the intercept value. The discussion about the reason of the intercept value has been described (lines from 299 to 304).

20. Line 296: unneeded repetition of the considered pigments

The words have been deleted (Line 307).

21. Line 297: "absorption", not "abruption"

The word has been corrected (Line 307).

22. Line 299: Sentence "The dominant species was …" is a repetition of results.

The sentence has been removed (Line 310). Also, sentence "These results suggest" has been corrected (Line 310).

23. Line 309: the typical cell concentration of the study site was 4.9 x 10 e4 cells per litre. To my experience, the lower threshold to see snow discolorations by one's eye is about 5 x 10 e6. Thus my question, did you see red snow visually at the study site? This should be mentioned in the results.

We could not see red snow visually at the study site in 2014 season. However, red snow appeared visibly on surface snow at the lower site of Qaanaaq Glacier when the cell concentration of the red cyst of *Sanguina nivaloides* was 3.2×10^6 cells L^{-1} (Onuma et al., 2018). To our knowledge, the cell concentration was slightly lower than the concentration in the other sites reported by previous studies. So, we assumed that the minimum value of typical red snow is 3.2×10^6 cells L^{-1} in this study. The explanation has been added (Lines from 319 to 322).

24. Line 310: delete non-existing reference "Sutton et al. 1972". There exists only a PhD of Mrs. Sutton from that year, a fine work though which was never published as a paper. There are many good papers for the concentration of Sanguina nivaloides in red snow.

The reference has been deleted, so some reference (Takeuchi and Koshima, 2004; Takeuchi et al., 2006; Stibal et al., 2007; Tanaka et al., 2016; Procházková et al., 2018) have been added in the manuscript instead (Lines from 320 to 321). The range of the typical red snow concentration has been modified (Line 320). Also, the snow albedos were recalculated using the newer range of the algal cell concentration with PBSAM. Accordingly, the results in Figures 6 and 7 and the sentences in from Discussion 4.5 to Discussion 4.8 have been modified.

Reference:

Takeuchi, N. and Kohshima, S.: snow algal community on a Patagonian glacier, Tyndall glacier in the Southern Patagonia Icefield, *Arct. Antarct. Alp. Res.*, 36, 91–8, 2004.

Takeuchi, N., Dial, R., Kohshima, S., Segawa, T. and Uetake, J.: Spatial distribution and abundance of red snow algae on the Harding Icefield, Alaska derived from a satellite image. *Geophys. Res. Lett.*, 33, L21502, doi: 10.1029/2006GL027819, 2006.

Stibal, M., Elster, J., Ŝabacká, M. and Kaŝtovská, K.: Seasonal and diel changes in photosynthetic activity of the snow alga Chlamydomonas nivalis (Chlorophyceae) from Svalbard determined by pulse amplitude modulation fluorometry. *FEMS. Microbiol. Ecol.*, 59, 265–273, doi:10.1111/j.1574-6941.2006.00264.x, 2007.

Tanaka, S., Takeuchi, N., Miyairi, M., Fujisawa, Y., Kadota, T., Shirakawa, T., Kusaka, R., Takahashi, S., Enomoto, H., Ohata, T., Yabuki, H., Konya, K., Fedorov, A., Konstantinov, P.: Snow algal communities on glaciers in the Suntar-Khayata Mountain Range in eastern Siberia, Russia. *Polar Sci.*, 10, 3, 227-238, doi: 10.1016/j.polar.2016.03.004, 2016.

Procházková, L., Remias, D., Holzinger, A., Řezanka, T. and Nedbalová, L.: Ecophysiological and morphological comparison of two populations of Chlainomonas sp. (Chlorophyta) causing red snow on ice-covered lakes in the High Tatras and Austrian Alps., *Eur. J. Phycol.*, 53:230–43, doi:10.1080/09670262.2018.1426789, 2018.

25. Chapter 4.3 (lines 316 – 337): I have serious problems with this part. It should either be rewritten or omitted. There are wrong biological assumptions about growth of red snow algal cysts (as stated in the beginning), which simply does not take place on the snow surface. The bloom that you can see is a (physiologically active) resting stage.

In this study, cell concentration of red cyst of *S. nivaloides* was calculated with "snow algae model". As we mentioned at Major comment 3, we have described the detailed assumption and current issue of the snow algae model (Lines from 336 to 358).

26. Chapter 4.4: A "typical" red snow bloom should be defined more clearly. Only two references for average cell numbers are given. Furthermore, Painter et al 2001 is inappropriate in this context, because they clearly state that they did not any field measurements. Moreover, the number taken from Lutz et al 2014 from location MIT-17 is not the average value for red cysts in that study, but a rather low value for a bloom. For being representative, I strongly recommend to include certain further studies of "Chlamydomonas nivalis" and then recalculate the albedo reduction of a "typical" red bloom.

As we mentioned at Major comment 4, the definition of "typical red snow" has been added in the manuscript (Line 319). And, we have modified the range of "typical red snow" in the manuscript. Accordingly, the snow albedos were recalculated using the newer range of the algal cell concentration with PBSAM. Based on your comment, we have added model validations with two field observation data (Takeuchi et al., 2006 and Takeuchi, 2013). In this study, we used only field observation data collected by Painter et al. (2001, Fig. 1). To our understanding, the data of the figure 1 seemed to be obtained from field measurement and sampling although the other data were not obtained from those. In Lutz et al. (2014), the snow albedo in the visible band and algal cell concentration were observed simultaneously at Mit-17, so we consider that the model validation can be conducted using the observational data. To explain clearly, we have summarized the information about these model validations as a table (Lines from 357 to 359 and Table 2). Based on these validations, we have discussed about possible biological factors affecting snow albedo (cell size, algal community and pigment composition) (Lines from 362 to 385).

Lines from 357 to 385 in the revised manuscript:

We validated the albedo reduction for high algal abundance using the snow albedos of red snow surface on oligotrophic polar or alpine snow reported by Previous studies (Painter et al., 2001; Takeuchi et al., 2006; Takeuchi, 2013; Lutz et al., 2014) (Table 2). The algal cell concentrations obtained from their field measurements were used as input variables in surface (0–2 cm) and subsurface (2–10 cm) snow. These algal cell concentrations were converted into C_{OC} using equation (3). Our observational data on day 215 (meteorological, snow physical and impurity conditions) were used as other input data of these simulations. The simulation using the cell concentration observed by Painter et al. (2001) demonstrated that the difference between Alb-DB and Alb-DBA was 0.062, which is equivalent to the albedo reduction by snow algae, and in agreement with the algal albedo reduction (0.07) observed by Painter et al. (2001). This reduction in albedo was also close to the result of another simulation with the bio-albedo model proposed by Cook et al. (2017a, algal albedo reduction = 0.07). Thus, both our PBSAM and the bio-albedo model can consistently reproduce the reduction in albedo based on the optical properties of *S. nivaloides*. The simulation using the cell concentration observed by Takeuchi (2013) suggested that the simulated albedo reduction closed to the observed that (model: 0.105, observation: 0.12). In contrast, the simulation using the cell concentration reported by Lutz et al. (2014) produced an albedo reduction by snow algae of 0.015, which was lower than that observed by them (0.09) and calculated with the bio-albedo model (0.09). This is probably owing to different algal pigments in the ice surfaces. Lutz et al. (2014) reported that glacier algae (filamentous cells: 6.1×10^6 cells L^{-1}) were found in addition to snow algae (spherical cells: 1.8×10^6 cells L^{-1}) in the samples collected at their study site (MIT-17). The phenolic pigments of glacier algae have a broader bandwidth of spectral absorption than the carotenoids and chlorophyll of *S. nivaloides* (Remias, 2012; Williamson et al., 2020). In the albedo simulation with the bio-albedo model, measured pigment compositions (total chlorophyll, primary and secondary carotenoids) were used as model parameters while our simulation only used MAC for snow algae (*S. nivaloides*). The simulation using the cell concentration reported by Takeuchi et al. (2006) showed that the simulated albedo reduction underestimated the observed albedo reduction (model: 0.072, observation: 0.099). This may be due to the difference between the observed and parameterized cell size. Our PBSAM assumed that the cell size of *S. nivaloides* is 11.4 µm, whereas that measured by Takeuchi et al. (2006) was 17.5 µm. Because the MACs for red snow were estimated using the cell size of 11.4 µm, the simulated mass absorption might underestimate the intact mass absorption for red snow algae. Unfortunately, we have only the validation data in the study site (MD, BC and OC concentrations and snow physical properties in surface and subsurface snow layers). The detailed time series observation, including analysis of cell size, pigment composition, algal community, should be conducted in other sites to evaluate our albedo model. Moreover, the detailed spatial measurements of algal cell abundance and snow albedo would also be needed because patchy distribution of red snow often appear on oligotrophic polar and alpine snow.

27. Line 353: Start sentence "The phenolic pigments of glacier algae have a broader bandwidth of spectral absorption than the carotenoids of S. nivaloides". Instead of citing Dial et al. 2018, which is rather a deductive/theoretical work, a reference showing real spectral data is more appropriate (e.g. Fig. 13.6 in Remias 2012, Springer Vienna)

The sentence has been modified as suggested (lines from 372 to 374). And, the following references have been added in the manuscript.

Reference:

Remias, D.: Cell structure and physiology of alpine snow and ice algae, in: Plants in alpine regions, Cell physiology of adaption and survival strategies, edited by: Lütz, C., *Springer Wien*, 202, 175–186, doi: 10.1007/978-3-7091-0136-0_13, 2012.

Williamson, C. J., Cook, J. M., Tedstone, A., Yallop, M., McCutcheon, J., Poniecka, E., Campbell, D., Irvine-Fynn, T., McQuoid, J., Tranter, M., Perkinse, R. and Anesio, A.: Algal photophysiology drives darkening and melt of the Greenland Ice Sheet, *PNAS*, 117, 11, 5694-5705, doi:10.1073/pnas.1918412117, 2020.

28. Line 363: Again, Sutton 1972 is not a paper and Painter et al 2001 give no numbers to cite for.

These reference have been deleted, so some reference (Takeuchi and Koshima, 2004; Takeuchi et al., 2006; Stibal et al., 2007; Tanaka et al., 2016; Procházková et al., 2018) have been added in the manuscript instead (Lines from 391 to 392).

29. Line 388: replace "but" with "and"

The word has been corrected (Line 417).

30. Chapter 4.8: Needs to be updated. Please think over the “snow algae growth model” and the sense of using hypothetical high snow temperatures for any calculations.

As we mentioned at Major comments 3, these explanations have been added to the discussion part in the manuscript (Lines from 328 to 355).

31. Growth of snow algae takes place in deep layers of snow with very constant conditions around 0.5°C. The air temperature plays generally no big role since the snow pack starts to be water logged from the bottom, and this occurs earlier than air temperatures raise above zero.

We also think that melting water is an important factor affecting algal growth. Onuma et al. (2018) reported that cells of *S. nivaloides* were not observed from bottom to surface in snowpack at this study site on mid-June in 2014. This is probably due to existence of super imposed ice on the bottom layer. In the case, the red algal cells appear to have originated from windblown algal spores in the atmosphere, but they are not likely from the remaining snow of the previous melt season. Moreover, snow surface temperature was almost 0°C at the study site from late June to early August in 2014. Logistic model may reproduce the temporal change in algal abundance under such conditions. Because the explanation has been described in Onuma et al. (2018), the brief explanation has been added to our manuscript as suggested (Lines from 328 to 355).

32. Line 586: Reference Painter et al 2001 incomplete, authors missing. “Thomas” instead of Thimas”.

The author name has been corrected (Line 622).

33. Legend to fig 1: “sampling site”, not “sites”

The word has been corrected (Fig. 1).

34. Legend to fig. 5: say “Temporal changes in algal cell concentration and …”

The words have been replaced as suggested (Fig 5).

35. Figure 7: This is a bit vague considering the theory of cell growth and snow temperatures of +1.5°C

In our snow algae model, snow algal cell concentration gradually increased with snow melting, which means that snow temperature on surface exceed 0°C. And, snow temperature becomes 0°C when the temperature exceeds 0°C by the warming test. Therefore, the sensitivity test of temporal changes in the algal cell abundance can be conducted with the snow algae model using different snow temperature conditions. The explanation has been described (Lines from 445 to 446).