Reply to Dr. Marian Yallop (Reviewer#2)

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Dear Dr. Yallop,

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:

The role played by snow algae in contributing to albedo is currently of relevance and likely to be of interest to the larger cohort of scientists working in this field. This paper describes seasonal changes in the 'cyst stage' of a species they have identified as mostly, 'Chlamydonomas nivalis' type cells, documenting changes in numbers with time and modelling the contribution these cells make to a physically based snow albedo model. This species has now been renamed as Sanguina nivaloides (Procházková et al. 2019. The measurements have been made on a snowpack in northwest Greenland during the ablation period of 2014. Samples were also collected to quantify mineral particles and organic and black carbon content. However, an assumption is made that the cells are actively growing on the ice, i.e. that cell division leads to an increase in numbers through time. However, the cysts do not divide on the surface of the snow, but will, once buried, potentially provide the inoculum for the following year should suitable conditions arise. In the spring or early summer, once melt water forms, the flagellated algal cells will swim up to the snow surface to form a bloom. On the surface, they lose their flagella and formation of the red pigments occur. Members of the so-called water-melon snow are likely more speciose than was once thought. The development of blooms on the surface can show considerable spatial and temporal heterogeneity, at any one point in time, making it difficult to reliably quantify their distribution. This patchiness may be due to species-specific pigment differences as well as change in their relative abundance, and these factors needs to be carefully considered for inclusion in any model where the aim is to quantify their contribution to albedo. However, I do not have expertise in the modelling sections and my comments refer to the biological sections of the manuscript.

As you pointed out, we have to establish microbial and albedo models based on an appropriate biological assumption. Previous study (Onuma et al., 2018), we observed temporal changes in algal cell concentration of *Sanguina nivaloides* on surface snow in Qaanaaq Glacier and reproduced the temporal change with a Logistic model, but the cells observed were mostly cyst. As cyst does not increase by cell division, the expression of "algal growth" may inappropriate for the model. However, 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 336 to 343). Also, we have modified the algal species name (*Chlamydomonas nivalis*) to *Sanguina nivaloides* in the whole of the manuscript (Procházková et al., 2019 has been added as a reference).

Regarding to the life cycle of *Sanguina nivaloides* in snowpack, the cells were not observed from bottom to surface in snowpack at this study site on mid-June in 2014 reported by Onuma et al. (2018). 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. Because the discussion has been described in Onuma et al. (2018), the brief explanation has been added to our manuscript only (Lines from 336 to 343).

Regarding to spatial heterogeneity of the blooms, we used spatial mean of snow impurity concentrations and snow physical properties at the study site as input variables in order to simulate temporal changes snow albedo including the effect of red snow. The model parameters required by “snow algae model” in this study were obtained from spatial mean cell concentration observed at the site. Therefore, we focused on temporal change in “site mean” snow albedo in this study. The explanation has been added (Line 127). Unfortunately, we did not conduct the detailed spatial observation (the spatial distribution of algal cell concentration and snow albedo). Because the spatial heterogeneity of red snow is important to estimate accurately snow melting with an albedo model, we have added the point as a future task in the manuscript (Lines from 383 to 385).

Reference:

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.

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):

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

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.

Major Comments:

It is recommended that consideration be given to rewording the title for two reasons: i) the named algae are green algae, members of the Chlorophyta or green algae, and readers may be confused into thinking that this paper is about red algae (Rhodophyceae); ii) these particular algae are not considered to grow (as in cell division) once on the surface; they rapidly form cysts, though the cysts themselves may potentially show size changes through time, and they can still be photosynthesising but at very low rates i.e. they can still be metabolically active if the conditions are right. But, it is these cysts that will eventually act as the inoculum for the next year hence their persistence on the surface is fundamental for species survival from year to year. They also form an important food source for a number of grazers. Through the text, including the abstract, it is important that the term red algae is revised accordingly. It needs to be emphasised that the cells, on reaching the surface would turn into cysts and that an increase in the concentration of cell numbers on the surface is as a result of cell accumulation as the snow melts and algae concentration as they get behind.

For this reason, all reference to algal growth must be removed. That said, it is possibly that some other microbes may be found growing on the snow but the particular species mentioned here would not. The researchers may find these additional papers of use. Fogg (1967) Phil. Trans. Soc , 252, 279-287. Fjerdingstad et al., 1974, Arch. Hydrobiol. 73, 70-83 as well as the newer review by Hoham & Remias, Journal of Phycology, 2020. Line 27, clarify what is meant by proper estimates?

Many references are made in relation to the growth of the snow algae on the surface, as the snow is melting. It would be very useful to add in more detail about the life cycle of the collective group of snow algae, detailing the light triggers that promote the of the biflagellate stage to the ice surface and their modification to form the resulting cyst stage, with loss of the flagellae. The transition period from one form to another, and the time period over which this may happen, is critical. Fogg et al. (1974) report that the increase in cell numbers in snow is sometimes as a result of cell concentration due to ablation (sublimation) which leaves the algae behind. Previous researchers report on active photosynthesis in these surface cells, though possibly activity would cease once the surface temperatures become too high. The review of Hoham and Remias, (2020) would also be useful here.

We have incorporated your suggestions. First, the title were altered to "Temporal changes in snow albedo, including the possible effect of red snow algae, simulated with a physically based snow albedo model" according to your suggestion. We agree with your biological suggestion. Unfortunately, we did not conduct the detailed biological observation to quantify temporal changes in life stage, photosynthesis and metabolically active of *Sanguina nivaloides*. So, we have described the current status and issue of our snow algae model in the manuscript (Lines from 336 to 343). Because many reference paper in the manuscript have reported the temporal changes in algal abundance, which was resulted from "algal growth and/or accumulation", those have remained in the manuscript. Also, the following references have been added to the manuscript as suggested.

References:

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.

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.

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

Suggest revise wording:

1. Line 33, add Yallop et al., 2012 to the references reporting changes in surface albedo with ice melt;

The reference has been added (Line 34).

2. Line 41 – check all references made to ranges for visible light as they vary through the text;

The wavelength in the visible band has been corrected (400-700 nm, Line 42).

3. Line 45 – What is meant by ppbw (provide full definition);

ppbw is an abbreviation of parts per billion weight, a subunit of ppb that is used for part of weights like micrograms per kilogram (μg/kg). To explain simply, we modified the unit to μg/kg from ppbw (Line 46).

4. Line 46 Suggested reordering of this sentence: : : :.. was reported to be lower, by 0.7%, than that by BC: : :;

To explain clearly, the value (0.7%) has been changed to 'approximately 1%' (Line 47).

5. Line 49 – change absorb to absorbs;

The word has been corrected (Line 50).

6. Line 51 – after present add an on;

The word has been added (Line 52)

7. Line 57 Revise to read A physically based snow : : :: : :.;

Following the another reviewer's comment, the define article has been added to the sentence beginning (Line 58).

8. Line 83 – and elsewhere – revise references to 'growth' of cells on the surface and references to growth model where the 'growth' is likely resulting from an accumulation of cells in a defined area rather than active division of cells.

As we mentioned at Major comment, we have added the more detailed assumption of snow algal growth (Lines from 336 to 343).

9. Line 65, Yallop et al 2012 discussed potential ice algal albedo impacts not snow;

The reference has been removed (Line 69).

10. Line 96, Field not filed;

The word has been corrected (Line 100).

11. Line 103 – through more recent molecular work it is likely that any surface blooms may contain a number of different species that have very similar morphologies and it may be better to use Chlamydomonas spp., to infer that. There is also an indication that there were some cells that were not spherical red cells. Can any more information be provided regarding the identity of these cells?;

Unfortunately, the detailed molecular work has not been conducted in this study. Our study focus on the contribution of red snow to snow albedo, so we consider that the detailed discussion would be outside the scope of our paper. However, the point is important to reveal the contribution of snow algae to snow albedo. We have added the future plan in the manuscript (Lines from 381 to 383).

12. Line 116. It would be useful to add more information about the density samples (make, model);

In this study, we used the snow density as input variable for PBSAM, so the snow properties were observed. The objective of the measurement has been described (Lines from 122 to 123). And, the information of the density sampler has been added (Line 120).

Lines from 119 to 123 in the revised manuscript:

Snow temperature was measured with a thermistor sensor (CT-430WP, Custom Ltd, Tokyo, Japan). The snow density was measured using a density sampler (volume: 100 cm^3). Variation of snow layer thickness at each observational date relative to that on day 168 was defined as the relative snow surface level for estimating snow melting. The snow properties (the optically equivalent snow grain size, snow temperature, snow density and snow layer thickness) were measured to simulate snow albedo with a physically based snow albedo model.

13. Line 120 . It is recommended that more information is provided in the text to provide details about the spatial sampling protocol.

The snow sample corrections have been conducted in about 15x15 m spatial scale. The information has been added (Lines from 126 to 127).

14. Line 135 – change bag to bags;

The word has been corrected (Line 144).

15. Line 145 – after USA), change the ‘in’ to an ‘on’;

The word has been replaced (Line 153).

16. Line 145 – were the samples preserved or rather maintained. Using the term may imply some preservative was added.

The word has been changed to ‘maintained’ as suggested (Line 153).

17. Line 192 cell sizes were measured. Do these sizes account for any shrinkage as a result of the preservative used?;

In this study, cells obtained from snow sample stored in a freezer were used to measure the cell size. Unfortunately, we did not measure such shrinkage in this study. However, the effect of the cell shrinkage on light absorption in snowpack should be considered, so the information of the counted cell has been described (Line 199).

18. Line 194 and 195– remove the ‘s’ from compositions;

The ‘s’ has been removed (Line 203).

19. Line 195 – revise sentence as meaning is not clear;

As you know, we assumed four light absorption pigments (chlorophyll-a, chlorophyll-b, primary carotenoids, and secondary carotenoids) to simulate light absorption caused by red snow in this study. Also, we assumed the concentration of each pigment in the algal cells were based on Cook et al. (2017, JGR). However, the information was missing. The explanation has been described (Lines from 204 to 205).

Lines from 200 to 205 in the revised manuscript:

Because the effect of light absorption of snow algae on snow albedo should be calculated quantitatively in an albedo model, we calculated the imaginary part of refractive indices for *S. nivaloides* according to Cook et al. (2017a, equation (2) and (3)). The imaginary part of refractive indices for the spectral region from 400 to 750 nm was calculated based on the pigment composition (chlorophyll-a, chlorophyll-b, primary carotenoids, and secondary carotenoids) that were assumed as the compositions of *S. nivaloides* by them. The concentrations of each pigment in the algal cells were based on their study (Cook et al., 2017a, table 2; ‘High End-Member Scenario’).

20. Line 245 – Why is there a – sign in the equation for cell numbers?;

To prepare an input data for PBSAM, the concentration of algal cells was converted into that of OC using the equation. To explain clearly, multiplication symbol has been inserted between ‘5.3×10^{-6}’ and ‘C_{algae}’ (line 255). In addition, the unit for ‘C_{oc}’ has been added (Line 256).

21. Line 261: Relevant to this comments is the potential for aggregation of material on the snow. The cells can be sticky and aggregate to form larger clumps, together with mineral particles and other associated matter, including bacteria. Aggregation may affect their motility.

Temporal changes in MD and algal cell concentrations in surface and subsurface snow gradually increased from late June to early August in 2014 at the study site. These results suggest that such aggregation did not significantly affect temporal change in algal cell concentration in the case of this study. Because we have already discussed about the effect of MD concentration on algal growth on surface snow in previous study (Onuma et al., 2018), we believe that the discussion would be outside the scope of our paper.

22. Line 285 – change the word 'constitution' for 'constituent';

The word has been corrected (Line 295).

23. Line 268 – change 'amount' to 'amounts';

The word has been corrected (Line 298).

24. Line 309, here and elsewhere in text, if the cell numbers being reported are averages, can the SD or SE of cell number be added ;

The cell numbers were obtained from three snow samples, which were collected from three surfaces selected randomly at the study site. The standard deviation has been added to the sentence as suggested (Line 318). In addition, we have added "(mean ± SD)" in the result section 3.2 (Line 236).

25. Line 351 more literature and information could be added to support this statement that there may be different pigments in ice surfaces. The authors are referred to the new paper by Williamson et al. 2020 (PNAS , www.pnas.org/cgi/doi/10.1073/pnas.1918412117), for further views on the role of pigments. Importantly, whilst it is possible that snow algae may be found in ice environments, some of the major players on the ice sheet e.g. Ancylonema may not grow on the snow. Further, the latter species is actively growing and not in a resting stage hence it might be expected that their pigments would be very different.

We agree with your suggestion. The effect of algal pigment and species on surface albedo should have been discussed more detailed. We have added the following paper as references in the manuscript. And, the discussion about the effect of algal pigment and species on the snow albedo has been added (Lines from 372 to 374).

References:

Williamson, C. J., Cook, J. M., Tedstone, A., Yallop, M., McCutcheon, J., Ponieckae, 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

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.

Lines from 371 to 374 in the revised manuscript:

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).

26. Line 410 onwards – references of growth of snow algae need to be removed here, though some snow algae may have vegetative stages in the snow.

As we mentioned at Major comment, we have described the detailed explanation of “algal growth” in the manuscript. Because Onuma et al. (2018) has reported the temporal changes in algal abundance of red cyst (*Sanguina nivaloides*), which was resulted from “algal growth and/or accumulation”, it has remained in the manuscript. However, another one (Onuma et al. 2016) has been removed due to research on *Chloromonas nivalis* (Line 440).