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Prof. Tedesco
Editor, The Cryosphere

Dear Prof. Tedesco,

We would appreciate the time and effort you have dedicated to providing insightful feedback on ways to strengthen our paper. Please see enclosed our responses to the all reviewers' comments as well as the revised marked-up manuscript entitled as "Observations and modelling of algal growth on a snowpack in northwest Greenland" by Yukihiko Onuma et al. [Paper # tc-2017-252] submitted to the journal The Cryosphere. We have revised the manuscript according to the all reviewers' comments. We hope that the revised manuscript is suitable for publication. We hope for your favorable reply.

Sincerely yours,
Yikihiko Onuma and co-authors

Reply to Reviewer#1

The submitted manuscript aims to address a worthwhile gap in our knowledge of snow algae – namely the ability to model the growth of algal blooms over a season. The paper combines empirical observations with a simple growth model, building upon previous work by the same group that applied a Malthusian model to explain the population dynamics of the snow algal bloom by adding a carrying capacity. I enjoyed reading the paper and appreciated the careful field measurements; however, I have two queries for the authors, along with some minor typographical corrections.

We would appreciate very much a number of constructive comments. We also appreciate that you spent your precious time for us. We glad in being able to hear that you enjoyed reading our paper. Our responses (blue text) to each the reviewer's comment (in black text) were described as follows. We also indicate revisions in the updated manuscript with yellow marker as suggested.

Major Comments:

1. The model assumes no input or removal of cells, indicating that the population dynamics are dominated by in situ cell proliferation. However, no mention is made of the effects of scavenging by melting snow. The algae are likely to become concentrated onto the snow surface as the snowpack melts, and if this is the case then the authors would have measured an increase in surface biomass simply due to the concentrating effects of snow melt. Can the authors show that this was not the case? Similarly, it is hard to envisage zero cell export from the system. I suspect the snowpack algal population dynamics to be the result of in situ growth, scavenging by snow melt, export in meltwater and a small contribution by wind-delivery. Can the authors provide any data or observations to support all these factors being negligible apart from in situ growth?

As the reviewer pointed out, algal cell abundance is possibly increased by the effects of scavenging or wind-delivery and reduced by the effect of melt water. We conducted additional analysis to discuss the effect of scavenging on algal growth in snowpacks (please see the Figures S1 and S2 in this response letter). The results show vertical profiles in algal cell concentration, snow density and snow temperature in snowpit of the study sites before the first appearance of snow algae on the surface. The vertical profiles showed that all of the snow layers in the study sites did not include any algal cell, indicating that a scavenging by snow melt does not affect a temporal change in algal abundance. The effects of wind-delivery appeared to be small enough to calculate algal growth because the initial concentration of algae on the surface, which was likely due to wind in the study sites, was substantially smaller than the final concentration (Site-A: 3.1×10^3 cells m^{-2} vs. 3.5×10^7 cells m^{-2}, Site-B: 7.4 cells m^{-2} vs. 5.0×10^5 cells m^{-2}). The movement of algal cells by

melt water also appeared to be small enough to calculate algal growth because algal cell concentrations in the study sites gradually increased with snow melting except for the period from day 201 to 214 at Site-A. Therefore, we simulated the temporal changes in algal cell concentration using logistic model based on the assumption that there is no inflow or outflow of algal cells on the snow surface. We have revised the manuscript to discuss the effects of scavenging, wind-delivery and melt water on a temporal variation in algal abundance (from pg 8 line 30 to pg 9 line 4). And, we have added the method and result of the snowpit observation to the discussion about the origination of algal cell (pg 4 lines from 4 to 6, pg 6 lines from 13 to 14 and pg 7 lines from 5 to 6).

2. I think the authors overstate the utility of the model. As it stands the manuscript shows that a logistic modelling approach is appropriate for predicting the population dynamics of snow algae for specific field sites; however, insufficient information is provided to enable the application of the model elsewhere. The fact that between these two sites the coefficient of determination for the model applied to observations varies between 0.64 and 0.96 suggests to me that additional site specific factors influence the growth rate. K is, as the authors discuss, dependent upon the nutrient availability and available space, but no quantitative link is drawn between either variable and the value of K. The slope of the model is assumed to be entirely dependent upon time, but it sees unlikely that this assumption would often be satisfied. Presumably, the rate of growth is in reality affected by many more variables. For example the study by Onuma et al. (2016) found algal blooms to initiate just 24 hours after melting began which the authors attribute to either a different algal species (can you confirm this with observations?) or 'weather conditions'. This suggests that the growth rate varies between sites and cannot be assumed constant. As I understand it, weather conditions are precisely what you are trying to analyse as potential drivers of algal growth in this paper, so it seems contradictory to invoke them as an additional source of uncertainty. It seems likely that the initiation and growth rate of snow algal blooms are the result of a combination of meteorological factors plus site specific variations such as nutrient availability in the snowpack that may well be difficult to unpick, limiting the predictive capability of the model on other snowpacks. Can the authors provide any more data or discussion to support the applicability of the model?

We also consider that there probably is an insufficient information for applying of logistic model to various fields. The model requires three parameters, which are initial cell concentration, growth rate and carrying capacity, to calculate temporal change in algal cell abundance, and they are likely to vary in different snow fields or regions. The initial cell concentration and carrying capacity are likely to be associated with abundance of mineral particle on the snow surface. The carrying capacities in various fields may be determined by approximation using the relationship between observational abundance of algal cells and mineral dust on the snow surface. The growth rate may be similar in other sites as far as the algal species is same, i.e. *Cd.nivalis*. However, further observations are necessary for estimation of the

model parameters in various fields. This study is the first attempt to establish the algal model based on only a single glacier and season, thus, we could not say the feasibility of the model to be applied in more extensive areas. We have weakened the statements of the application to other regions and mentioned only possibilities to extend the glacier and ice sheet (from pg 11 lines from 7 to 14). Also, we have added the explanation about the determination of the carrying capacity in various fields by the approximation to the manuscript as suggested (pg 10 lines from 25 to 26).

Specific Comments:

1. pg 1 line 23: change 'bloom' to 'blooms', change 'changes' to 'change'

The words have been corrected (pg 1 line 23).

2. pg 1 line 24: change 'bloom' to 'blooms'

The word has been corrected (pg 1 line 24).

3. pg 2 line 20: delete 'works'

The word has been deleted (pg 2 line 19).

4. pg 2 line 26: these references are a mixture of ice algae and snow algae. Ice algae has been suggested to enhance ablative losses to the GrIS by reducing albedo (see more recent papers by Tedstone et al. 2017 and Stibal et al. 2017). To my knowledge, evidence for accelerated snow line retreat due to snow algal blooms has not yet been presented for Greenland. I suggest rewording this sentence accordingly or providing specific references for accelerated snow line retreat.

The sentence has been revised as suggested (pg 2 lines from 25 to 27). We have added the explanation about reduction of surface ice albedo due to ice algal bloom. The following reference has been added at pg2 line 27.

Stibal, M., Box, J. E., Cameron, K. A., Langen, P. L., Yallop, M. L., Mottram, R. H., … Ahlstrøm, A. P.: Algae drive enhanced darkening of bare ice on the Greenland ice sheet, Geophysical Research Letters, 44, doi: 10.1002/2017GL075958, 2017.

Tedstone, A. J., Bamber, J. L., Cook, J. M., Williamson, C. J., Fettweis, X., Hodson, A. J., and Tranter, M.: Dark ice dynamics of the south-west Greenland Ice Sheet, The Cryosphere, 11, 2491-2506, doi: 10.5194/tc-11-2491-2017, 2017.

5. Pg2 line 28: The Lutz studies were limited to the visible wavelengths and were not really measuring albedo, but a

proxy. Better to say that they showed algae can modulate snow reflectance in the visible wavelengths.

The sentence has been revised as suggested (pg2 line 28).

6. Pg3 line 5: superscript kmˆ2

The word has been corrected (pg 3 line 10).

7. pg4 line 4: normalising to area presumably requires that the algae only inhabit an extremely thin layer on the upper surface of the snow – other studies (e.g. Thomas et al., 1979; Hodson et al., 2017) indicate that subsurface red algae can exist. Are you confident that the algae were confined to the upper surface? Is this supported by your observations?

We do not have algal abundance data in subsurface snow layer after algal appearance in surface snow layer of the glacier. However, the vertical profiles in algal cell concentration in snowpack of the study sites show that there were no algal cells in snowpack before snow algae first appear in surface snow (Figures S1 and S2) as the response to major comment 1. In addition, snow algal cells are likely to be supplied from the atmosphere on surface snow in the study sites. These results suggest that snow algal cells concentrated to surface snow although a part of the algal cells may be flowed to subsurface snow by the melt water. We have revised the manuscript to discuss the effect of algal cells in subsurface snow on algal growth in surface snow (pg 9 lines from 1 to 2).

8. Pg6 line 21: change ‘active radiation’ to ‘photosynthetically active radiation’

The words have been changed (pg 6 line 31).

9. pg 7 line 24: delete ‘can’

The word has been deleted (pg 8 line 11).

10. pg 8 line 33: statistical significance should be supported by test name and values.

We have added a result of statistical test (Student’s *t*-test) to the sentence (pg 10 lines from 2 to 3).

11. pg8 line 28: change ‘snowfileds’ to ‘snowfields’

The word has been corrected (pg 9 line 30).

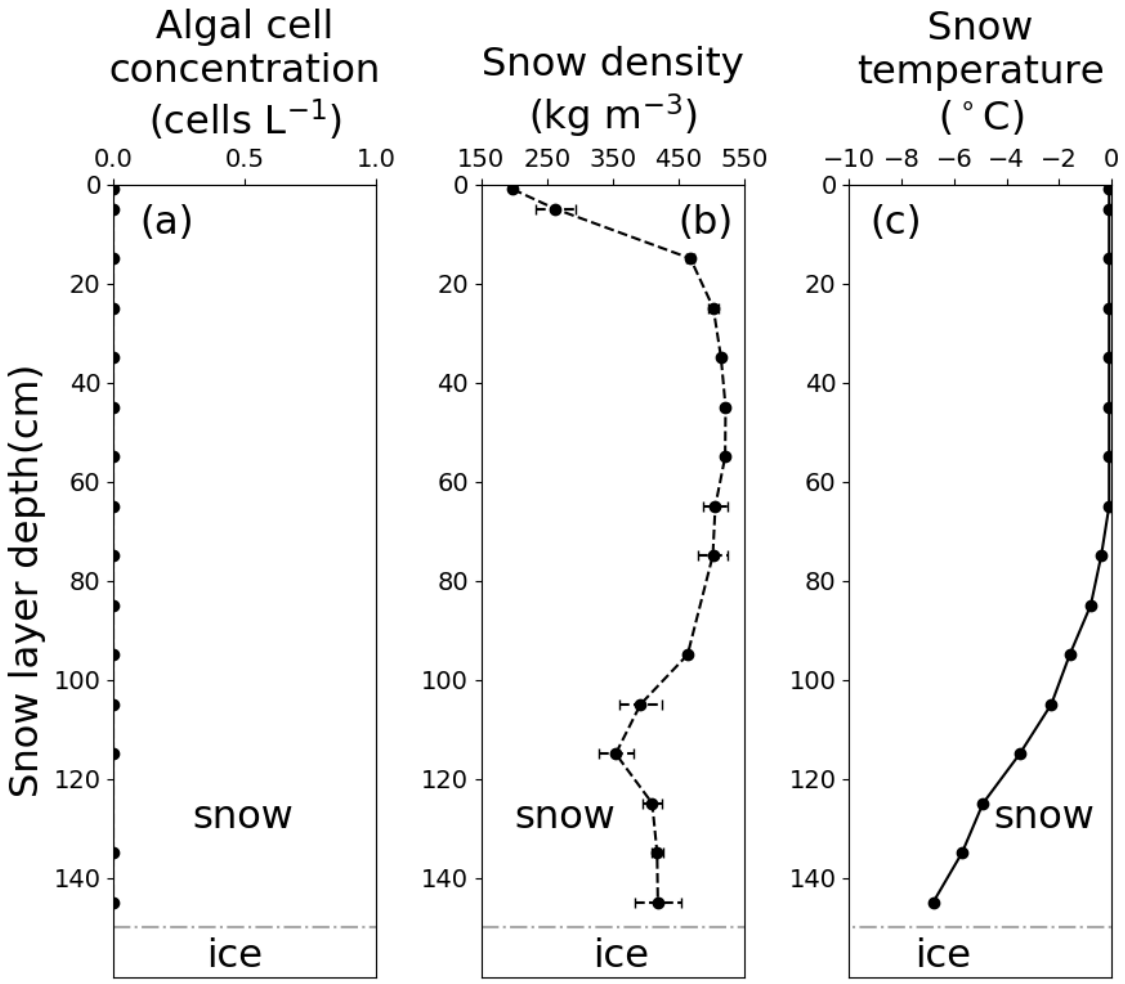

Figure S1. Vertical profiles of snow algal abundance and physical properties in a snow pit on day 162 at Site-A. (a) algal cell concentration, (b) snow density, (c) snow temperature in snow. Standard deviation shown by error bars.

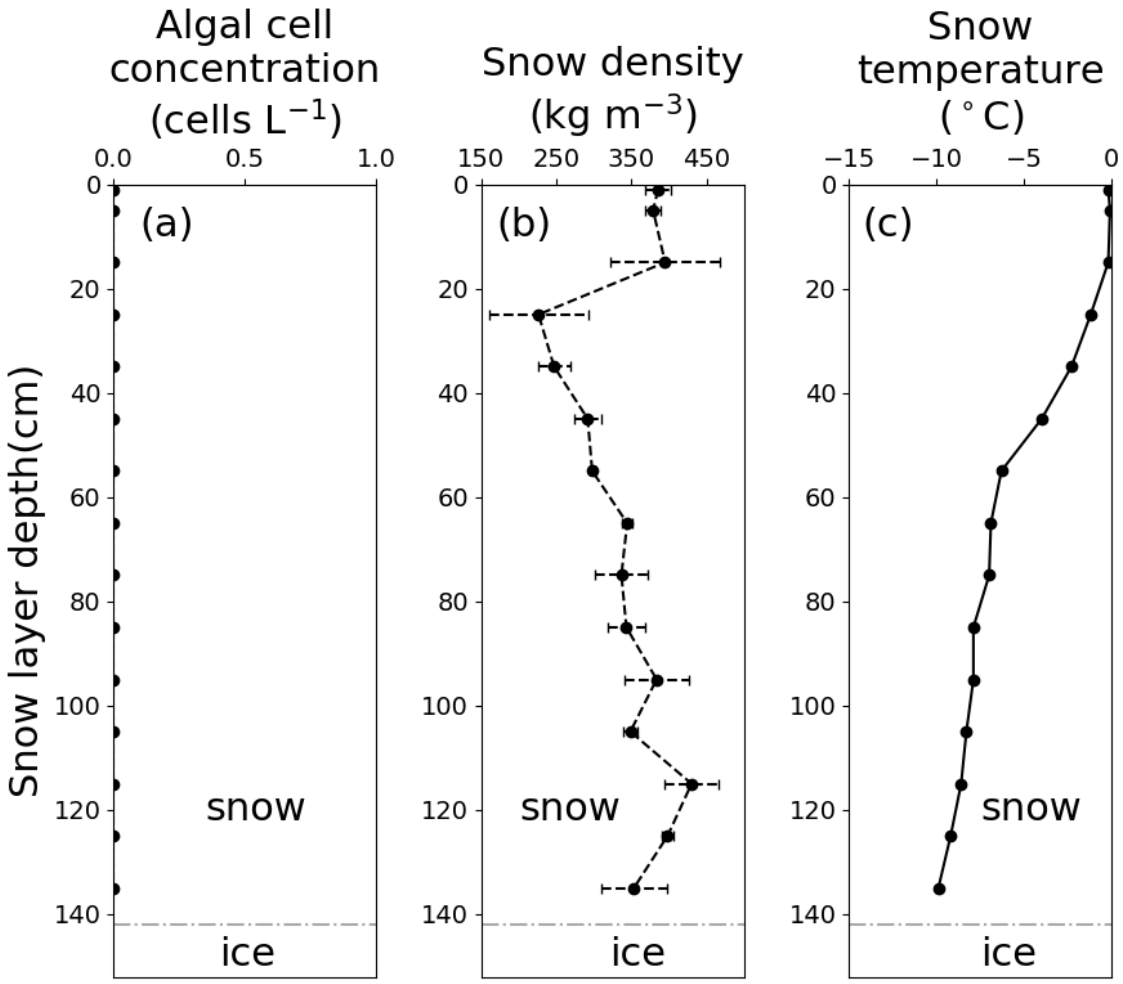

Figure S2. Vertical profiles of snow algal abundance and physical properties in a snow pit on day 168 at Site-B. (a) algal cell concentration, (b) snow density, (c) snow temperature in snow. Standard deviation shown by error bars.

Reply to Reviewer#2

Summary:

The manuscript tries to understand the link between snow algae growth and its relationship with albedo and ablation rates. The authors use field observations to monitor changes in snow algae over the melt season and apply these results to a model to simulate algae blooms. This research is relevant to further understanding of how algae abundance on snowpacks evolution over a season and what effects they have on surface albedo and melt rates. While I believe this work is relevant to the community, I think the manuscript could be written in a more compelling way, with greater connections and applicability to the Greenland ice sheet. And, while the model serves its purpose for this study, I think its functionality should not be overstated. And, the linkage with snow algae to surface albedo and melt rates is not made in the manuscript. I think greater emphasis and connection with albedo and melting should be added. And, what these observation and modeling efforts mean for implementation into regional climate models.

We would appreciate very much a number of constructive comments. We also appreciate that you evaluated our approach to further understanding of temporal change in algal abundance on snowpacks although our manuscript needs more revising. Our responses (blue text) to each the reviewer's comment (in black text) were described as follows. In addition, we indicate revisions in the updated manuscript with yellow marker as suggested.

Major Comments:

2. How representative is the model for use in other regions, beyond a glacier ice cap? Can the numerical model be feasibly used elsewhere on the ice sheet?

The model requires three parameters, which are initial cell concentration, growth rate and carrying capacity, to calculate temporal change in algal cell abundance, and they are likely to vary in different snow field or regions. We would think that the growth rate may be similar in other sites as far as the algal species is same, i.e. *Cd.nivalis*. The other two parameters, which are the initial cell concentration and carrying capacity, are likely to be associated with abundance of mineral particle or chemical properties on the snow surface, however, further studies are necessary. This study is the first attempt to establish the algal model based on only a single glacier and season, thus, we could not say the feasibility of the model to be applied in more extensive areas. We have weakened the statements of the application to other regions and mentioned only possibilities to extend the glacier and ice sheet (from Pg 11 lines from 7 to 14).

3. What are the larger impacts of this study? I think the authors should discuss this further and link the field and

modeling study to broader application and regions of the Greenland ice sheet.

We established this algal model to quantify the algae on the entire Greenland Ice Sheet and to evaluate their impact on surface albedo and melting rate of the snow. We plan to couple this model with a regional snow physical model (e.g. Niwano et al., 2018) to simulate snow albedo in future. Also, the model would be useful to know the algal life cycle on the ice sheet. We have added more detailed explanation on the broader applications of the model in the text (Pg 11 lines from 14 to 17) with the following reference.

Niwano, M., Aoki, T., Hashimoto, A., Matoba, S., Yamaguchi, S., Tanikawa, T., Fujita, K., Tsushima, A., Iizuka, Y., Shimada, R. and Hori, M.: NHM–SMAP: spatially and temporally high-resolution nonhydrostatic atmospheric model coupled with detailed snow process model for Greenland Ice Sheet, The Cryosphere, 12, 635–655, https://doi.org/10.5194/tc-12-635-2018, 2018.

4. There appears to be large uncertainty associated with the algae cell observations (Fig. 7b). How can the authors argue that a good fit is achieved between the field and modeled algal cell concentration? There needs to be further discussion on the utility of the logistic model as well as its deficiencies. How can we improve the model? What data and additional variables are needed? And, what is the greater link to surface albedo and melting?

We agree the model has a large uncertainly, particularly in the late of the melting season. Although our model has an uncertainly, it simulated the timing of algal blooming and the other of magnitude of algal abundance well. Again, this study is the first attempt to establish the algal model based on only a single glacier and season. More data of temporal change of algal abundance could reduce the uncertainty. Other factors affecting algal growth (e.g. inflow or outflow of algal cells in snowpack) may improve the model, however, we would not propose more complex model because of utility for coupling with the climate model. We'll try to simulate a temporal change in snow albedo coupling the algal model with a snow physical model (e.g. Aoki et al., 2011; Niwano et al., 2012) in the future. We have added the discussion of uncertainty and application of the model in the manuscript to reflect reviewer's comments (from Pg 2 lines from 31 to 34, Pg 9 line 14 and Pg 11 lines from 7 to 14). The following references have been added at Pg 2 line 32.

Aoki, T., Kuchiki, K., Niwano, M., Kodama, Y., Hosaka, M., and Tanaka, T.: Physically based snow albedo model for calculating broadband albedos and the solar heating profile in snowpack for general circulation models, J. Geophys. Res., 116, D11114, https://doi.org/10.1029/2010JD015507, 2011.

Niwano, M., Aoki, T., Kuchiki, K., Hosaka, M., and Kodama, Y.: Snow Metamorphism and Albedo Process (SMAP) model for climate studies: Model validation using meteorological and snow impurity data measured at Sapporo, Japan, J. Geophys. Res., 117, F03008, https://doi.org/10.1029/2011JF002239, 2012.

Specific Comments:

12. Pg. 6 line 2: Change to '3.1*10^3 cells m^-2'. And, again on line 4.

The words have been corrected (Pg 6 lines 11 and 14).

13. Pg. 6 line 17-18: What evidence do you have to validate that the red algal cells originate from windblown spores? Is there a way to verify this further and possible local sources (eg. nearby tundra)?

We don't have a direct evidence to prove the source of algal spores. A study on mineral dust on this glacier showed that they are likely to be supplied from local ground surface (e.g. moraine near the glacier), rather than the distant areas (Nagatsuka et al., 2014; 2016). As the initial algal concentration was greater in the site where the mineral dust was more abundant, we would think that the algal spores may be originated from the same as mineral dust. We have discussed the source of the algal spores more carefully in the text (Pg 7 lines from 8 to 11) and the following references have been added at Pg 7 line 9.

Nagatsuka, N., Takeuchi, N., Uetake, J. and Shimada, R.: Mineralogical composition of cryoconite on glaciers in northwest Greenland. Bull. Glaciol. Res., 32, 107–114, doi:10.5331/bgr.32.107, 2014.

Nagatsuka, N., Takeuchi, N., Uetake, J., Shimada, R., Onuma, Y., Tanaka, S. and Nakano, T.: Variations in Sr and Nd isotopic ratios of mineral particles in cryoconite in western Greenland. Front. Earth Sci., 4, 93, doi: 10.3389/feart. 2016.00093, 2016.

14. Pg. 7 line 5-6: reword sentence structure.

The sentence has been revised (Pg 7 lines from 22 to 24).

15. Pg. 7 Equations 1 and 2: These equations may be better placed in the Methods section.

We thank this suggestion and agree that is another option to present our study. However, our study has not only the establishment of the model, but also describe the observational results of algal temporal change on the glacier. So, we finally decided to keep the equations to be placed in discussion section, as we would think it would be readable.

16. Pg. 8 line 2-3: are these numbers correct? The text states the initial concentration was substantially smaller than the final concentration. Check the concentration numbers.

We checked the concentration numbers in the sentence, but there was no contradiction in the concentration numbers in the sentence. We have revised the sentence because it seems to cause a misunderstanding (from Pg 8 line 31 to Pg 9 line 1).

17. Pg. 8 line 4-5: Why aren't the authors using two separate carrying capacities for Site-A and Site-B, if they have different maximum concentrations of algal cells?

Results showed that the increasing rate of the algal concentration at Site-A appeared to be slow down at the end of the study period, in contrast, that at Site-B continued to increase significantly. Thus, we considered that algal concentration did not reach the carrying capacity at Site-B. The algal cell concentration at Site-B would increase further after the study period because the calculated snow surface temperature at Site-B was above 0°C after the day. Therefore, we used the only carrying capacity at Site-A. We have added the explanation about the carrying capacity at Site-B to the manuscript (Pg 8 lines from 25 to 29).

18. Pg. 8 line 21-22: The text of 100 times more at Site-A than Site-B is redundant to the previous few lines of text.

We have revised the sentence (Pg 9 lines from 23 to 25).

19. Pg. 24 Fig. 7b and c: Error bounds are needed for the logistic model (solid) line. Similarly, for Fig. 8b and c.

We may add the uncertainly of the model as error bounds for the line, however, it is difficult to quantify the uncertainly (confidence level) for the logistic model line in the study. The variance of the algal cell concentration calculated by the logistic model probably would not be constant, but increase over time, therefore, the confidence level (error bound) is likely to vary and is too complicate to be reproduce quantitatively with the model. We have added the explanation about the confidence level to the manuscript (Pg 9 lines from 7 to 9).

Observations and modelling of algal growth on a snowpack in northwest Greenland

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Abstract. Snow algal bloom is a common phenomenon on melting snowpacks in polar and alpine regions and can substantially increase melting rates of the snow due to the effect of albedo reduction on the snow surface. In order to reproduce algal growth on the snow surface using a numerical model, temporal changes in snow algal abundance were investigated on the Qaanaaq Glacier in northwest Greenland from June to August 2014. Snow algae first appeared at the study sites in late June, which was approximately 94 hours after air temperatures exceeded the melting point. Algal abundance increased exponentially after the appearance, but the increasing rate became slow after late July, and finally reached 3.5×10^7 cells m^{-2} in early August. We applied a logistic model to the algal growth curve and found that the algae could be reproduced with an initial cell concentration of 6.9×10^2 cells m^{-2}, a growth rate of 0.42 d^{-1}, and a carrying capacity of 3.5×10^7 cells m^{-2} on this glacier. This model has the potential to simulate algal blooms from meteorological data sets and to evaluate their impact on the melting of seasonal snowpacks and glaciers.

1 Introduction

Snow algae are cold-tolerant, photosynthetic microbes growing on snow and ice and are commonly found on glaciers and snowfields worldwide. Snow algal blooms occur on thawing snow surfaces and changes the colour of the snow to red or green (Thomas and Duval, 1995; Hoham and Duval, 2001; Takeuchi, 2013). Red snow algal blooms (usually by *Chlamydomonas* (*Cd.*) *nivalis*) commonly occur in polar and alpine snow fields (Hoham and Duval, 2001; Segawa et al., 2005; Takeuchi et al., 2006; Lutz et al., 2016; Tanaka et al., 2016; Ganey et al., 2017).

The conditions required for the growth of snow algae are the occurrence of liquid-water, solar radiation, and nutrients. Snow algal cells are typically present in the liquid water film surrounding snow grains when the snow melts (Fukushima, 1963). Field observations showed that snow algae begin to grow when the air temperature is above the freezing point for several days, suggesting that algal growth requires a certain amount of water content in the snow (Pollock, 1972; Onuma et al., 2016). A field study on algal photosynthesis suggested that algal growth requires at least 1% of incident photosynthetically active radiation in the snowpack, promoting photosynthesis and germination of algae (Curl et al., 1972). After the algae appears on

the snow surface, nutrient depletion (particularly nitrates) in the snowpack can cause shifts in life cycle phases and decrease the growth rate (Hoham et al., 1989). Previous studies have shown that the abundance of snow algae increases as the snow melts. For example, snow algal abundance on a glacier in Alaska continued to increase during the melting season until the snowpack completely melted on the glacier surface (Takeuchi, 2013). Snow algal abundance on a seasonal snowpack in Japan increased exponentially with snow melting until the snowpack completely melted (Onuma et al., 2016). Such temporal changes in snow algal abundance can be affected by the snow conditions, such as water content, solar radiation, and nutrient availability.

A numerical model could be utilized to reproduce the seasonal change in algal abundance on snowpacks, to understand algal growth in snowfields on a regional or worldwide scale, and to evaluate their effects on the surface albedo and resultant melting rate. The effect of algae on surface albedo can be physically calculated using an albedo model based on algal abundance (Cook et al., 2017a; 2017b). A temporal change in snow algal abundance could also be reproduced using a numerical model. Many models have been proposed and applied to temporal changes in the abundance of photosynthetic microbes in aquatic environments such as lakes or oceans. For example, there has been a model for cyanobacteria in lakes, which can reproduce their exponential growth using their initial concentration, growth rate, and nutrient concentration (Chen et al., 2009). Additionally, a model for algae (diatoms) growth in sea ice was developed using a sea ice physical model (Pogson et al., 2011). This model can reproduce the temporal change in chlorophyll a concentration in Arctic sea ice from the initial chlorophyll a concentration, algal growth rate, and grazing rate. The exponential growth of snow algae observed on a seasonal snowpack in Japan was reproduced using a Malthusian model (Onuma et al., 2016). Although this model might be effective for the seasonal snowpacks that exist for a short period and disappear in spring or early summer, it is questionable whether the model is suitable ~~works~~ for algae on permanent snowfields or glaciers.

The Greenland Ice Sheet, the second largest continuous body of ice in the world, is known to be inhabited by snow algae. Several studies have reported the visible red snow caused by blooms of *Cd. nivalis* over the ice sheet (Lutz et al., 2014; Uetake et al., 2010; Takeuchi et al., 2014). The ice sheet is reportedly losing mass due to an increase in temperature and decrease in surface albedo during the last two decades (Rignot et al., 2008; Wientjes and Oerlemans, 2010; Box et al., 2012). ~~Decline in snow surface albedo by algal blooms might have increased surface melting rates and decreased mass of the ice sheet in recent years (Yallop et al., 2012; Aoki et al., 2013; Lutz et al., 2016).~~ Decline in surface albedo by snow and ice algal blooms can increase surface melting rates and thus is likely one of the factors to cause mass loss of the ice sheet in recent years (Yallop et al., 2012; Aoki et al., 2013; Lutz et al., 2014; Lutz et al., 2016; Tedstone et al., 2017; Stibal et al., 2017). Observation of a glacier in south east Greenland showed surface ~~albedos~~ reflectance in the visible wavelengths for red snow (49%) to be lower than that of clean snow (75%), and that snow algal growth might lead to a positive feedback, increasing the melting rate of the glacier (Lutz et al., 2014). Quantification of snow algal abundance is important for estimating the melting rate of snow over the ice sheet. Niwano et al. (2015) demonstrated that the snow albedo and snow melting in Greenland Ice Sheet can be simulated by a snow physical model (Niwano et al., 2012) that incorporates a physically based snow albedo model (Aoki et al., 2011). Establishment of a numerical model for algal growth possibly lead to simulate the snow melting including the effect of algal growth on snow albedo by coupled snow microbial-physical model. However, there is little information on the

temporal changes in snow algal abundance on a snowpack in Greenland, and a numerical model for the snow algal growth has not been established to date.

In this study, biological and meteorological observations were conducted on the Qaanaaq Glacier located in north west Greenland in order to quantify the temporal change in snow algal abundance and establish a numerical model for algal growth. Temporal changes in algal abundance on the snow surface were quantified at two locations on the glacier from June to August in 2014 and were fitted to a simple numerical equation. Factors affecting the parameters of the equation are discussed in terms of meteorological data and, physical and chemical snow data from the study sites.

2 Study sites and methods

The investigation was conducted at the Qaanaaq Ice Cap in northwest Greenland (Fig. 1) from June to August in 2014. The Qaanaaq Ice Cap, which lies on a small peninsula of north west Greenland, covers an area of 286 km^2 and has an elevation of approximately 1,110 m a.s.l. (Takeuchi et al, 2014; Sugiyama et al, 2014). We selected two study sites at different elevations (Sites-A and B) on the Qaanaaq Glacier, which is an outlet glacier of the ice cap and is easily accessible on foot from Qaanaaq village. Site-A is a snowpack located at an elevation of 551 m a.s.l. towards the middle of the glacier and is likely formed by snowdrift. Since the depth of the snowpack was deeper than that of surrounding areas, the snow persisted through much of the melting season. Site-B is located at 944 m a.s.l., and was close to the equilibrium line of the glacier (Tsutaki et al., 2017). Meteorological data used in the study were collected with an automatic weather station (AWS), which was installed at Site-B in 2012 by the Snow Impurity and Glacier Microbe effects on abrupt warming in the Arctic project (SIGMA) (Aoki et al., 2014). Air temperature and solar radiation were collected hourly from April to August 2014 using the AWS. Aoki et al. (2014) provided a more detailed description of the AWS. The temperature sensor and pyranometer of the AWS were placed at heights of 3.0 m and 2.5 m above the snow surface, respectively. Air temperature at Site-A was calculated from the air temperature collected at Site-B with a temperature lapse rate, which was assumed as -7.80×10^{-3} K m^{-1} (Sugiyama et al., 2014). Solar radiation at Site-A was measured hourly from day 172 (21 June 2014) to 214 (2 August 2014) with a pyranometer (EKO ML-020) installed at 1.5 m above the snow surface. The measured time of the hourly meteorological data is defined as Local Time (LT = Greenwich Time – 2 h) in summer.

Snow pits were observed once weekly during the study period at both sites to determine vertical profiles of snow type, temperature, density, and liquid-water content. The snow temperature was measured with a thermistor sensor (CT-430WP, Custom Ltd, Tokyo, Japan). The volumetric liquid-water content in snow layers was obtained from snow density and snow permittivity, which were measured using a density sampler and dielectric probe (Denoth, 1994), respectively. Snow surface temperature was obtained from direct measurements and from calculating the observed downward and upward longwave radiant fluxes assuming the emissivity of the snow surface to be 0.98 (Armstrong and Brun, 2008), following the protocol of Niwano et al. (2015).

Surface snow collection and snow pit observation were performed, simultaneously from days 162 to 214 (nine times total) at Site-A and from days 168 to 215 (eight times total) at Site-B. Samples were collected from one to five randomly selected surfaces (depth of 0 cm to 2 cm) using a stainless-steel scoop. The sampling area ranged from 100 to 900 cm^2 and was recorded for each collection. Snow layers below the surface were also collected from snow pits at Site-A on day 162 and Site-B on day 168. The samples collected were from the surface layer (depth = 0 – 2 cm), the subsurface layer (depth = 2 – 10cm), and the layers of every 10 cm down to the previous summer layer (depth = 150 cm for the site-A and 142 cm for the Site-B). All of the ~~snow~~ samples were preserved in Whirl-Pak® bags (Nasco, Fort Atkinson, Wisconsin, USA). Electrical conductivity (EC) and pH for the collected samples were measured using a portable pH-conductivity meter (F-54, HORIBA, Japan) after the samples were melted in Qaanaaq village. Samples used for algal cell analysis were collected separately. These samples were melted and preserved in 3% formalin in 30 ml clean polyethylene bottles before being transported to Chiba University, Japan, for analysis.

Algal abundance was obtained by cell counting and was represented as cell numbers per unit surface area of snowpacks. Water samples of 20–1000 µl were filtered through a hydrophilized PTFE membrane filter (pore size 0.45 µm, Millipore). The number of algal cells on the filter was counted two to five times for each sample using an optical microscope (BX51, OLYMPUS, Japan) and cell concentration (cells L^{-1}) were obtained from mean cell counts and filtered sample volumes. Cell numbers per unit area (cells m^{-2}) were calculated using the cell concentration and area of sample collection. To obtain a cell volume biomass (biovolume), mean cell volumes were estimated by measuring the size of 5–50 cells for each species using a microscope and mean cell volume was obtained geometrically. Total algal volume per unit area (mL m^{-2}) per taxon was obtained by the multiplying cell count and cell volume.

Abundance of mineral particles in snow was quantified using another set of samples collected from the snow surface. Melted samples were dried (60°C, 24 h) in pre-weighed crucibles then combusted (500°C, 3h) in an electric furnace to remove organic matter. The mass of mineral particles per area (g m^{-2}) was obtained from the combusted sample weight and sampling area since only mineral particles remained after combustion.

3 Results

3.1 Meteorological conditions

Meteorological observations on the Qaanaaq Glacier showed that air temperature was below 0°C from April through most of June and increased above 0°C from late June through early August (Fig. 2a). The daily mean air temperature at Site-B ranged from -25.8°C to -11.1°C in April and from -19.7°C to -7.9°C in May. It first exceeded 0°C in daytime on day 154 (3 June 2014) and remained above 0°C from late June to early August. This air temperature record indicates that snow melting occurred continuously from late June to August at the study sites.

Solar radiation gradually increased from April to mid-July, before decreasing (Fig. 2b). At the location of the Qaanaaq Glacier, the sun never set from day 108 (18 April 2014) to day 241 (29 August 2014). Monthly mean solar radiation at Site-B

for April, May, June, and July was 165, 276, 296, and 244 W m^{-2}, respectively. The daily mean solar radiation in July ranged from 71 and to 375 W m^{-2} (mean: 218 W m^{-2}) and from 90 to 383 W m^{-2} (mean: 244 W m^{-2}) at Sites-A and B respectively, indicating that the solar radiation did not significantly vary among sites.

3.2 Physical and chemical conditions of surface snow

Snow observations showed that the surface snow was consistently wet from late June to early August at both sites (Figs. 3 and 4). When the observation was started on day 168 (17 June 2014), the surface snow at Site-B was fresh dry snow without surface melt. This snow became granular on day 176, implying that the snow surface began to melt. Surface snow density was 386 kg m^{-3} on day 168 and gradually increased until day 215 (3 August 2014, 489 kg m^{-3}). The mean snow grain size was 0.3 mm on day 168, 0.9 mm on day 181, and varied between 0.7 and 0.9 mm until day 215. Snow surface level decreased by 121 cm during the study period (47 days). Surface snow temperature was –0.2°C on day 168 and 0°C from days 176 to 215, except day 197 (–0.1 °C). Hourly surface snow temperature was calculated from longwave radiation and showed that the duration temperature was above 0°C for 885 h of 1129 h during the study period. The volumetric liquid-water content of surface snow was 6.3% on day 181 and varied between 3.8 and 4.9% until day 215. Changes in snow properties were similar between sites. For example, the surface snow of Site-A was granular and the surface snow temperature was 0°C after day 179. The results indicate that the snowpacks at both sites melted continuously from late June until early August.

The mass of mineral particles in surface snow gradually increased from June to early August at both sites, and it was consistently greater at the lower site (Site-A) than at the higher site (Site-B) (Figs. 3 and 4). The mineral abundance at Site-B was 3.0×10^{-3} g m^{-2} on day 176 and gradually increased to $7.6 \pm 3.0 \times 10^{-1}$ g m^{-2} (mean ± SD) until day 215. The abundance at Site-A was 1.4 g m^{-2} on day 179 and gradually increased to 6.6 ± 1.9 g m^{-2} until day 214. A statistical test demonstrated that the temporal changes in mineral abundance were significant at both sites (one-way ANOVA, Site-B: $F = 4.95$, $P = 0.02 < 0.05$; Site-A: $F = 2.74$, $P = 0.004 < 0.01$). The comparison of the mineral abundance in August between Sites-A and B showed that their difference was statistically significant. (6.6 ± 1.9 vs. $7.6 \pm 3.0 \times 10^{-1}$ g m^{-2}; Student's *t*-test, $t = 4.10$, $P = 0.009 < 0.01$).

The EC and pH of surface snow did not show seasonal trends or differences between the sites. The EC ranged from 1.5 to 4.0 µS cm^{-1} (mean: 2.7 µS cm^{-1}) and from 0.4 to 3.2 µS cm^{-1} (mean: 2.4 µS cm^{-1}) at Sites-A and B, respectively. The pH ranged from 5.5 to 6.2 (mean: 5.9) and from 5.3 to 6.1 (mean: 5.8) at Sites-A and B, respectively. There was no significant difference in EC or pH between sites in late June (Student's *t*-test, EC: $t = 2.47$, $P = 0.13 > 0.05$; pH: $t = 2.32$, $P = 0.15 > 0.05$). The EC and pH in July and August did not significantly vary among sites.

3.3 Snow algae on snow surface

Microscopic observation revealed that the red spherical algal cells were dominant at both study sites. Algal cells (Fig. 5) contained a reddish-orange and/or green pigment and were 21.3 ± 2.3 µm in diameter. The cell volume biomass of this alga accounted for over 95% of the total algal biomass at both study sites. This alga was likely *Chlamydomonas* (*Cd.*) *nivalis* since

the shape, size, and pigmentation (Fig. 5) corresponded with the taxon observed previously in 2007 and 2012 on this glacier (Uetake et al., 2010; Takeuchi et al., 2014).

The other cell types were present in the samples in trace amount. One was spherical in shape with orange or green pigment, and its cell size was smaller (9.0 ± 2.2 μm) than the previously described algae. Another cell was also spherical but with pale blue-green pigments and was much smaller in size (4.6 ± 1.2 μm). These types of algal cells were likely the undefined alga and *Chroococcaceae cyanobacterium* reported by Uetake et al. (2010), respectively.

3.4 Temporal changes in algal cell concentration of surface snow

Microscopic analysis revealed that the algal cell appeared on the surface snow in late June and gradually increased until late July (Fig. 6). Algal abundance was 7.4 cells m^{-2} at Site-B when the algae first appeared on day 181 and then increased to 5.0 × 10^5 cells m^{-2} until day 215, although abundance decreased occasionally on days 190 and 197 (Fig. 6b). The algal cells at Site-A first appeared on day 179 (3.1×10^3 cells m^{-2}), then their abundance exponentially increased until day 201 (2.2×10^7 cells m^{-2}) (Fig. 6a). Temporal changes in algal abundance were significant at both sites (one-way ANOVA, Site-A: F = 2.45, P = 0.006 < 0.01; Site-B: F = 2.91, $P = 5.9 \times 10^{-5} < 0.01$). The snow pit samples collected before the appearance of the algae (on days 162 at Site-A and 168 at Site-B) contained no algal cell at in all of the snow layers down to the last summer surface.

The algal abundances on the snow surface at Site-B continued increasing until early August, whereas the abundances at Site-A did not significantly increase between days 201 to 214 (Fig. 6). The mean algal abundance at Site-A was 2.2×10^7 cells m^{-2} on day 201 and 3.5×10^7 cells m^{-2} on day 214. The algal abundance on day 201 was 637 times that of day 195; however, algal abundance on day 214 was only 1.6 times that of day 201. The temporal change in algal abundance at Site-A was not significant between days 201 and 214 (one-way ANOVA, F = 4.56, P = 0.26 > 0.01).

4 Discussions

4.1 Origin of snow algae and their growth condition on the Qaanaaq Glacier

The red snow phenomenon observed on the Qaanaaq Glacier is likely to occur every summer according to previous studies on the glacier (Uetake et al., 2010; Takeuchi et al., 2014). Additionally, the species causing this phenomenon are likely the same as those typically occurring in Arctic snowfields. The dominant algal cell, *Cd. nivalis*, has been widely reported in Arctic snowfields (Spijkerman et al., 2012; Takeuchi, 2013; Hisakawa et al., 2015; Lutz et al., 2016; Tanaka et al., 2016).

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 previous melting season. Algae growing on the snow surface are usually derived from spores transported by wind or animals from distant places (up to hundreds or kilometers) or from motile cells that migrated from the lower layers of the snowpack (Müller et al., 2001; Remias, 2012). The migration of motile cells in the snowpack requires solar radiation as well as liquid water (Hoham, 1980). However, ~~incident~~ photosynthetically active radiation can only penetrate to a depth of 1

m in wet snowpacks (Curl et al., 1972). When snow algae appeared on the snow surface at the study sites, the previous summer surface was located deeper than 1 m from the present surface (229 cm and 110 cm at Sites-A and B, respectively). The depth appeared to be too great for these cells to migrate to the surface. Furthermore, there was superimposed ice over the last summer surface in the snowpack at Site-B when the algae appeared (Aoki et al., 2014). The superimposed ice layers seem to block algal migration to the surface. The lack of algal cell in the snow pit samples also suggest the algal cell are not derived from the lower snow layers. Therefore, the algal cells are unlikely to have originated from beneath the snow~~, but from the atmosphere~~. Alternatively, algal cells might have been transported from the ground surface surrounding the glacier or from distant sources via atmosphere. Previous studies reported that mineral dust on glaciers in northwest and southwest Greenland is mainly supplied from local ground surfaces (e.g. moraine near the glacier), rather than the distant areas (Nagatsuka et al., 2014; 2016). Therefore, the algal spores, which have been washed out from the glacier and stayed on the ground, may be supplied with such dust around the glacier by wind.

Meteorological records suggest that the initiation of algal growth requires the air temperature to remain above 0°C for a certain period of time after the previous snowfall. The snow algae at both Sites-A and B appeared two days apart from each other. Prior to algal appearances, the hourly air temperature remained above 0°C for 94 h from day 175 at Site-A and for 136 h from day 176 at Site-B; there was no snowfall during this time at either site. The period from the last snowfall appears to be important in initiating snow algal growth, as fresh snow coverage inhibits photosynthesis of the snow algae under the snow. Additionally, snowmelt is required for the initiation of algal growth (Fukushima, 1963; Onuma et al., 2016). Snow algae on a snowpack in Japan has been reported to appear when air temperatures exceed 0°C for 24 h, which is likely the minimum requirement for initiating snow algal growth (Onuma et al., 2016). The duration was longer in this study than that which was observed in Japan. The longer duration may be due to a difference of algal species or weather conditions on this glacier. ~~Although further studies are necessary to determine the meteorological conditions necessary for the initiation of snow algal growth, these results suggest that continuous melting for a minimum of 94 h is required on the Qaanaaq Glacier.~~ These results suggest that continuous melting for a minimum of 94 h is required for the initiation of algal growth on the Qaanaaq Glacier although further studies are necessary to determine the snow physical conditions for the initiation.

4.2 Approximation of the algal growth curve with a numerical model

In order to reproduce the observed algal growth with a numerical equation, we applied a logistic model that utilizes a general differential equation of microbial growth to the observed algal growth curve. An increase in microbial cells can simply be expressed by a differential equation known as the Malthusian model, which is defined by an initial cell concentration and algal growth rate (Lavoie et al., 2005). The Malthusian model is based on the assumptions that microbial abundance increases by cell division of all present cells at a constant rate, that there is no addition or removal of cells in the habitat, and that light, nutrients, and habitable space are unlimited. According to this model, the microbial growth curve is calculated as follows (Cui and Lawson, 1982):

$$X = X_0 e^{\mu(t-t_0)}, \quad (1)$$

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}. The Malthusian model has been applied to observational microbial abundances in sea ice (Lavoie et al., 2005) and in snowfield (Onuma et al., 2016). However, the algal abundance at Site-A did not significantly increase after late July, despite the air temperature remaining above 0°C and a lack of snowfall, indicating that the Malthusian model could not represent the algal growth curve on the surface snow of the Qaanaaq Glacier. The decreased growth rate observed on the glacier suggests that algal abundance has a limited capacity in this habitat. A logistic model is a microbial growth equation with a carrying capacity, and thus could represent the algal growth curve observed in this study. The temporal change of the logistic model is represented as follows (Cui and Lawson, 1982):

$$X = \frac{K}{1+\frac{K-X_0}{X_0}e^{\mu(t_0-t)}}, t = d - d_f, \quad (2)$$

where K is the carrying capacity of algae in the snow surface (depth = 2 cm) and t_0 ~~can~~ is the day of the first appearance of algae on the snow surface. Since snow algae can grow only on the melting snow surface, we assumed that algal growth was interrupted when snow surface temperature was below 0°C. Thus, t represents the number of the days during which the mean temperature was above 0°C. This equation was fitted to the observational algal cell concentrations at Sites-A and B through Poisson regression. The observational data used are from the day of algal appearance (days 179 at Site-A and 181 at Site-B, t_0) through the last day of the study period (days 214 at Site-A and 215 at Site-B, t_{max}). This regression is based on the assumption that there is no inflow or outflow of algal cells on the snow surface. ~~Although the algal abundance on surface snow is possibly affected by algal cells carried by wind and from deeper snow, such effects appeared to be small enough to calculate algal growth because the initial concentration of algae on the surface (3.1×10^3 cells m^{-2} on day 179 at Site-A), which was likely due to wind, was substantially smaller than the final concentration (3.5×10^7 cells m^{-2} on day 214 at Site-A).~~ To fit Poisson regression to the observed algal cell concentrations, carrying capacity was assumed to be 3.5×10^7 cells m^{-2} at both sites based on the observed maximum concentration of algal cells (day 214 at Site-A). Although it is uncertain whether the algal concentration ~~on day 214~~ at Site-A was the greatest on day 214 in this ~~during the~~ summer, the carrying capacity ~~on the glacier~~ was likely around ~~3.5×10^7 cells m^{-2}~~ the value since the cell concentrations ~~of all of algal types~~ hardly increased from day 201 to 214 despite air temperatures remaining above 0°C. In contrast, the algal cell concentration at Site-B continued to increase significantly until day 215, suggesting that it did not reach the level of the carrying capacity at this site. The cell concentration would increase further after the day because the snow surface temperature calculated at Site-B kept above 0°C for a week. Although the carrying capacity possibly varies in different snow surfaces, it was assumed to be a same at Site-A and B in this study since they are on the same glacier.

No inflow of algal cells on the snow surface was assumed for this calculation because wind-delivery of algal cells appeared to be smaller compared with the abundance during the growth period. The initial concentration of algae on the surface (3.1×10^3 cells m^{-2} on day 179 at Site-A and 7.4 cells m^{-2} on day 181 at Site-B), which is probably equivalent to the algal cells of the wind-delivery, was substantially smaller than the final concentration (3.5×10^7 cells m^{-2} on day 214 at Site-A and 5.0×10^5

cells m^{-2} on day 215 at Site-B). Outcropping algal cells from the subsurface snow also appear to be insignificant because no algal cell was detected in all of the snow layers below the surface. The outflow of algal cells by melt water is also likely to be insignificant to affect the algal cell abundance on the snow surface since the algal cell concentration kept increasing during the study period.

Fitting the data to the model showed that the coefficients of determination ~~of~~ in the regressions (R^2) were 0.64 and 0.96 at Sites-A and B, respectively, suggesting that the algal growth curve was reproduced well with the equation (Table. 1, Figs. 7 and 8). However, the confidence levels cannot calculate for the regression curve because the standard deviations for the observed algal cell concentration increased over time, therefore, the uncertainty of the calculated algal abundance appears to become larger in the late of the melting season. The decline of algal cell concentration observed from days 201 to 208 at Site-A was not reproduced in the calculated growth curve. ~~The calculated growth curve at Site-A did not reproduce the reduction of algal cell concentration from days 201 to 208.~~ This is likely the reason for the lower R^2 value at Site-A. However, the calculated ~~algal~~ cell concentration (3.4×10^7 cells m^{-2}) was consistent with the observed abundance (3.5×10^7 cells m^{-2}) ~~at Site-A~~ on day 214, which was the day when algal cell concentration on surface snow was the greatest during the observational period; this suggests that the model can accurately reproduce the cell abundance in the order of magnitude and the timing when algal cell concentration reached the carrying capacity.

4.3 Factors affecting parameters of algal growth model

The growth rates (μ) obtained from the regression of the algal growth curve did not significantly differ between the two sites, whereas the initial cell concentration (X_0) at the lower site was 100 times greater than that of the higher site (Table 1).

The difference in initial cell concentration (X_0) between the two sites was likely attributed to the abundance of initial algal spores supplied from the atmosphere. ~~The initial cell concentration observed at Sites-A and B were 6.9×10^2 cells m^{-2} and 6.3 cells m^{-2}, respectively, and that of Site-A was approximately 100 times more than that of Site-B (Table 1). The abundance of mineral particles on the snow surface was also significantly greater at Site-A (1.4 g m^{-2}) than Site-B (7.0×10^{-3} g m^{-2}).~~ The initial cell concentration observed at Sites-A and B were 6.9×10^2 cells m^{-2} and 6.3 cells m^{-2}, and the abundance of mineral particles on the snow surface was also significantly greater at Site-A (1.4 g m^{-2}) than Site-B (7.0×10^{-3} g m^{-2}, Table 1). The sources of mineral particles on the Qaanaaq Glacier were mostly from local sediments, such as soil and moraine near the glacier (Nagatsuka et al., 2014). Therefore, the initial algal spores on surface snow are likely supplied with mineral particles by wind from surrounding ground surface. There is little information on the abundance of initial algal spores on snow surface. Estimation of initial algal concentrations from mineral particle abundance could be applied to this model in the other glaciers or ~~snowfileds~~ snowfields since the abundance of mineral particles is widely available by observation, the surface mass balance model on the Greenland Ice Sheet (Goelles et al., 2015), and atmospheric circulation models (Ginoux et al., 2001).

The growth rates (μ) obtained from both sites were similar, suggesting that growth rates on the glacier are constant. The growth rates were 0.39 d^{-1} and 0.42 d^{-1} at Sites-A and B, respectively (Table 1). Although solar radiation might affect algal

photosynthesis and thus their growth rate on the snowpack, the effect is unclear since there was no significant difference in the July solar radiation among the two sites (218 vs. 244 W m^{-2} for Sites-A and B, respectively; Student's *t*-test, $t = -0.99$, $P = 0.32 > 0.05$). According to the measurement of t~~T~~he growth rate of isolated snow algae, *Chloromonas nivalis* in the culture, it was 0.6 d^{-1} at 18°C water (Leya et al., 2009), which ~~was~~ is significantly greater than the growth rate of 0.39–0.42 d^{-1} in the present study (Table 1). The lower growth rate in our study is likely due to the lower temperature of the algal habitat compared to the culture conditions, as growth rate of fresh water algae is dependent on water temperature (Eppley, 1972). The growth rate of snow algae may also vary among algal species although further study is necessary.

The carrying capacity of snow algae may be determined by nutrient availability in the snowpack. The carrying capacity was estimated to be 3.5×10^7 cells m^{-2} in this study, based on the observed growth curve ~~in this study~~ (Table 1). Although there are no observational data on the carrying capacity of snow algae, it could be represented by the cell concentration of snow algal bloom reported late in the melting season in previous studies. Cell concentrations of snow algal blooms reported previously in various geographical locations ranged from 5.1×10^7 to 7.5×10^9 cells m^{-2} (Table 2), suggesting that carrying capacity varies among sites and might be determined by environmental conditions. There are two possible factors affecting carrying capacity: (1) the reduction in physical space available for microbial growth (i.e. the volume of liquid melt water, McKindsey et al., 2006) and (2) the exhaustion of resources for the algae on the snow surface (Cui and Lawson, 1982). The maximum algal cell volume on surface snow (depth = 2 cm) at Site-A (day 214) was substantially smaller compared to the total volume of liquid-water in the surface snow obtained from the water content (0.19 mL m^{-2} vs. 500 mL m^{-2}); this indicates that the physical space for algal growth in the habitat is not a factor affecting carrying capacity in this study. Nutrients such as nitrogen and phosphorus are essential elements for algal growth and are usually supplied from the atmosphere to the snow surface as aerosols. Phosphorus supplied that is carried by wind to glaciers in the form of phosphate minerals easily becomes a limiting factor for algal growth compared to nitrogen, as the concentration of phosphorus was less than that of nitrogen in glaciers (Stibal et al., 2008). ~~–~~Addition of nutrients from outside likely increases snow algal abundance in the snowpacks reported by Ganey et al. (2017). ~~Therefore, the supply of nutrients in the form of mineral dust and/or nitrogen aerosol to the glacier likely determines the carrying capacity in the snowpack, although further study is necessary to substantiate this claim.~~ Therefore, the carrying capacity may be determined by approximation using the relationship between observational abundance of algal cells and mineral dust on the snow surface although further study is necessary to substantiate this claim.

5 Conclusions

The temporal changes in snow algal abundance on snowpacks of the Qaanaaq Glacier in northwest Greenland were studied. Spherical algal cells filled with red pigment, which are likely *Cd. nivalis*, were dominant on the snowpack. The algal cells first appeared on the snow surface in late June when snow ~~from the previous season~~ had melted and the air temperature remained above 0°C exceeded for approximately 94 h. Algal abundance increased exponentially for a month, and then the growth rate

decreased mid-July, even though the air temperatures remained above 0°C and no snowfall occurred. A logistic model was applied to the observed algal growth curves to reproduce abundance numerically using three parameters; the initial cell concentration (X_0), growth rate (μ), and carrying capacity (K). The growth curves were reproduced accurately with coefficients of determination (R^2) of 0.64 and 0.96 at the lower and higher sites, respectively. Our observational results suggest that the model parameters can be determined using the environmental conditions (physical and chemical snow properties and meteorological conditions) of the glacier; ~~thus, this logistic model could be applied to the snow algae on various glaciers and snowfields.~~ thus, this logistic model has a potential to reproduce the snow algae on glaciers or ice sheet scale although further studies are necessary to determine the three parameters of the model. The parameters determined in this study were based on the observation of a single glacier and season, more observation data of the algal seasonal growth could reduce the uncertainty of the model. In order to validate and calibrate the model parameters in more extensive areas of the glacier or the ice sheet, satellite images could be useful as recent study successfully quantified the red algal abundance on an icefield in Alaska (Ganey et al., 2017). Furthermore, it is important to understand the life cycle of snow algae including the process of atmospheric transportation of the algal spores and effect of nutrient dynamics within the surface snow. Our results demonstrate that a simple numerical model could simulate the temporal variation in algal abundance on snow surface on a Greenlandic glacier. In future, coupling this algal model with a regional climate model in Greenland, such as the model proposed by Niwano et al. (2018), would enable us to estimate snow melting regarding the effect of algal blooming. In addition, the model would be useful to know the algal life cycle on the ice sheet. ~~Although more research is necessary to validate the model, our results demonstrate that this simple numerical model could simulate the temporal variation in algal abundance on snow surface. This model is useful for quantifying algal growth on snowpacks worldwide, physical snow models or global climate models, and evaluating the effects of algae on the surface albedos and melting rates of snowpacks.~~

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Table 1: List of the parameters of a logistic model of snow algal growth obtained from the data of each study site.

Site	Initial cell Concentration X_0 (cells m^{-2})	Growth rate μ (d^{-1})	Carrying capacity K (cells m^{-2})
Site-A	6.9×10^2	0.42	3.5×10^7
Site-B	6.3	0.39	3.5×10^7

Table 2: List of maximum algal cell concentrations of red algal bloom reported from various snow fields over the world. Maximum algal cell concentrations per area (cells m^{-2}) were obtained by calculation from reported maximum algal cell concentrations per volume (cells mL^{-1}) assuming the snow density of granular snow to be 500 kg m^{-3} and the depth of collected samples to be 0.02 m.

Study sites	Algal species	Maximum algal cell concentration (cells m^{-2})	References
Oregon, USA	*Chlamydomonas nivalis*	2.3×10^9	Sutton, 1972
Washington, USA	*Chloromonas brevispina*	5.0×10^9	Hoham et al., 1979
Antarctica	*Mesotaenium berggrenii*	1.0×10^9	Ling and Seppelt, 1990
Antarctica	*Chloromonas rubroleosa*	2.0×10^9	Ling and Seppelt, 1993
California, USA	*Trochiscia americana*	6.3×10^8	Thomas, 1994
Svalbard	*Chloromonas alpine*	7.5×10^9	Spijkerman et al., 2012
Alaska, USA	*Chlyamidomonas nivalis*	5.1×10^7	Takeuchi, 2013
SE-Greenland	*Chlyamidomonas nivalis*	5.0×10^8	Lutz et al., 2014

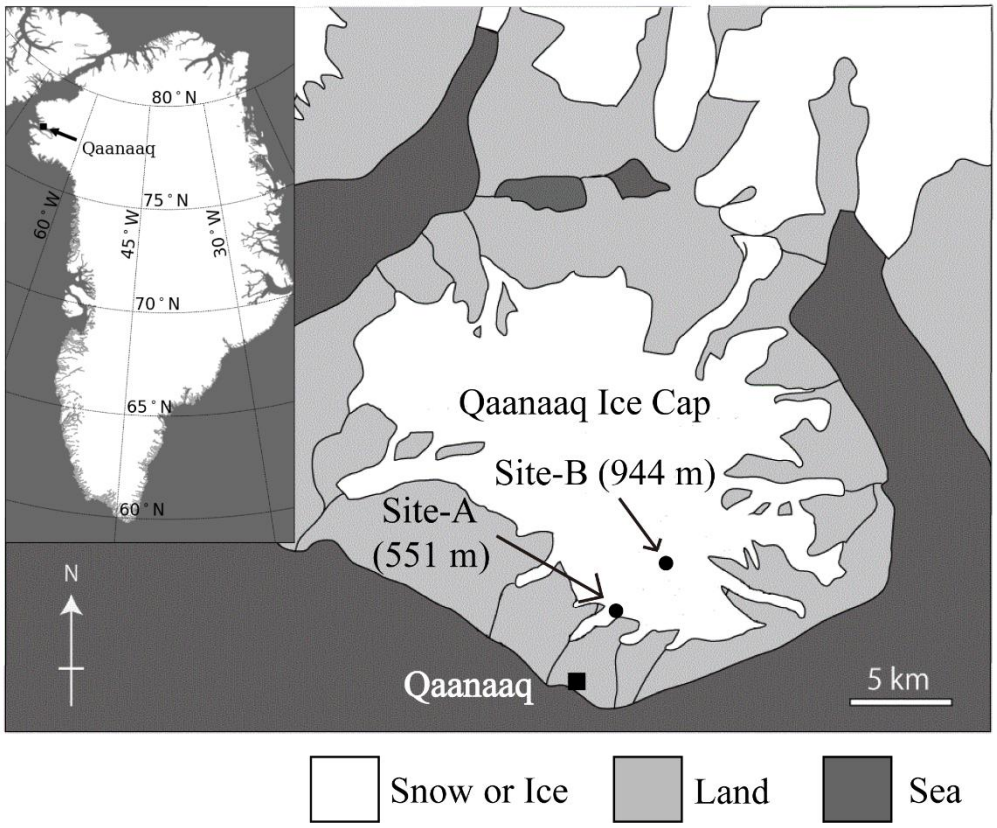

Figure 1: A map of the Qaanaaq Ice Cap in northwest Greenland, showing the location of sampling sites on the glacier.

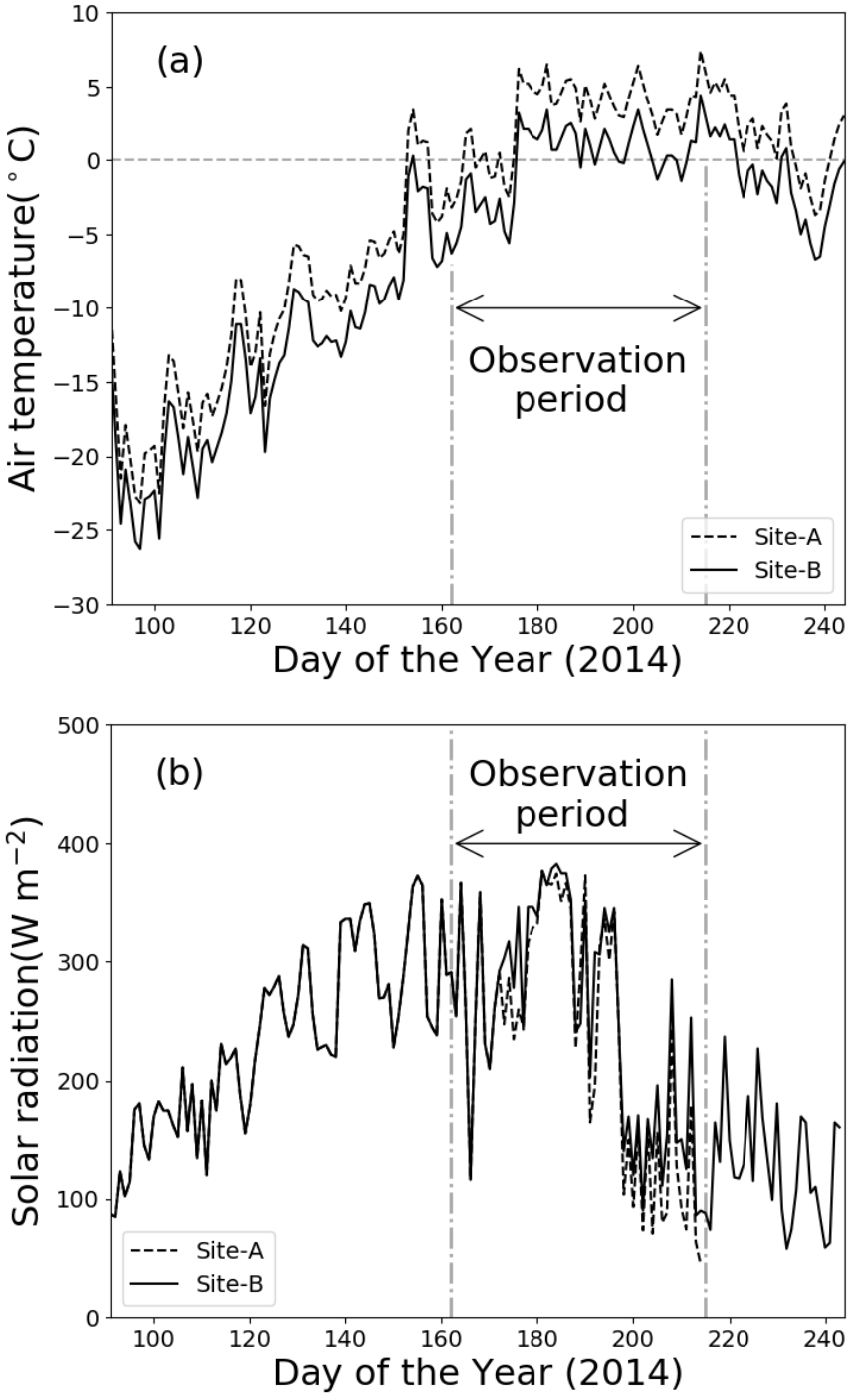

Figure 2: Meteorological conditions at Sites-A and B from 1 April to 1 September 2014. (a) Daily mean air temperature, (b) solar radiation.

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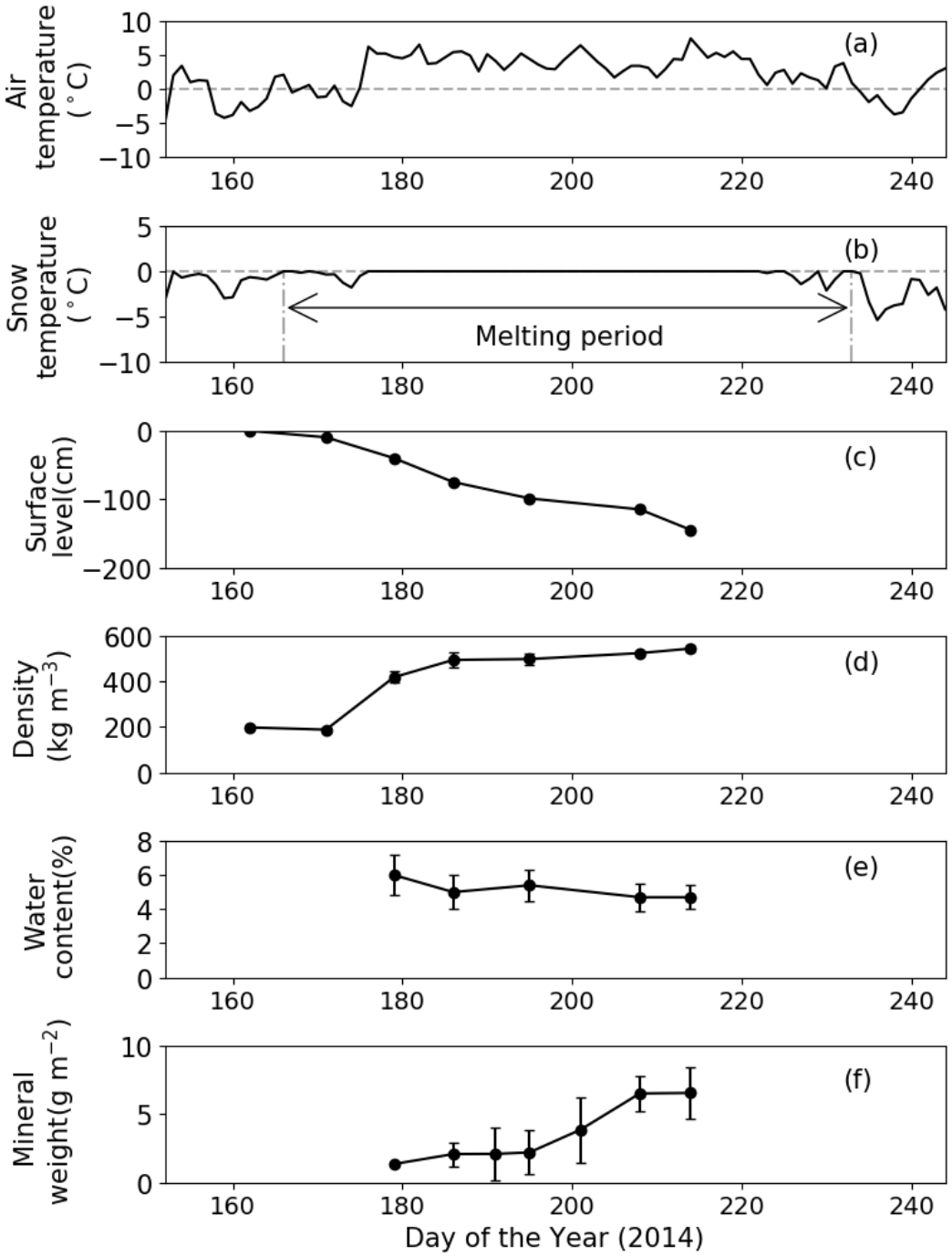

Figure 3: Meteorological and physical conditions of surface snow at Site-A from 1 June to 1 September 2014. (a) Mean daily air temperature, (b) mean daily snow surface temperature calculated from observed downward and upward longwave radiant fluxes, (c) relative snow surface level at the site (0 cm on day 162), (d) snow density, (e) volumetric liquid-water content of snow, and (f) abundance of mineral particles. Melting period in (b) is defined as a period from first day until last day when mean daily snow surface temperature was 0°C from 1 June to 1 September 2014. Standard deviation shown by error bars.

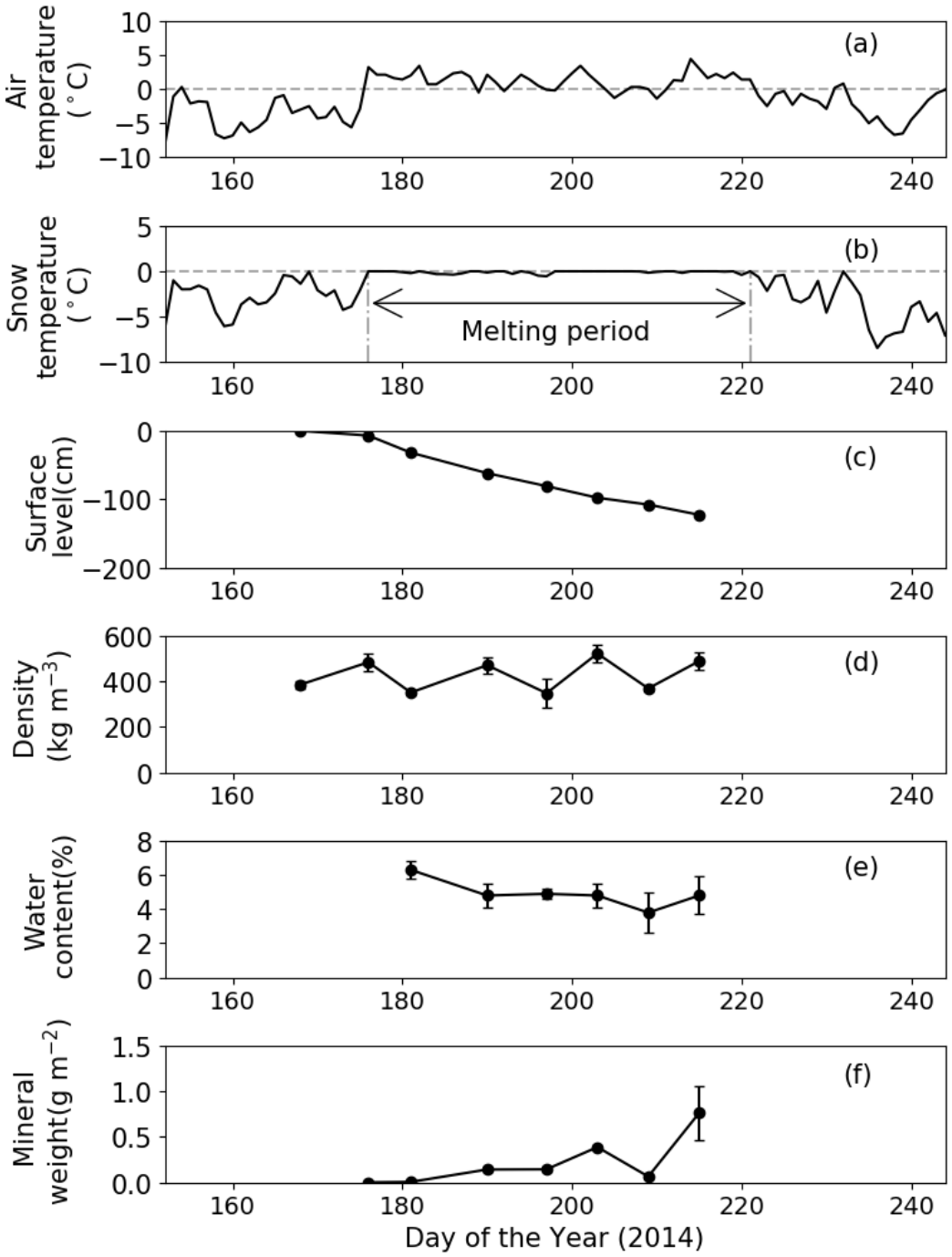

Figure 4: Meteorological and physical conditions on surface snow at Site-B from 1 June to 1 September 2014. (a) Mean daily air temperature, (b) mean daily snow surface temperature calculated from observed downward and upward longwave radiant fluxes, (c) relative snow surface level at the site (0 cm on day 168), (d) snow density, (e) volumetric liquid-water content of snow, (f) abundance of mineral particles. Melting period in (b) is defined as a period from first day until last day when the daily mean snow surface temperature was 0°C from 1 June to 1 September 2014. Standard deviation shown by error bars.

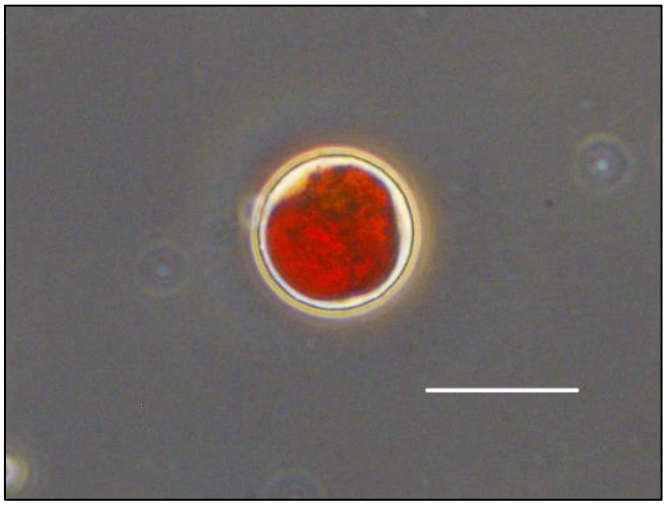

Figure 5: Photograph of snow algal cell observed on the snow surface at Site-A. An oval red cell with secondary carotenoids, most likely mature spores of *Cd. nivalis*, which is the dominant species at both sites. Scale bar = 20 µm.

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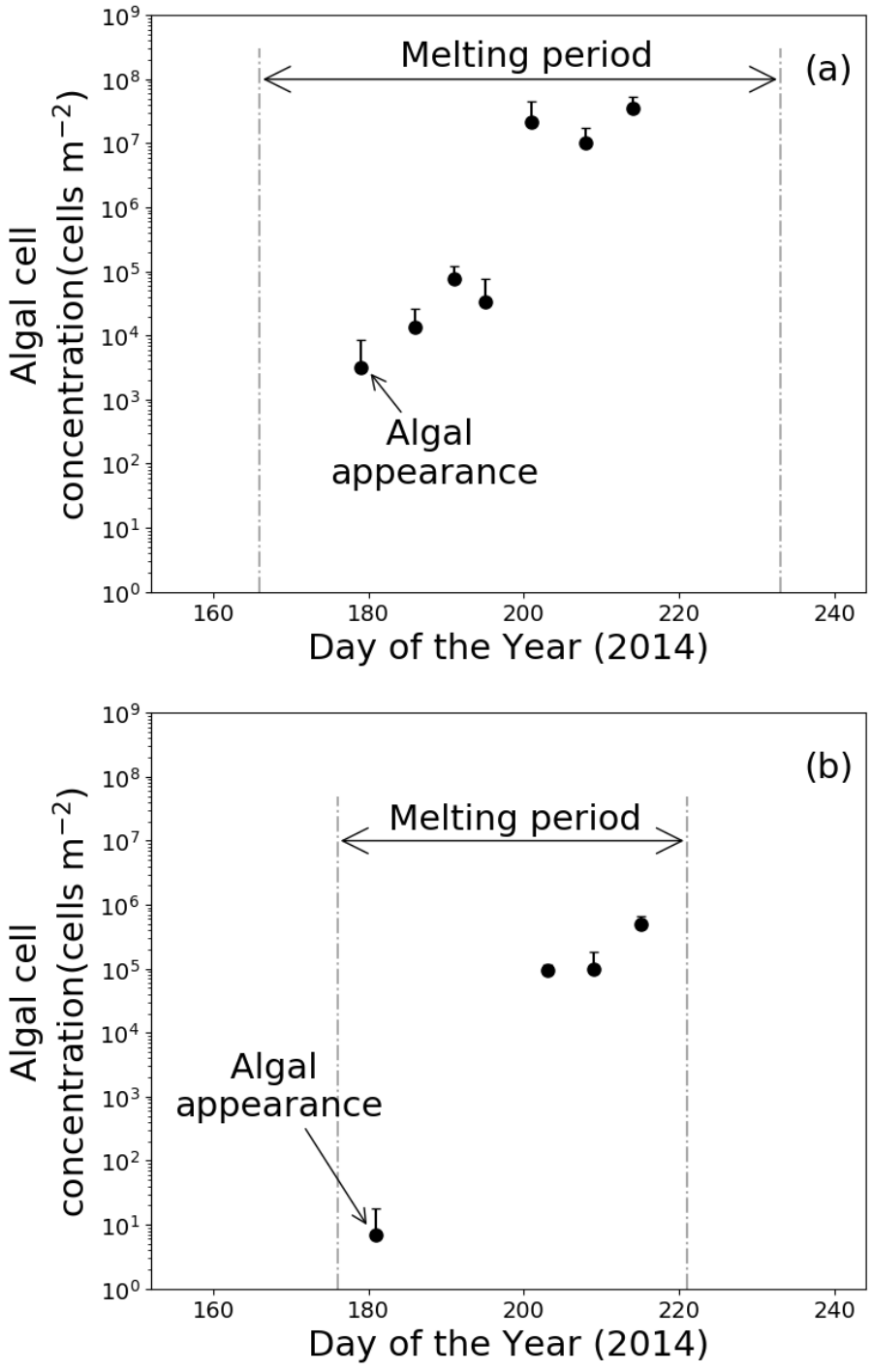

Figure 6: Temporal changes in algal abundance on snow surface at (a) Site-A and (b) Site-B. Melting period in (a) and (b) indicated in Figs. 3 (b) and 4 (b), respectively. Standard deviation shown by error bars.

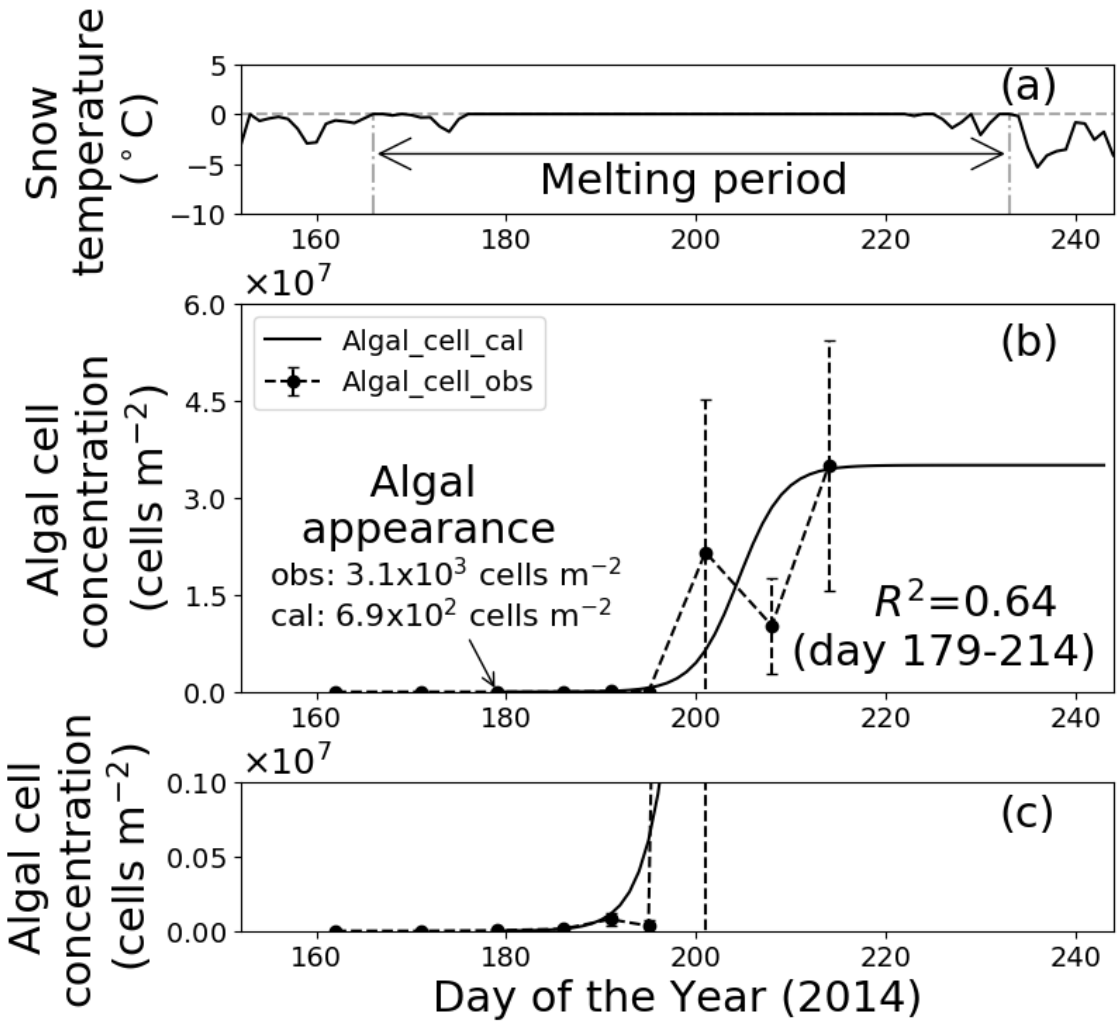

Figure 7: Temporal changes in snow temperature and algal abundance on the surface at Site-A. (a) Mean daily snow surface temperature, (b) observed and calculated algal abundance, and (c) enlargement of the observed and calculated algal abundance between 0 and 1.0 × 10^6 cells m^{-2}. Surface snow temperature was calculated from observed downward and upward longwave radiant fluxes. Solid marks indicate observed algal abundance. Solid lines indicate algal abundance calculated from regression by logistic model. Standard deviation shown by error bars.

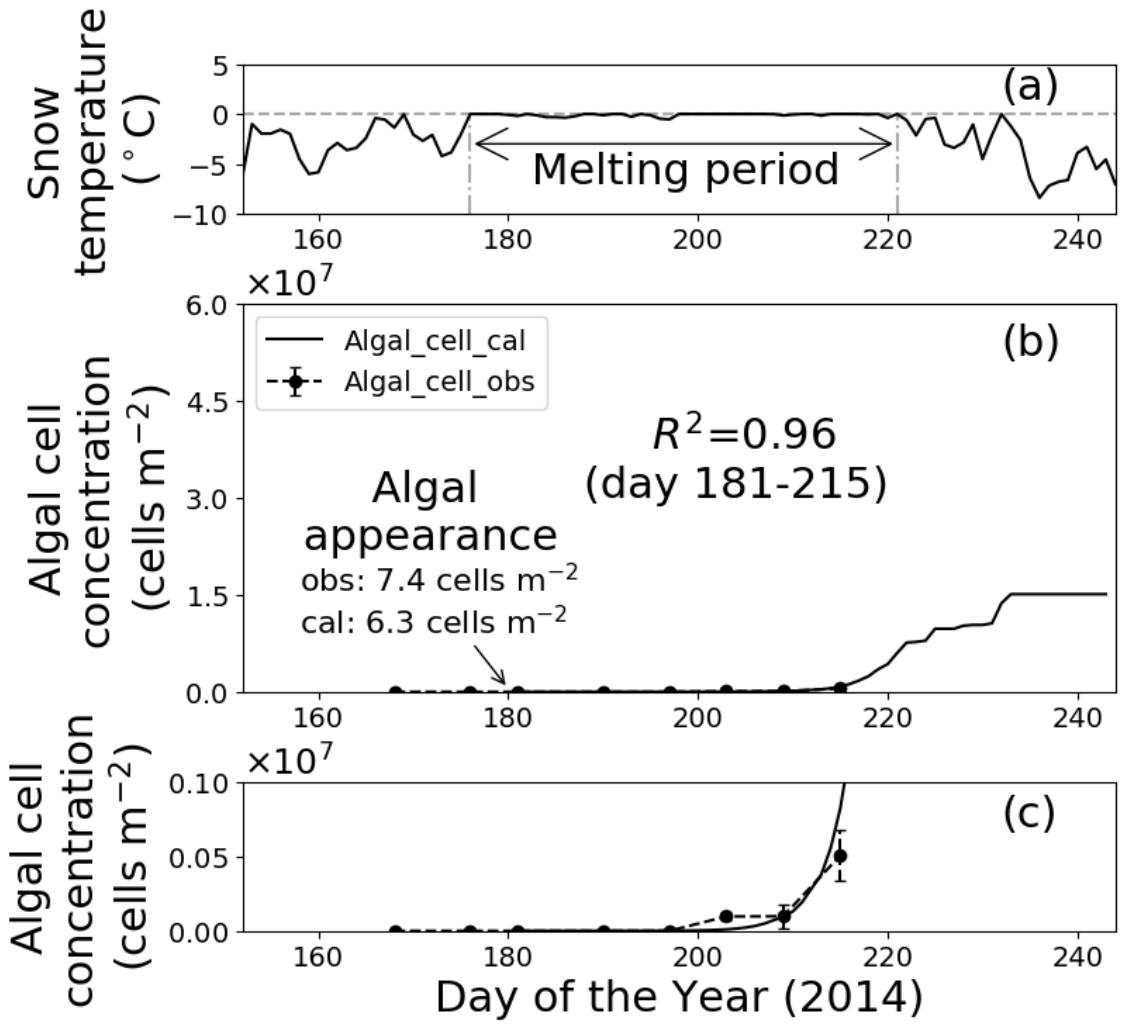

Figure 8: Temporal changes in snow temperature and algal abundance on surface snow at Site-B. (a) Mean daily snow surface temperature, (b) observed and calculated algal abundance, and (c) enlargement of the observed and calculated algal abundance between 0 and 1.0×10^6 cells m^{-2}. Surface snow temperature was calculated from observed downward and upward longwave radiant fluxes. Solid marks indicate observed algal abundance. Solid lines indicate algal abundance calculated from regression by logistic model. Standard deviation shown by error bars.