Anonymous Referee #1

Overall:

The authors have presented a paper that attempts to quantify biomass over the western Greenland Ice Sheet using the well known "rededge" technique that they refer to as "2BDA", which is often used for detecting chlorophyll containing biota such as photosynthetic algal blooms in oceanic and lacustrine environments, vegetation and crop mapping. Biomass quantification over the Greenland Ice Sheet is a worthy research goal because Greenland Ice Sheet glacier algae very likely play an important role in controlling the ablation zone albedo that is not yet accounted for in energy balance models. This is well within the scope of The Cryosphere and the scientific question is worthy of consideration in this journal. There are some very useful aspects to the paper, including demonstration that there are ablation zone albedo processes that SMB models currently do not account for, the albedo time series over the western ablation zone, and the comparison between different band ratios. However, there are some major issues that need to be addressed before I can recommend publication. More detail is provided below.

Response: We greatly appreciate the reviewer's careful review of our manuscript. Many thanks for suggesting to use SNICAR model to assess the sensitivity of 2BDA index to various dust concentrations. In this revision, we believe the manuscript has been greatly improved by incorporating the reviewer comments. Please see our responses below.

Major Comments:

1)There is past literature that emphasises the importance of discounting abiotically generated rededge signals before assuming them to be diagnostic of photosynthetic life (see Sparks et al. 2009; Seager et al. 2005). The vulnerability of the rededge to false positives is demonstrable using a simple radiative transfer model (easily replicated inbrowser via http://snow.engin.umich.edu/). Fig 1A shows the results from SNICAR runs where all variables were held constant except the mass concentrations of completely inorganic impurities (Flanner et al.'s (2009) "global average dusts, type 4"). The lowest 2 spectral albedo curves returned a false positive 2BDA result (1.002 and 1.005). In Figure 1B, the model is run again identically but with a hematiterich mineral dust taken from Polashenski et al. (2015), giving eight 2BDA false positives (1.004, 1.015, 1.026, 1.031, 1.039, 1.043 1.046). Tedesco et al. (2013) suggested that hematiterich red dusts are present in the GrIS ablation zone (we note that Cook et al. (in review) disagreed about that but their paper remains unpublished). Taking Tedesco et al. (2013) to be correct about the prevalence of red dusts on the Greenland ablation zone therefore invalidates the rededge as a biomarker due to the demonstrable potential for false positives. Convincing empirical data is required to demonstrate that the 2BDA signal is exclusively biological and robust to these types of false positive results.

A) B)

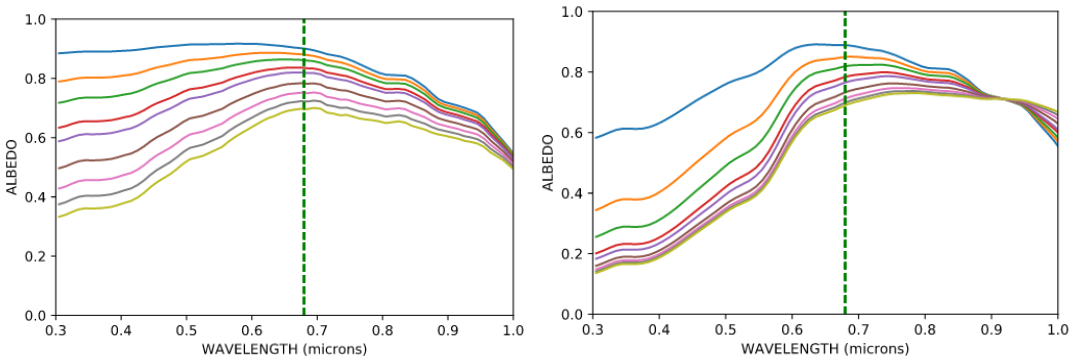


Fig 1: A) SNICAR runs with diffuse irradiance, homogenous snow with grain diameter 500 micron, density 400 kg m^3 and Flanner et al. (2009)'s "dust 4" in the upper 1 mm, in mass concentrations of 0.1, 0.3, 0.5, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0 ugdust/gice. B) Identical SNICAR runs but with Polashenski et al. (2015)'s high hematite dust.

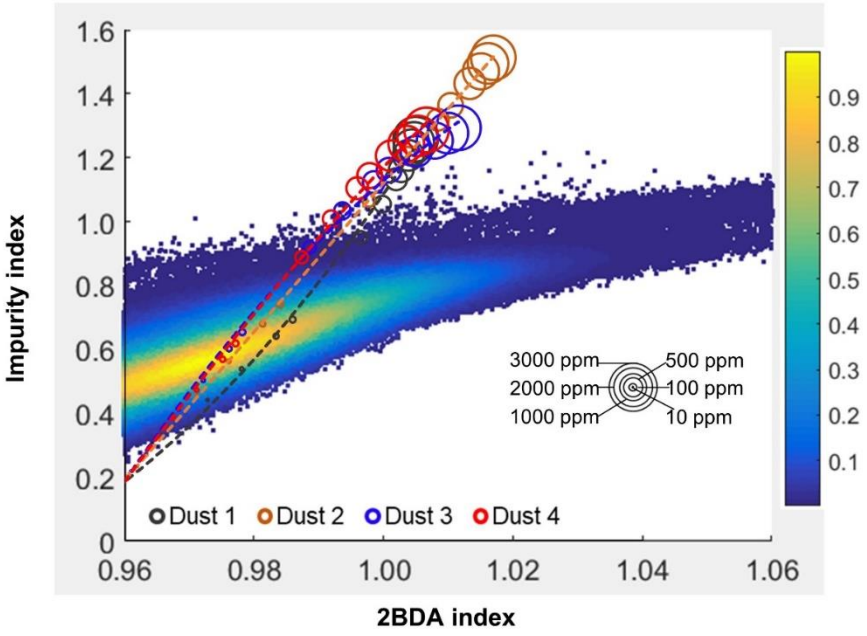
Response: We thank the reviewer for pointing out the issue of potential impacts by dusts. In this revision, we addressed this concern by conducting SNICAR simulations with various parameter settings as the reviewer suggested. We would like to clarify that our objective is not to define a universal biomarker for detecting photosynthetic life. To our understanding, the two papers the reviewer mentioned that address the potential false signal resulting from dusts (Sparks et al. 2009 and Seager et al. 2005; not in the reference list), are in the extraterrestrial context.

However, our research is conducted based on the understanding that widespread glacier algal blooms occur on the bare ice zone in southwest Greenland, which have been confirmed by numerous studies (Cook et al., 2020; Lutz et al., 2014; Remias et al., 2012; Ryan et al., 2018; Stibal et al., 2015; Stibal et al., 2017; Williamson et al., 2019; Yallop et al., 2012). Nevertheless, to evaluate the sensitivity of the 2BDA index to various dust sizes and concentrations, we performed radiative transfer modeling experiments using SNICAR, by setting the grain size of snow to 500 microns and 1500 microns. However, we cannot generate the same results using the dust concentrations specified by the reviewer (0.1, 0.3, 0.5, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0 ug_{dust}/g_{ice}). Using these parameters, the 2BDA index is less than 0.97 for all dust sizes (dust 1, dust 2, dust 3, and dust 4) when the grain size is 1500 microns, and less than 0.98 when grain size is 500 microns. The 2BDA index would be over 1.0 only when the dust concentrations are greater than ~800 ppm.

In this revision, we added a discussion section (Section 5.1) to specifically discuss this issue. Using a grain size of 1500 microns produces a spectral curve that is closer to the MERIS bare ice spectra. The SNICAR experiments were performed with the following parameters: direct incident radiation, a solar zenith angle of 60 degrees, clear-sky conditions (for Summit Greenland), a snow grain effective radius of 1500 micron (to approximate the ice surface), a snowpack thickness of 100 m (to avoid any influence of the sub-snowpack albedo), a snowpack density of 400 kg/m^3, and dust concentrations of (0.1, 0.3, 0.5, 0.8, 1, 1.5, 2, 2.5, 3, 5, 8, 10, 30, 50, 80, 100, 300, 500, 800, 1000, 1500, 2000, 2500, and 3000 ppm) for four dust sizes (dust 1: 0.1–1.0μm; dust 2: 1.0–2.5μm; dust 3: 2.5–5.0μm; dust 4: 5.0–10.0 μm). We also tested different density values but these did not affect the simulation results. In addition to the 2BDA index, we also calculated the impurity index for the SNICAR simulations, and found that the impurity index is more sensitive to dusts than the

2BDA index (Response Fig. 1, Fig. 10 in manuscript). Figure 1 (below) shows scatterplots of impurity index vs. 2BDA index calculated for the SNICAR simulations (with the diameter of circles representing the magnitude of dust concentrations for four different dust sizes), and the density scatterplots from the MERIS data (impurity vs. 2BDA indices over bare ice). The results indicate that relatively high concentrations of dust would increase the 2BDA index, but would also result in a large increase in the impurity index. By contrast, the upper bound of the impurity index we calculated from the MERIS data is around 1.0, below the impurity index values for the highest dust concentrations. These results suggest that relatively high 2BDA values (especially above 0.99, corresponding to an impurity index of 1.0) are unlikely to be caused by dusts, because the presence of dusts would also result in an impurity index of above 1.0. This indicates that for our study area, the glacier algae identified with a 2BDA index greater than 0.99 are less likely to be false positives caused by dusts. Finally, even below this threshold, the slope of the 2BDA vs. impurity index is shallower than the SNICAR-generated curves, suggesting that the 2BDA index is generally more sensitive to chlorophyll-a than to dust.

With regard to the possible presence of hematite-rich dust, the samples of Tedesco et al. (2013) were from cryoconite holes, and is not necessarily representative of the ice surface; and hematite concentration is actually very low. Cook et al. (2020) also found that the local bare-ice mineral dust is poor in hematite and rich in weakly absorbing quartz and feldspar minerals. Therefore, the hematite has a negligible influence on the detected chlorophyll-a signal at the red-NIR region.



Response Figure 1 (Figure 10 in the manuscript). Scatterplots of impurity index vs. 2BDA index for SNICAR simulations for different dust sizes (dust 1, dust 2, dust 3, and dust 4) with variant concentrations (circle labels represent different dust sizes and circle size indicates the concentration magnitude). The density scatterplot is generated using the MERIS-derived impurity index vs. 2BDA index over bare ice from 2004 to 2011 for our study region.

2) The authors do not account for the spectral albedo of the ice itself. Ice albedo can vary dramatically independently of light absorbing particles and cause the 2BDA value to change, undermining the biomass quantification. Figure 2 shows identical simulations to Fig 1, except the grain size is increased to 1500 microns. False positive results are returned as before, but the value of the 2BDA indexes and therefore the retrieved biomass – change (Flanner et al. (2009) dust =1.0009 and 1.004; Polashenski et al. (2015) dust = 1.0018, 1.014, 1.026, 1.032, 1.040, 1.043, 1.045, 1.046). The retrieved biomass therefore changed without any change in impurity loading. On real glacier ice where the ice albedo can vary by tens of percent independently of impurity concentration due to weathering crust development, meltwater accumulation and drainage, topography, impurity mixing and glaciological structure, the potential for highly error prone retrievals is likely very high. The authors need to demonstrate that their band ratio is not vulnerable to this uncertainty, or that they can quantify and correct for it.

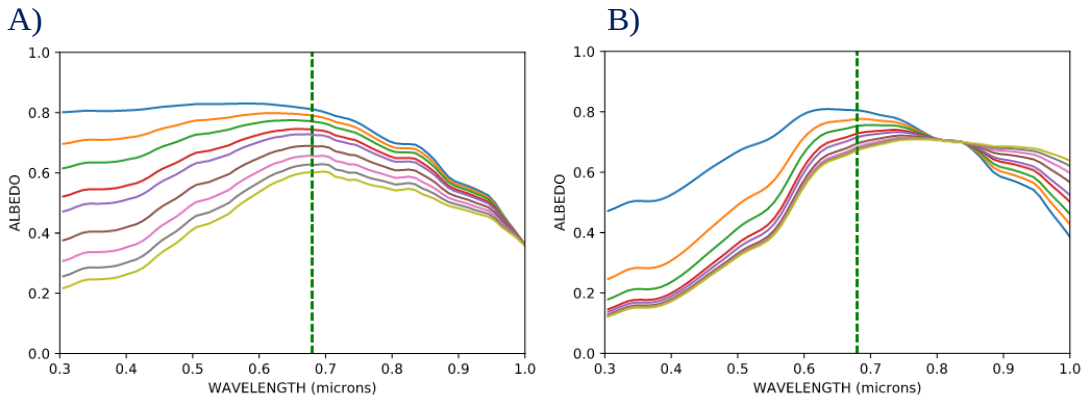


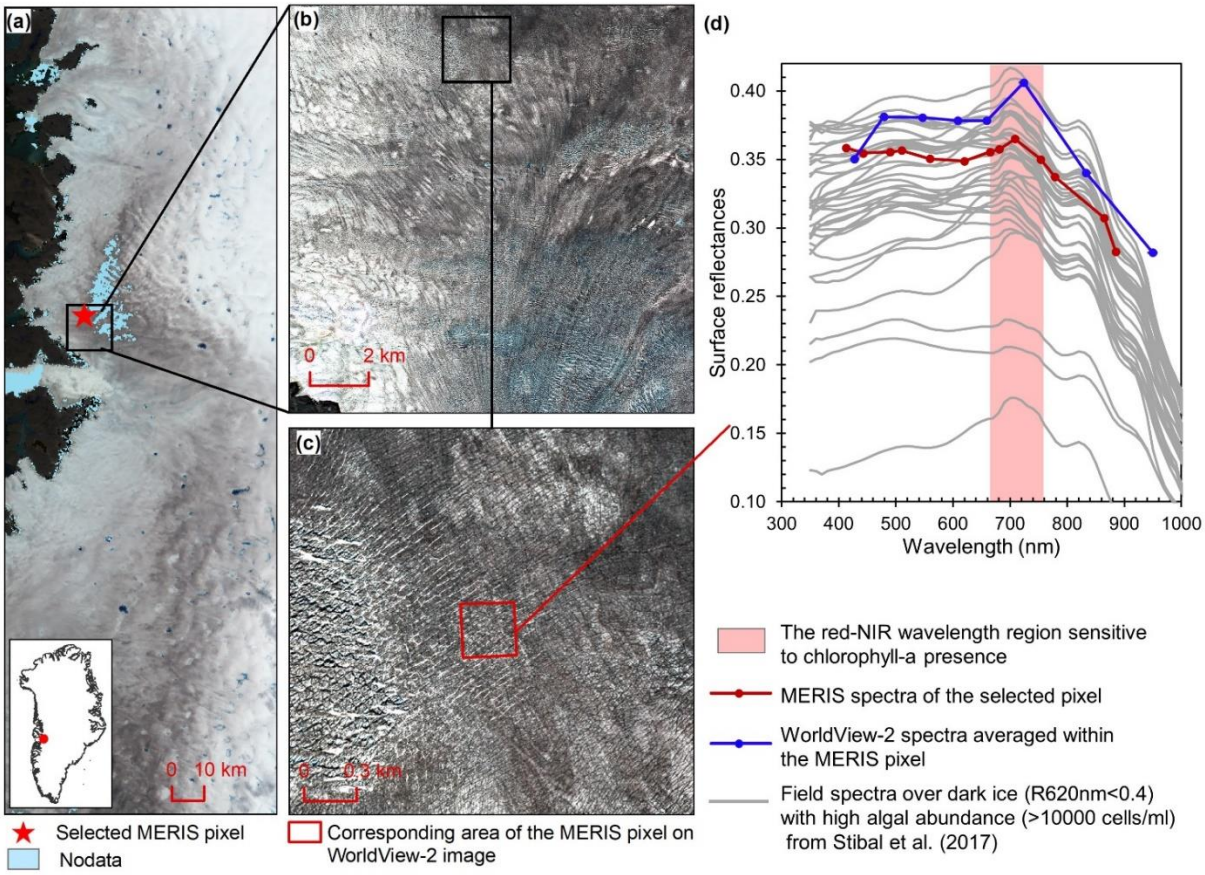
Fig 2: A) SNICAR runs with diffuse irradiance, homogenous 1500 micron, 400 kgm^3 snow with Flanner et al. (2009)'s "dust 4" in the upper 1 mm, in mass concentrations of 0.1, 0.3, 0.5, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0 ugdust/gice. B) Identical SNICAR runs but with Polashenski et al. (2015)'s high hematite dust.

Response: The sensitivity of the 2BDA index to dust presence (over snow with a 1500 microns grain size to approximate ice) has been discussed above.

We agree on the point that ice albedo changes with impurity concentration, meltwater presence, topography and crevasses, as discussed by Ryan et al. (2018). But also, as suggested by Ryan et al. (2018), the distributed impurities explain most of the spatial variability of surface albedo. In addition, it should be noted that variations in albedo due to other factors including water, other impurities, and ice albedo does not necessarily affect the 2BDA index. The band ratio between 709 nm and 665 nm (both bands have bandwidths of 10 nm) is specifically designed for chlorophyll-a, and less affected by dusts as we discussed above. To our knowledge, the meltwater, weathered crust, and crevasses do not cause the pattern of increasing reflectance from 665 nm to 709 nm. In our revised Figure 2d, it is clearly shown that the MERIS exhibits the red-NIR spectral signature caused by chlorophyll-a, which matches multiple field hyperspectral data measurements over algae-abundant dark ice.

3) The authors do not adequately address the problem of scale mismatches between the normal length scales of typical algal blooms (biomass varies dramatically over 110 m length scales) and the satellite used to gather their data (300 x 300m). Surface heterogeneity must surely introduce major uncertainties as the spectral reflectance of each pixel is the combined product of many highly variable surfaces. How would, for example, cryoconite, surface water, dust, crevasses and surface topography at the subpixel scale affect their biomass quantification? These unquantified factors must influence the predicted cell concentration independently of realworld changes to the mass concentration of algae, but they are not discussed in the paper.

Response: In this study, we did not investigate scale issues in depth, and these issues are beyond our current research scope. However, based on our SNICAR experiments, and analysis of the 2BDA and impurity indices, the 2BDA index is less sensitive to the presence of dust, which means that the high 2BDA index is uniquely biological. Given the sensitivity of MERIS to the presence of chlorophyll-a, the 2BDA index can capture well the chlorophyll-a signal generated by glacier algae. In terms of spatial heterogeneity, according to the UAV mapping results by Ryan et al. (2018), the areal percentage of the distributed impurities is up to 65%~95% within individual MODIS pixels (500-meter resolution) over the dark zone in southwest Greenland. Our comparison between the MERIS spectra, WorldView-2 spectra, and field hyperspectral data (Fig. 2) shows that the chlorophyll-a signature at the red-NIR region is quite consistent between those different source measurements with different spatial scales. We agree that it is important to investigate the pixel mixture problems in the future and the limit of algae distribution within each pixel that can cause detectable chlorophyll-a signal. We have acknowledged those issues in our discussion section.



Revised Figure 2: Comparison between the MERIS, WorldView-2, and field spectra over algae-abundant dark ice. (a) MERIS Level-2 image (true colour composite) acquired on 5 July 2010. Pixels with missing data are shown in blue. (b) WorldView-2 surface reflectance image acquired on 9 July 2010 over the square area in (a). (c) Zoomed-in WorldView-2 image, with the area (red square) corresponding to the selected MERIS pixel in (a). (d) Reflectance spectra for MERIS and WorldView-2 (2010), and field hyperspectral measurements collected over the algae-abundant dark ice at S6 by Stibal et al. (2017) in 2013.

4) There is insufficient detail regarding the use of field spectroscopic measurements as "ground truth". Only one single field spectrum is presented in the paper and the measurement conditions are not reported. Has it been picked because it matches well with the MERIS spectrum, is it a mean (in which case of how many samples, and what do the error bars look like) or is it the only available spectrum? How do other spectra in the field dataset compare? Can the authors provide evidence to suggest that centimeter scale field spectroscopy measurements are truly representative of the biomass over entire MERIS pixels?

Response: We have revised the text to include more details on how we used the field data by Stibal et al. (2015) and Stibal et al. (2017). In our study, we used those field data in a qualitative way to validate the spatial variations of algal concentration magnitude derived from the satellite data, and to compare the field hyperspectral measurements over algae-abundance ice with the MERIS spectra and WorldView-2 spectra. The field measurements are collected after the period of MERIS measurements, precluding direct comparison with field data. In this revision, we revised Fig. 2d to include additional field spectra collected over dark ice (R620nm<0.4) with high algal abundance

(cell concentrations greater than 10000 cells/ml). As illustrated by Fig.2d, the spectral characteristics at the red-NIR region match well between MERIS spectra, WorldView-2 spectra and field spectra. The match between MERIS spectra (300 meter) and WorldView-2 spectra (2 meter) also indicate that the chlorophyll-a signal cannot be masked out because of large spatial scales, given the high areal percentage of the distributed impurities within the MERIS pixel, as illustrated by Fig.2 (in the manuscript) and as suggested by Ryan et al. (2018) that the areal percentage of the distributed impurities about 65~95% within individual MODIS pixels (500-meter resolution).

5) The authors are selective with their citing of literature under review. If they wish to include papers still under discussion they should explain why the issues of spatial scale encountered in 20 m Sentinel2 pixels discussed by Cook et al (in review) and Tedstone et al. (in review) do not also apply to their 300 m MERIS pixels. If they decide to stick to published literature they should explain how the presence of hematiterich dusts on the ablating Greenland Ice Sheet as reported by Tedesco et al. (2013) does not invalidate their assumption that the rededge is uniquely biological.

Response: We removed the references to all discussion papers since they are not referenceable. The paper by Cook et al. (2020) is now published, and we have included this citation in our introduction section and discussion section. We also discussed the potential impact of hematite dust (Tedesco et al. 2013) on the 2BDA index in the discussion section. As we mentioned above, the hematite has a negligible impact on the 2BDA index in our context.

Specific Comments:

Title: As suggested by Daniel Remias in the open discussion forum, please adopt the generally accepted terminology "glacier algae" that distinguishes these algae from those found in sea ice.

Response: As suggested, we have changed 'ice algae' to 'glacier algae' throughout the text.

General point about chlorophyll: Referring to "chlorophyll" is somewhat ambiguous as it could imply total chlorophyll or one of several chlorophyll variants. Please be specific that you mean chlorophylla.

Response: We have revised the text as suggested.

L39: Any citation for yellow/orange snow algae? They are normally thought of as green or red.

Response: We have added the citation (Anesio et al., 2017) for the yellow/orange pigmentation of snow algae.

L71: The authors rightly criticise carotenoid based remote sensing methods because of possible false positives due to "dirt" but ignore the potential for equivalent rededge false positives due to dust.

Response: In this revision, we ran a number of SNICAR simulations with variant dust sizes and concentrations. Based on the SNICAR simulations, we calculated both 2BDA and Impurity Index for different dust configurations, and evaluated the potential impact of dust presence on 2BDA index. Please see details in the revised discussion section.

L75: The authors claim chlorophyll is the appropriate pigment to use to identify ice algae despite also stating that the coloration of the algae is primarily due to purpurogallin pigments. Why, then, is that not the appropriate pigment to use to identify glacier algae?

Response: Compared with the purpurogallin pigment, Chlorophyll-a is more appropriate for mapping glacier algae for the following reasons:

1) Chlorophyll-a is the primary photosynthetic pigment of glacier algae (Williamson et al., 2018). The ocean color satellite sensors like Envisat MERIS and Sentinel-3 OLCI are designed to capture the Chlorophyll-a signal from highly-absorptive and optically complex water bodies, which means that the ocean color sensors are highly sensitive to the chlorophyll-a presence, making them very useful tools for glacier algae detection based on the biological signatures.

2) According to the studies by Remias et al. (2012) and Williamson et al. (2018), the spectral signatures (absorption peaks) of the purpurogallin pigment are concentrated in the UV region (278 nm, 304 nm, and 389 nm, Remias et al.,2012). To our knowledge, no satellite sensor can detect these spectral signatures. Although the purpurogallin pigment is very likely to account for the brownish-grey colour of glacier algae, its absorption over the entire visible spectrum is quite uniform, making it difficult to differentiate from other dark impurities. In contrast, chlorophyll-a can generate very strong spectral signatures at the red and NIR region, which can be supported by the field hyperspectral measurements for both snow algae and glacier algae. (e.g. Ganey et al., 2017; Painter et al., 2001; Stibal et al., 2017; Cook et al., 2020).

   We have revised the text to discuss and compare the suitability of purpurogallin vs. chlorophyll-a for glacier algae mapping.

L75: "owing to its unique spectral signatures between 665 710nm (Gitelson, 1992; Painter et al., 2001; Wang et al., 2018)": Chlorophylla absorbs in narrow bands around 680 nm and 440 nm. Any effects extending up to 710 nm are due to interactions with the surrounding medium. This is why Painter et al. (2001) was able to use the narrow 680 nm absorption feature as a diagnostic tool for Chlorophylla detection.

Response: By 'unique spectral signatures between 665-710nm', we are referring to the absorption between 665-681 nm and the reflectance peak around 710nm. Painter et al. (2001) used the 680nm absorption feature by calculating the integral of the absorption scaled by its continuum spectra. Painter et al. (2001) retrieved the continuum spectrum by linearly interpolating the reflectance peaks at 630 nm and 700 nm, which similarly to our study, essentially used the relative difference between the absorption and reflectance features at the red-NIR region. Their method is specifically applicable for hyperspectral data like AVIRIS, but is limited for satellite multispectral data. We have revised the text to improve the clarity.

L79: "Quantification of ice algae biomass from satellite data based on the chlorophylla feature has received less attention since the chlorophyll related satellite bands designed for land generally have coarse spectral resolutions." This is just one of many reasons why remotely detecting algae over glacier ice is not simple. Other complexities include the complex pigmentation of the algae, the spatial resolution of the remote sensing instruments relative to the typical length scales of

individual surface features (including algal blooms) and critically the optics of the underlying ice that vary dramatically over space and time and which are not yet well described. These issues are as important as the spectral resolution and must be acknowledged.

Response: We have revised the text to acknowledge these issues.

L100 – 120: Much more detail is required here. For example, how many actual field samples were used to validate your remote sensing retrievals? What were the biomasses measured at those sites? What were the measurement conditions? On which dates were spectra available at which sites? Were the measurement times conistent and how do they compare to the satellite overpass times? What was the sensor footprint size for the field measurements and how were these upscaled to the satellite pixel scale?

Response: We have revised this section and made clarifications on how we used the field measurements. It should be noted that we utilized those field data in a qualitative way for comparison with the satellite signals, rather than in a quantitative way for direct algal biomass inversion. The Envisat MERIS was operational from March 2002 to April 2012. To our knowledge, there were no field data coincident with the satellite data. In our study, we estimated the growth rate (population doubling time) and albedo reduction rate (for each population doubling) using a simple mathematical conversion and empirical relationship established from the Sentinel-3 OLCI data and field data (Wang et al. 2018). We did not directly estimate the algal biomass or abundance from MERIS data since no coincident field data are available. We attempted to apply the Sentinel-3 retrieved empirical relationship to estimate the population doubling time and albedo reduction rate due to algae, and the results match well with the field observations.

Figure 1: Please provide details of the field spectrum presented as the dashed line. Where/when was it collected and how does it compare to other field spectra presented in this paper?

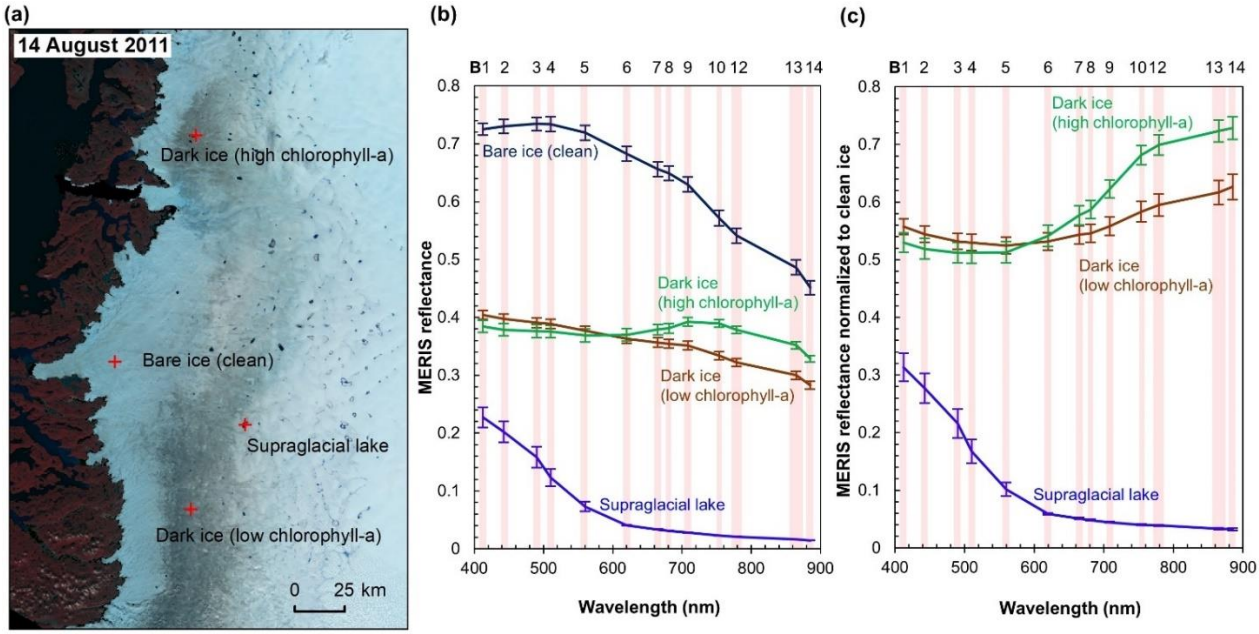
Response: We have added more details in the figure caption to describe the field spectrum.

Figure 1: Spectral response functions of (a) MERIS (red), OLCI (blue), and (b) MODIS (black), and WorldView-2 (orange) over the spectral range of 350-1050 nm. All the MERIS and OLCI bands are within the 350-1050 nm range, where photosynthetic and photoprotective pigments have spectral responses. Four MODIS bands (over land) and eight WorldView-2 bands are within this spectral range, but with much coarser spectral resolutions. In both sub-plots, the dashed line shows hyperspectral ASD field spectroradiometer data (right vertical axis) collected over algae-abundant ice (Stibal et al., 2017), containing the chlorophyll-a signal at the red-NIR wavelengths (red highlighted region). The plotted field spectrum (sample code: Ab.25.06.14.D1) was measured on 25 June 2014 at 67°04.779'N, 49°24.077'W (near the automatic climate station S6 along the K-transect), with an algal abundance measurement of 121664 cells/ml (Stibal et al., 2017).

L209: Chlorophylla is the primary photosynthetic pigment, but not the primary light absorbing pigment. In both the studies you have cited the chlorophylla absorption feature is actually extremely subtle – in fact in Cook et al. (in review) it was only really discernable in the derivative spectra and indistinguishable in the raw reflectance. In Stibal et al. (2017) the spectrum are presented with a very truncated yaxis to make the pigment feature discernable.

Response: We agree with the reviewer on the point that Chlorophyll-a is the primary photosynthetic pigment but not the primary light absorbing pigment. However, this does not mean that Chlorophyll-a cannot be used as the biomarker to detect glacier algae. According to the

literature, the purpurogallin pigments are the primary light absorbing pigments for glacier algae. As we mentioned above, the characteristic spectral signatures generated by purpurogallin pigments (that might be used as biomarker for glacier algae detection) are concentrated in the ultraviolet region (278 nm, 304 nm, and 389 nm). To our knowledge, current satellite sensors cannot capture the spectral signals at these wavelengths, which means that the spectral properties of purpurogallin pigments at UV region cannot be utilized for glacier algae detection from space. The absorption features of the purpurogallin pigments are quite uniform over the entire visible spectrum, with no characteristic spectral signatures that can be used by satellite sensors to differentiate glacier algae from other dark materials. Although the Chlorophyll-a spectral signature (between 665 nm and 710 nm) generated by glacier algae is not as strong as the algal blooms in aquatic systems, the spectral characteristics of Chlorophyll-a are indeed present on the spectral curve, which are particularly obvious in the derivative spectra (shown in Cook et al. 2020) and the normalized spectra (revised Fig. 3c).



Revised Figure 3: MERIS spectra of different surface types. (a) MERIS Level-2 image (false colour composite) acquired on 14 August 2011 and locations of the four different sample sites. Each site has an area of 1.2 km by 1.2 km, composed of 16 MERIS pixels. (b) MERIS surface reflectance in 13 spectral bands over the four sites, illustrated by the mean and standard deviation values for each band over each site. (c) Normalized surface reflectance relative to the clean ice spectra.

L211: "pure ice" has lower reflectance at red wavelengths compared to shorter wavelengths.

Response: We have revised the text as 'Pure ice has lower reflectance at 709 nm compared to shorter wavelengths (Hall and Martinec, 1985).'

L216220: This line of reasoning borrows heavily from studies of chlorophylla dominated species in other environments and still requires the rededge to be validated over glacier ice where LAP and meltwater mixing, complex pigmentation and ice optics are potential confounding variables.

Response: We agree that the mixture of dusts, algal pigments, meltwater, and ice optics could complicate the surface spectra. In this revision, we discussed the potential impacts of these variables on the 2BDA index by incorporating the SNICAR simulations. Although the 2BDA index is developed and well-validated for ocean color applications, the rationale for glacier algae detection based on the chlorophyll-a spectral signature at the red-NIR region is very similar to the algal detection in aquatic environments, particularly for the turbid case 2 waters (Blondeau-Patissier et al., 2014; Matthews, 2011). Similar to the dark ice surface, the case 2 waters are also optically complex, largely affected by the colored dissolved organic matter (CDOM) and suspended sediments. The 2BDA index based on the 665nm and 710nm bands utilizes the reflectance peak near 710 nm, which has been widely tested and validated for the case 2 waters. Using Fig.2, we intend to show that the algae-laden ice has the chlorophyll-a spectral signature, which is consistent between the 300-meter MERIS spectra, 2-m WorldView-2 spectra, and the in-situ hyperspectral data. Multiple in situ spectra have been added to Fig. 2 illustrating that the chlorophyll-a spectral signature is present across multiple measurement samples and dates.

Figure 2: How did the authors select the field spectrum to plot on this figure? Is this the average of all available? If so please provide error bars and number of observations. Also, 184 cells/mL reported in the legend is a tiny amount of algae, unlikely to explain the albedo reduction observed –is this a typo? What was the mineral dust type and concentration in the same area – could it also explain the rededge? How much of the albedo reduction can be attributed to the algae and how much to melt water/dust? If the absorption is mostly due to chlorophylla as the authors suggest, why is the absorption maximum outside of the chlorophyll absorption range shown in Fig 2c and why does it extend across the visible wavelengths? Why do the field spectra and remotely sensed spectra diverge below ~640 nm?

Response: The field spectrum we selected from Stibal et al. (2017) is used here as an example to show the chlorophyll-a spectral characteristics (665-710 nm) over the algae-abundant ice, and the satellite data (2-meter resolution WorldView-2 and 300-meter MERIS imagery) have similar spectral features at this red-NIR region. The selection criteria include high measured algal abundance (184184 cells/ml) and dark appearance (R620nm<0.45, consistent with the dark ice delineation criteria by Shimada et al., 2016 and Tedstone et al. 2017). To further illustrate the red-NIR spectral signature of glacier algae, we added multiple field spectra from locations where algal cell concentrations were measured at greater than 10,000 cells/ml to Fig. 2, showing consistent spectral shapes at this wavelength region. For detailed information about the field data, including dust composition and albedo reduction caused by different variables, please refer to Stibal et al. (2017). As mentioned above, we have added a section analyzing the impact of dusts on 2BDA index in the revised discussion. 'The absorption maximum outside of the chlorophyll absorption range' can be explained by the purpurogallin pigments. The low absorption and uniform absorption in this range actually emphasizes the importance of using the 'red-edge' feature to detect glacier algae. We are not suggesting that 'the absorption is mostly due to chlorophyll-a', instead, we are suggesting to use the chlorophyll-a feature (absorption at 665 nm and reflectance peak at 710 nm) to detect glacier algae. We have revised the text to clarify this point. The divergence between the field spectra and satellite spectra below ~640 nm may be caused by two reasons: 1) the uncorrected Rayleigh scattering effect that affects shorter visible wavelengths (particularly the blue band). and

2) spectral mixing with ice. Both can make the reflectance at shorter wavelengths higher, however, the reflectance ratio between 710 nm and 665 nm is less affected.

Figure 3: A) "Agust"->August; B) The authors present spectra for "dark → ice (more chlorophyll)" and "dark ice (less chlorophyll)". However, there does not seem to be any positive 2BDA signal in the latter spectrum at all. Is it actually "dark ice (no chlorophyll)"? If so, there are additional darkening processes occurring on the ice. What processes are darkening the ice in those areas and to what extent do those ice darkening processes also influence the biomass retrievals in areas where there is a positive 2BDA result? What effect does this have on retrieved biomass? What is the detection limit for the 2BDA method?

Response: We have corrected the figure to refer to "high chlorophyll-a" and "low chlorophyll-a". To illustrate the chlorophyll-a signal better, we also plotted the relative surface reflectances (MERIS) for different surface types normalized to the clean ice spectra since the primary background spectral signal is from ice. For both water and ice, the spectrum shows a decrease in reflectance from 665 nm to 710 nm, which is opposite to the chlorophyll-a spectrum. A 2BDA signal of less than one therefore does not imply that there is no chlorophyll-a present. A smaller rate of decrease could still be produced by low amounts of chlorophyll-a. Using the 2BDA index, we do not intend to classify the ice surface into 'algae' vs. 'no algae'. We use the 2BDA index to show the magnitude of glacier algal blooms varying over space and time. We think it is more appropriate to use 'high chlorophyll-a' and 'low chlorophyll-a' to describe those two sites. We agree with the reviewer that more discussions and investigations are needed to quantify the impacts of other darkening processes on 2BDA index. In this revision, we added the analysis of dust impacts on 2BDA index based on SNICAR simulations in the discussion section. We found that by combining the 2BDA index with the Impurity Index, we can exclude the possibility of false positives when the 2BDA index is greater than 0.99.

L413: Cook et al. (in review) mention that a rededge signal was present in most of their algal hyperspectral data but they do not mention false positive rates and they opted not to use that method for their spatial upscaling. It would therefore be useful to know the false positive rate in the present study and how it scales to 300m MERIS pixels.

Response: Cook et al., 2020 (published online) showed that the 'red-edge' spectral signal due to chlorophyll-a is present in their hyperspectral measurements for algae-covered ice, which further supports the chlorophyll-a signal we observed on the 300-meter MERIS image and the 2-meter WorldView-2 image. According to the UAV mapping results by Ryan et al. (2018), the areal percentage of the distributed impurities is up to 90% within individual MODIS pixels (500-meter resolution) over the dark zone in southwest Greenland. Our Fig.2 shows the WorldView-2 image (2-meter resolution) within a MERIS pixel that has strong chlorophyll-a signal. Although we can observe spatial heterogeneity within one MERIS pixel, the dark materials are widespread over the entire area. We agree that it is important to investigate the pixel mixture problems in the future and the limit of algae distribution within each pixel that can cause detectable chlorophyll-a signal. Based on our discussion on dust impacts and the spatial scale of MERIS imagery, we think that using MERIS data is more likely to cause false negatives instead of false positives given the sensor detection limit to weaker chlorophyll-a signals.

L416: It is not clear to me from the manuscript precisely how you have inferred algal cell abundance. Please provide further methodological details.

Response: The methods for computing algal population doubling were described in Section 4.3 (Lines 363-376 in the original manuscript). However, this section may have been somewhat unclear. In this revision, we have clarified how the population doubling time was estimated based on the fitted coefficients between 2BDA and time. We did not directly infer the algal cell abundance using the 2BDA index, instead, we used the empirical relationship established based on the Sentinel-3 OLCI band ratio and previous field measurements (Wang et al., 2018) and mathematical conversions.

L450460: Another explanation for this is that the overall ice albedo is lower, there may be smoother ice and more water at the surface, and rather than there being less algae, the rededge signal is simply erased by an overall dampening of the spectrum across all wavelengths (i.e. putting dark impurities on dark ice has a less detectable effect that putting the same impurities on otherwise bright ice). Can the authors demonstrate that this is not the case?

Response: As we have discussed above, the 2BDA index is sensitive to the absorption and reflectance peaks of chlorophyll-a, which is not a feature of other surface types. As the 2BDA index is a ratio of two different wavelength bands, a uniform reduction in "background" albedo should have a small effect. A change in the shape of the "background" spectrum (the relative reflectance at 710 nm relative to 665 nm would be required to have a large impact on 2BDA. Observed spectra shown in Figure 2 suggest that differences in the average magnitude of the reflectance spectrum do not appear have a strong impact on the shape of the reflectance spectra, and therefore likely do not strongly impact the 2BDA index either.

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