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Interactive comment on "Optical properties of laboratory grown sea ice doped with light absorbing impurities (black carbon)" *by* Amelia A. Marks et al.

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The authors would like to thank the referee for their review of the paper "Optical properties of laboratory grown sea ice doped with light absorbing impurities (black carbon)."

Changes made to the paper based on the comments are detailed below on a point-by-point basis:

The abstract feels rushed and confused compared to the rest of the paper and does not do the paper justice.
The abstract has been rewritten:

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Discussion paper

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"Radiative-transfer calculations of the light reflectivity and extinction coefficient in laboratory generated sea ice doped with and without black carbon demonstrate that the radiative transfer model TUV-snow can be used to predict the light reflectance and extinction coefficient of sea ice typical of first year sea ice containing typical amounts of black carbon and other light absorbing impurities. The experiments give confidence in the application of the model to predict albedo of other sea ice fabrics.

Sea ices, ∼30 cm thick, were generated in the Royal Holloway Sea Ice Simulator (∼2000 L tanks) with scattering cross-sections measured between 0.012 and 0.032 m^2 kg^{-1} for four ices. Sea ices were generated with and without ∼5 cm upper layers containing particulate black carbon. Nadir reflectances between 0.60 and 0.78 where measured along with extinction coefficients of 0.1 to 0.03 cm^{-1} (e-folding depths of 10–30 cm) at a wavelength of 500 nm. Values were measured between light wavelengths of 350 and 650 nm. The sea ices generated in the Royal Holloway Sea Ice Simulator were found to be representative of natural sea ices.

Particulate black carbon at mass ratios of ∼75, ∼150 and ∼300 ng g^{-1} in a 5 cm ice layer lowers the albedo to 97%, 90%, and 79% of the reflectivity of an undoped "clean'" sea (at a wavelength of 500 nm)."

Much of the modelling community will be put off / not find this paper due to the terminology used. I suggest also quoting e-folding depths as extinction coefficients as these are the terms currently used by the majority of sea-ice models.

Throughout the paper "extinction coefficients" are now referred to in addition to "e-folding depths" (for the "snow" community) and the following explanation has been added to the text: *"At the completion of the experiment the extinction coefficient and e-folding depth are measured. The e-folding depth is the distance over which light intensity reduces to 1/e of its initial value and is the reciprocal of the extinction coefficient. The e-folding depth is reported in addition to the extinction coefficient."*

The laboratory description feels short and underplayed, this is a new facility and

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it is very difficult to visualise with the current amount of information provided. I suggest significantly increasing the information provided about the facility, although some could go in the supplementary section. I feel this is important, especially if the authors plan on using this paper as a background reference point to further papers using the facility. Some of the broad comments here are brought up in more detail in the specific comments.

The laboratory description had now been expanded to include further details of the facility including a further annotated figure of the facility, and two figures demonstrating the capabilities of the sea ice simulator (temperature profiles and daily reflectance measurements) and further technical specifications. These changes are described in more detail in the specific comments below.

Specific Comments: (Format for reference, e.g 5.4: refers to Page 5, line 4.)

1.3: Question the use of "simulated" throughout, it gives an initial impression of modelling rather than experimental. Could this be altered to laboratory or artificial or something similar?

The word "simulated" has now been replaced with "laboratory" throughout the manuscript.

Abstract General: It is not clear from the abstract what the focus of the paper truly is, and it feels rushed leaving more questions than useful data in its current form. I would suggest removing discussion of algae (as this is barely mentioned in the main manuscript) and refocussing the abstract on the less technical aspects. The mention of measuring e-folding and reflectance and then later calculating e-fold and reflectance from absorption and scattering values sounds confusing in an abstract and is confusing to the reader. I would remove technical detail in favour of adding extinction coefficients which may be of more value to the readership.

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The abstract has been completely rewritten. The discussion of algae has been removed from the abstract and the level of technical detail lowered.

3.9: I would argue that it is a medium sized facility, as somewhere like SERF is a large facility. Could this be phrased in a more impressive way? E.g. "sea-ice simulator designed to reproduce polar sea-ice growth conditions under UV and Visible lighting"

The phrase: *"The sea ice simulator is a large scale, UK based, laboratory sea ice tank designed to replicate warmer polar temperatures, the ocean and UV and visible wavelengths of solar radiation."* Has been replaced with: *"The sea ice simulator is designed to replicate a Polar sea ice growth environment under UV and visible wavelengths of solar radiation"*

3.14: What is the temperature stability of the cold room?

The following sentence has been added to the text: *"The air temperature within the container varies by $\pm 1^{\circ}C$ although thermocouples monitoring temperature at the ice surface show better temperature stability, whilst the temperature variation measured within the ice is less than the precision of the probes ($\pm 0.2^{\circ}C$). Every 12 hours the chiller removes ice build-up on the cooling plant and the air temperature rises briefly by $\sim 6^{\circ}C$."*

4.Fig1. Is there wind shear across the tank? It'd be good to have it added to the Figure.

A 20" fan located above the sea ice directed 110 m^3 min^{-1} of room air onto the ice at an angle of $\sim 45^{\circ}$. The air velocity across the surface of the ice was ~ 1.5 ms^{-1}. The velocity of the airflow produced by the fan has been added to figure 1.

The following text has also been added to the manuscript: *"An additional air fan, attached to the ceiling, blows cold, ambient air at the water surface, (~ 100 m^3 min^{-1}), increasing the heat flux from the ice surface, quickening ice formation and assisting the*

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production of columnar ice (Weeks, 2010).”

4.General. It’d be really nice to see the facility description fleshed out more, with some more technical details of what the chamber is capable of (especially as this is appears to be the first paper to come out from the laboratory). Some suggestions would be how temp / salinity of the ocean vary through time of an experiment as the ice grows, lighting consistency at the ice surface, room temperature vs time during ice growth. These are just suggestions, but it would be good to have more technical facility description. Could some annotated photos be added to go alongside the figures? This would not only allow a much better visualisation, but could well encourage potential collaborators.

Further technical details have now been added to the laboratory description, including:

An annotated photo of the facility (attached here as figure 1)

A further two figures (new figures 2 and 3, also attached here as figures 2 and 3) have been added to section 2.1 to demonstrate the facilities capabilities. Figure 2 shows the change in ice and water temperature profiles during ice growth. Figure 3 shows the change in ice reflectance during ice growth and the day-to-day reflectance stability of the optically thick ice.

The following additional pieces of text have been added to section 4:

“Figure 2 demonstrates that the temperature of the water beneath the sea ice is not thermally stratified, sea ice growth is from the surface downwards, ice temperature decreases linearly through the ice with depth and the ice surface temperature is at a constant –15°C”

“The short term variability of the lamps was less than 0.1% (after an initial warm-up) on the timescale of the measurement of reflectivity or e-folding depth. Note that both the value of nadir reflectance (relative to a Spectralon panel) and light penetration depth are not dependent on the illumination irradiance providing the irradiance does not

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change during the measurement. Figure 3 shows the change in nadir ice reflectance during ice growth and the day-to-day reflectance stability of the optically thick ice."

5.14: Model for the thermocouples? Details on precision / calibration if possible?

The following sentence has been added to this section: *"The precision on all the thermocouples at –15° C was measured as ±0.2° C"*

6.7: Again, could an annotated photo be added for the set up or an extra figure? It may not be implicit for non-experimentalists to imagine.

An extra, annotated, photograph has been added to this section as part of figure 1 (attached here as figure 1).

7.7: Clarify, is the tank emptied at this point or is bleach added?

The sentences *"Between experimental runs the tank is periodically bleached to remove any algae that may have grown. No algae was visible to the naked eye"*, has been changed for clarity to read *"The sea ice was melted and the resulting seawater was treated with aqueous hypochlorous acid (HOCl) and filtered between experimental runs to remove any algae that may have grown. No algae was visible to the naked eye"*

7.27. Can the authors clarify whether this is a range, or the result of two experiments? Is there any way of knowing where the differences in result occur from?

The value of 0.58 has been removed from the text and was an erroneous value left in from a previous edit.

8.Table 1: No mention of sigmascatt in the caption. Please add details.

The caption has been changed to include the sigmascatt, the caption now reads: *"Table 1: Optical and physical properties of sea ice for each run including the mass-ratio of black carbon added to the top layer of ice, density of ice and scattering cross-section*

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(σscatt) of both the top and bottom layers of the ice. The uncertainty. . ..."

9. Figure 2. Caption is not sufficient and needs fully re-composing.

The caption has now been changed to read *"Figure 2: a) Relative spectral absorbance of black carbon versus wavelength for various loadings of black carbon on the filter. b) Relative spectral absorbance versus wavelength for different mass loadings of polypropylene"*

11. Fig 3: It could be due to black and white printing, but the contrast seems very off. It is a really nice Figure to have, but it currently is not as clear as it could be.

Figure 3 (now figure 5) has been improved, previously it displayed well electronically as a pdf, but did not print well, so the image has been sharpened and annotated to make the black carbon particles clearer (attached here as figure 4).

11.5: The authors should be commended here for using a secondary method to calculate an important parameter for the work. This sort of thing is often overlooked and should be done much more in many fields of science.

Thank you

14.3 Is there any way of further discussing the fabrics of the ice? Is there any information in the cores that could be used? Currently the images in the SI are too small to really ascertain anything structural but maybe there is information within those images, which could be enhanced to help interpret the variability?

It has not been possible to enhance the images of the ice fabric any further and the sample no longer exist as they were melted for density measurements.

15.Fig 7: Please add a scaled absorption of algae (and what type of algae) be added here. An absorption cross-section for chlorophyll-A from Bricaud et al. (2004) from algal cells, and chlorophyll in ice from Mundy et al (2011) has been added to this figure to more clearly demonstrate the identity of the extra absorption (attached here

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as figure 5).

17.16: (and 19.10:) How does the uncertainty in the e-fold fitting procedure propagate through? There is much discussion about the other parameters but I feel that this is overlooked and that there are sources of error which are not propagated from the experimental side? Is there an easy way to estimate this?

Section 5.1.4 “Uncertainty in derived scattering and absorption cross-section and black carbon mass ratio” has been altered to read:

“Section 5.1.4 Uncertainty in derived scattering and absorption cross-section and black carbon mass ratio

The determination of the cross-section for light scattering and absorption, described in section 4.2.2, depends on varying their values to reproduce the measured values of the e-folding depth and the nadir reflectivity within the experimental uncertainties of measured values of the e-folding depth and the nadir reflectivity, all as a function of wavelength. The latter assists in constraining the determination of the values of the cross-section for absorption and scattering. The propagated uncertainty in the determined values of the cross-sections for light scattering and absorption from uncertainties in either the value of the e-folding depth or nadir reflectivity in isolation have not been calculated as our method fits both e-folding depth and reflectivity. Considering the experimental uncertainty in e-folding depth and nadir reflectivity gives a more representative uncertainty of the process. The uncertainty in the reflectance and e-folding depth measurement data of the undoped ice is shown in figures 7 and 8. Table 1 gives an indication of the uncertainty in the derived scattering cross-section which is estimated by varying the values of σscatt and σabs and still obtaining a good fit (by eye) to the experimental data within the uncertainties of the measured e-folding depth and nadir reflectivity.

20.25: Would the extra ice at the side have any impact on the e-folding depth? The *e*-folding depth is measured more than three *e*-folding depths away from the sides

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of the tank so the extra ice would have no effect on measured *e*-folding depth values. We have added the following comment to the text *"All measurements of the e-folding depth were made more than three e-folding depths from the sides of the tank so that any extra ice growth at the edges of the tank would no impact on the measurements."*

21.4: It is my feeling that if light is being reflected back from the base of the tank, then there would be excess light within the ice at depth, which would result in the e-folding depth becoming longer and not shorter. I would also disagree with the authors comparison to the blue ice seen in Grenfell and Maykut (1977) as this is described as "ice saturated, but not covered, with melt water". The ice created here is fresh, "dry" ice and has not been subjected to melt metamorphism and structural change such as the one described in Grenfell and Maykut 1977, and should not be compared as such.

The reference to the first year blue ice has been removed from the text, as has the explanation for the shorter e-folding depths being attributed to light reflected off the bottom of the tank. The paragraph now reads: *"Typical extinction coefficients of sea ice at around 500 nm are around 0.03 cm^{-1} (Grenfell,1977). Calculated extinction coefficients for the laboratory grown ice range from 0.1–0.03 cm^{-1}."*

Technical Comments:

2.26 Unclear, are these the first experiments or just the first experiments using TUV-snow?

The sentence *"The study presented here are the first experiments with the Royal Holloway Sea Ice Simulator to evaluate the TUV snow model for undoped sea ice. . .."* has been changed for clarity to read *"The study presented here includes the first experiments with the Royal Holloway Sea Ice Simulator, the first experiments to evaluate the TUV snow model for undoped sea ice, the first experimental results to demonstrate the change in reflectance owing to light absorbing impurities in sea ice and finally the first experiments to evaluate the TUV-snow model for reflectivity calculations for light*

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absorbing impurities in sea ice. ”

2.30 Personal preference, and may be disagreed by the editorial team, but this list of aims feels very wordy. Could it be bulleted?

The list of aims has now been removed following similar comments also from the second referee.

7.13 Extra space needed.

An extra space has been added.

9.8: Sentence currently doesn’t make sense, too many “for smalls”?

The sentence has been changed to read *“Grenfell et al. (2011) showed that for small amounts of black carbon the mass loading is directly proportional to the absorbance measured by the integrating sandwich spectrometer.”*

10.9 “with a”, not "in a"?

Agreed, “in a” has been changed to “with a”

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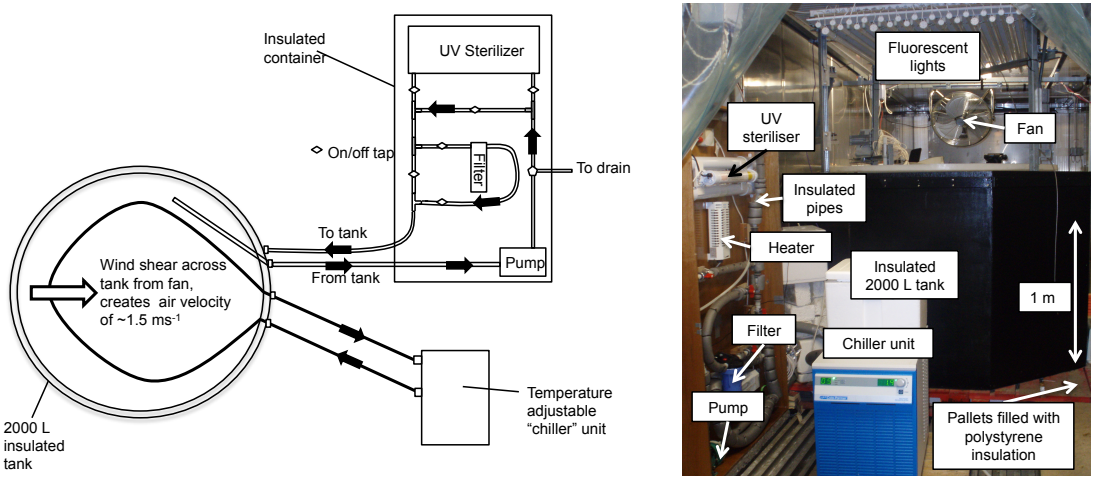

Fig. 1. Updated figure 1 now including annotated photo of sea ice facility

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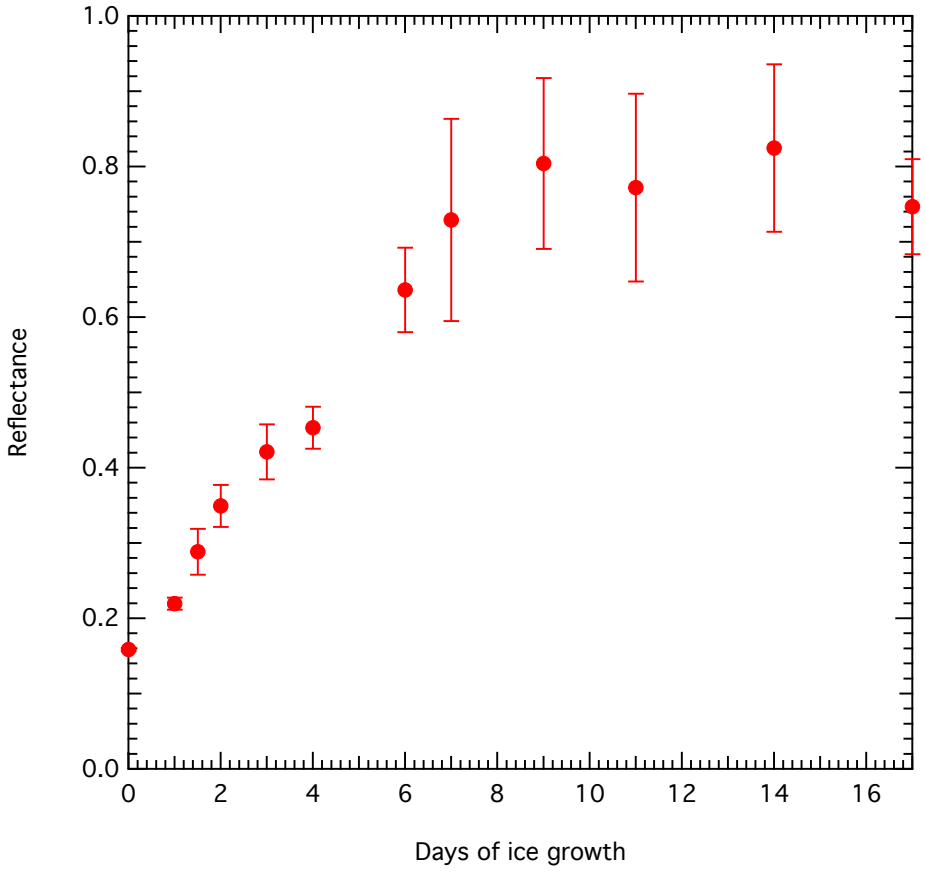

Fig. 2. New figure showing daily reflectance measurements during ice growth

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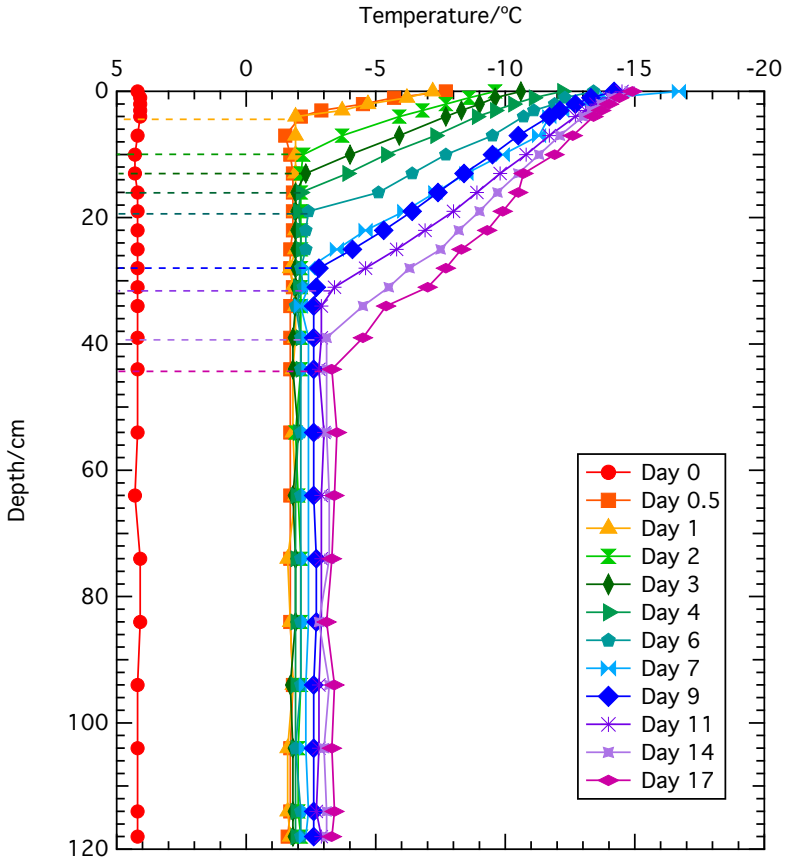

Fig. 3. New figure showing ice temperature profile measurements during ice growth

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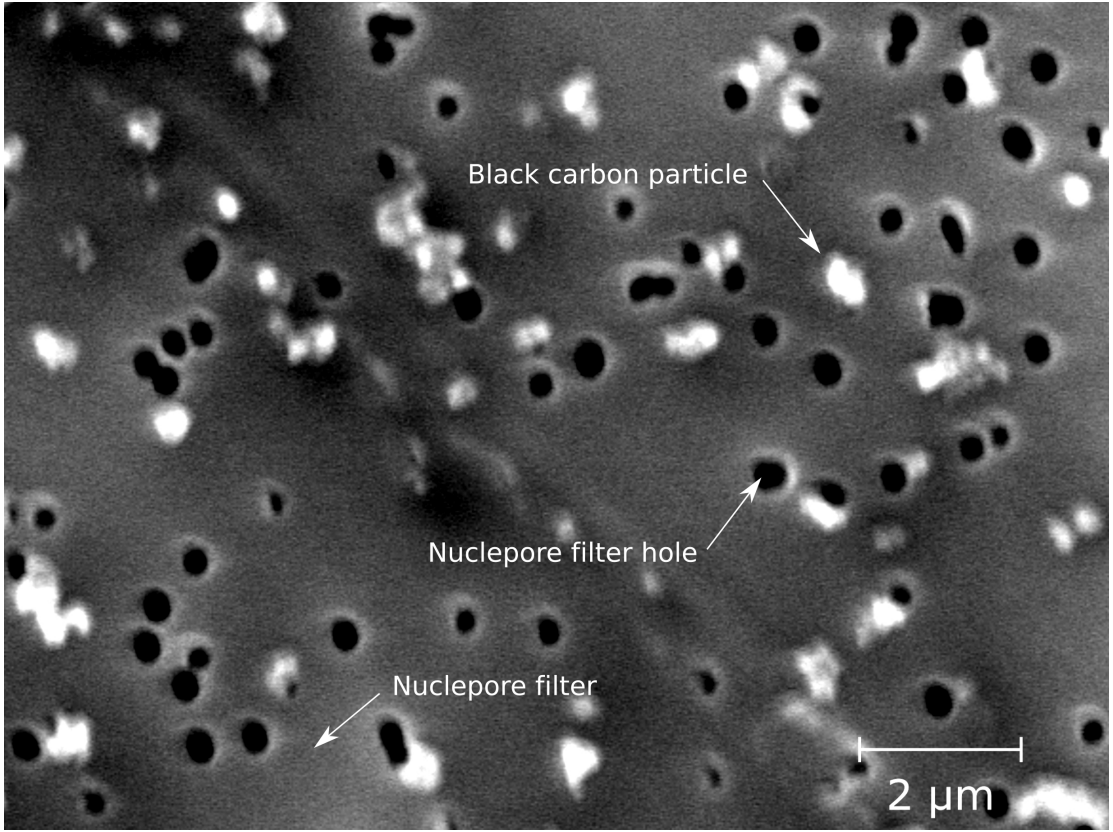

Fig. 4. Updated figure of EM image of black carbon particles now with annotations

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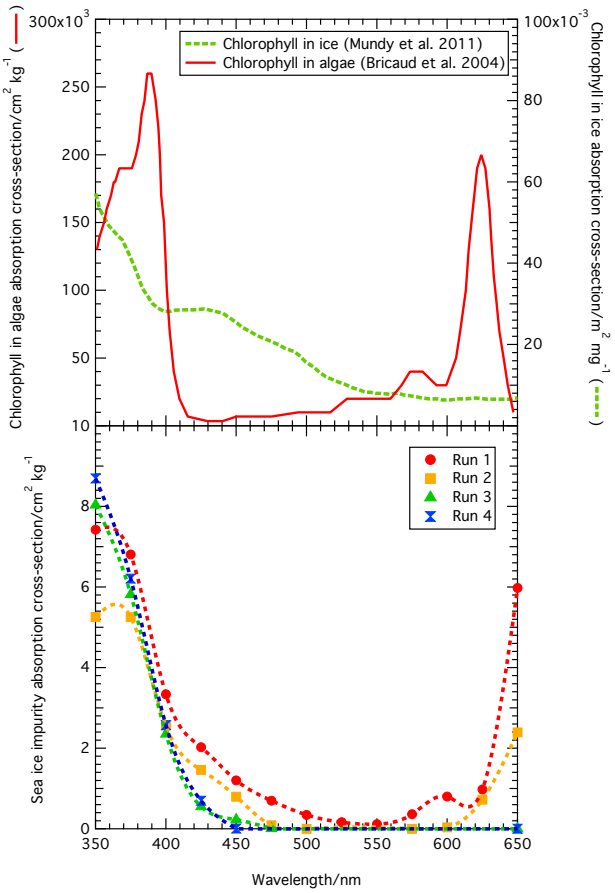

Fig. 5. Updated figure of ice absorption cross-section now including absorption cross-section of chlorophyll

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