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Interactive comment on "The effects of additional black carbon on Arctic sea ice surface albedo: variation with sea ice type and snow cover" *by* A. A. Marks and M. D. King

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The authors are grateful for this considerate and insightful review of their article

Referee comment: This paper explores the sensitivity of sea-ice albedo to black carbon (BC) additions in different types of ice, and also covered with snow of varying thickness and type. The approach taken in this study is a bit unconventional. Rather than starting with pure forward modeling of separated ice and BC species, the authors prescribe bulk optical properties for sea-ice needed to match measured albedo and penetration depth from Grenfell and Maykut (1977). Though unconventional, this approach adds diversity to the spectrum of methods applied to understand radiative

impacts of BC in sea-ice, and hence is valuable. A key limitation of this approach, however, is that the reported BC sensitivities are on the amount of light-absorbing matter that was present in the sea-ice observed by Grenfell and Maykut, possibly quite different in the 1970s than today, and also likely variable in space. This issue is certainly acknowledged by the authors (e.g., by using "additional black carbon" in the title and throughout the manuscript), though I think its importance and potential variability in space and time were understated. The authors could address this by exploring the sensitivity of BC-induced albedo reductions to a wider range of sea-ice optical properties (e.g., by varying the absorption cross-section of the unperturbed sea-ice). I suggest either carrying out such sensitivity studies, or clearly acknowledging in the abstract the limitation of basing the analysis on two sets of measured sea-ice properties from the 1970's. Otherwise, I found the discussion and analysis to be interesting, and I suggest publication in The Cryosphere after minor issues are addressed.

Response: *The authors will amend the text in the abstract and in the discussion highlighting the issue related to the modeling being based on the sea-ice properties of the 1970s. The following text will be added to the abstract:*

"..that suggest black carbon is the dominating absorbing impurity. The first year and multi-year sea ice is based upon a 1970s field study that recorded both reflectivity and light penetration in both sea ice and snow in the same study with the same equipment and in the same location over a large range in wavelength. The albedo response..."

The following more substantial and reflective text will be added to section 4.4 in the discussion:

"The optical properties of the sea ice and snow are based on a field study of snow and sea ice from the 1970s (Grenfell and Maykut, 1977). The black carbon content of this sea ice may not be representative of present day sea ice and the study refers to one sea ice location, north of Barrow, Alaska. Thus the results in this paper must be interpreted within this caution. However, the Grenfell and Maykut (1977) study is excep-

tional in the quality and amount of data it produces. To derive scattering and absorption cross-sections for the study presented here required monochromatic measurements of reflectivity, and light penetration over a wide range of wavelengths, sea ice types and snow types. Such a large dataset recorded in one study makes it an ideal, possibly unique, dataset. Confidence in using the Grenfell and Maykut (1977) study also comes from the work of Lee-Taylor and Madronich (2002). Lee Taylor and Madronich (2002) also calculated scattering and absorption cross-sections of the snow packs reported in Grenfell and Maykut (1977) along with more modern studies of other snowpacks. The values obtained in the Lee-Taylor and Madronich (2002) study suggest they can potentially be considered contemporary with the present century. However the black carbon content of the snowpack derived from the work by Grenfell and Maykut (1977) does appear large compared to the exhaustive study by Doherty et al. (2010)."

The suggestion by the reviewer about exploring the response of sea-ice albedo to a range of sea ice types is a current project and is itself a large (probably too large) article in its own right. It is currently being written up as two separate articles.

Minor issues:

Referee comment: Section 2.1-2.2: Related to my main comment above, do the sea-ice optical measurements conducted by Grenfell and Maykut (1977) represent the current state of science? Are there more recent measurements of sea-ice albedo and light extinction, and if so, how do they compare with those reported by Grenfell and Maykut (1977)?

Response: *The following text will be added (see above as well)*

"The optical properties of the sea ice and snow are based on a field study of snow and sea ice from the 1970s (Grenfell and Maykut, 1977). The black carbon content of this sea ice may not be representative of present day sea ice and the study refers to one sea ice location, north of Barrow, Alaska. Thus the results in this paper must be interpreted within this caution. However, the Grenfell and Maykut (1977) study is excep-

tional in the quality and amount of data it produces. To derive scattering and absorption cross-sections for the study presented here required monochromatic measurements of reflectivity, and light penetration over a wide range of wavelengths, sea ice types and snow types. Such a large dataset recorded in one study makes it an ideal, possibly unique, dataset. Confidence in using the Grenfell and Maykut (1977) study also comes from the work of Lee-Taylor and Madronich (2002). Lee Taylor and Madronich (2002) also calculated scattering and absorption cross-sections of the snow packs reported in Grenfell and Maykut (1977) along with more modern studies of other snowpacks. The values obtained in the Lee-Taylor and Madronich (2002) study suggest they can potentially be considered contemporary with the present century. However the black carbon content of the snowpack derived from the work by Grenfell and Maykut (1977) does appear large compared to the exhaustive study by Doherty et al. (2010)."

The authors require monochromatic measurements of both reflectivity and light penetration (within the sea ice) over a wide range of visible wavelengths for their approach to be successful. There is a great body of work on the reflectivity and transmission of light through sea ice by Perovich (amongst others) however the transmission measurements are not ideal for the analysis presented here. The other great advantages of the Grenfell and Maykut (1977) work is that the reflectivity and light penetration were recorded for many ice types at a similar time and that many ice types were studied. The co-measurements on the light reflectivity and light penetration of snow on the sea ice made the measurements ideal for the study presented here.

Referee comment: 944,7: "are calculated" - Please briefly explain the type of approach that was applied to calculate this (i.e., incorporation of measurements and modeling).

Response: *The text will be changed to read "Visible light absorption and light scattering cross-sections are calculated for a typical first year and multi-year sea ice and "dry" and "wet" snow types. The cross-sections are derived from the incorporation of previous field measurements into a radiative-transfer model. The variation of absorp-*

tion cross-section over the visible wavelengths suggest black carbon is the dominating absorbing impurity."

Referee comment: 945,4: Gardner -> Gardner and Sharp

Response: *Will be fixed.*

Referee comment: 947,4: A 1% reduction in 500 nm albedo caused by 100 ng g^{-1} of soot, ascribed to Grenfell et al (2002), sounds extremely small. It may be accurate, but I suggest verifying it and including possible explanations (in section 4) for why the sea-ice albedo modeled by Grenfell et al (2002) was so insensitive to BC.

Response: *The following text will be added:*

"Light et al. (1998), Grenfell et al. (2002) and Jacobson (2004) suggest for increasing the amount of black carbon in sea ice (without a snow cover) from 0–100 ng g^{-1} will decrease the albedo to 73%, 99% and 92% of the original values respectively, for a wavelength of 500 nm. For each of these studies the optical properties of the sea ice were different and the distribution of black carbon within the sea ice was different. Thus detailed comparison of the studies is difficult. For example, Grenfell et al. (2002) place black carbon in only a 1 cm layer at the sea ice surface, which may explain the relatively small decrease in albedo reported compared to Light et al. (1998) and Jacobson (2004) who distribute black carbon evenly through the sea ice."

Referee comment: 947,10-30: The analysis of reduced BC impact in snow-covered sea-ice is useful, but the snow overlying sea-ice may also be contaminated with BC, reducing surface albedo and altering evolution of the snow/ice column. I suggest briefly mentioning this.

Response: *The following text will be added. "...in the snow surface albedo. The reduced surface albedo caused by increasing black carbon in the snow layer on top of the sea ice is not considered in this study and the interested reader is referred to the work of Reay et al. (2012)."*

Referee comment: 947,21: The 8cm and 20cm appear to be reversed here.

Response: *The text will be corrected as Warren and Wiscombe (1980) state:*

"The liquid-equivalent depth for which the snowpack becomes effectively semi-infinite (i.e. albedo at all wavelengths is within 1% of that for an infinitely-thick snowpack) is 2 cm for grain radius r=50 μm (e.g. 20 cm of fluffy new snow, density=0.1 g cm^{-3}), about 8 cm for r=200 μm (e.g. 20 cm of fine grained old snow, density = 0.4) and 20 cm for r = 1000 μm (e.g. 50 cm of old melting snow of density =0.4)"

Referee comment: Equation 1: It is useful to include this, but the first two terms (σ^{ice} and σ^{+}) were not separated in this study, correct? I suggest clarifying at this point in the text that the approach taken in this study is to infer the sum of σ^{ice} and σ^{+}) from measurements.

Response*: The manuscript will now include the following explanative text.*

"where ,$\sigma_{abs}^{ice}(\lambda)$, is the absorption cross-section for pure ice (taken from Warren and Brandt, 2008), $\sigma_{abs}^{+}(\lambda)$, is the absorption cross-section. . . . . . is the wavelength of light. Thus when calculating the absorption cross-section,$\sigma_{abs}(\lambda)$ of the sea ice or snow from Grenfell and Maykut (1977) $\sigma_{abs}^{BC}(\lambda)$ is zero and $\sigma_{abs}^{+}(\lambda)$ can be calculated by subtracting $\sigma_{abs}^{ice}(\lambda)$ from $\sigma_{abs}(\lambda)$. The absorption cross-sections are specific absorption cross-section, i.e. per unit mass."

Referee comment: Equation 1: The symbol σ and term "cross-section" are often used to denote extinction/scattering/absorption cross section with units of m^2. Please clarify here that these are cross sections normalized to mass, with units of m^2 kg^{-1}

Response: *The following text will be added.*

"The absorption cross-sections are specific absorption cross-section, i.e. per unit mass."

Referee comment: 950,18: "diameter of 0.2μm" - Was a monodisperse size distribution assumed?

Response: *Yes and the following text will be added*

"...with a monodisperse diameter of 0.2 μm and..."

Referee comment: 950,20: Please list the BC mass absorption cross-section resulting from these assumptions.

Response: *The calculated black carbon absorption has been added to figure 2 of the manuscript, which is shown as figure 1 in this response.*

And the following text has been added "The absorption spectrum for black carbon in an ice matrix, shown in figure 2 at wavelengths 400–700 nm, is determined by a Mie calculation using the method outlined by Warren and Wiscombe (1980)."

Referee comment: 951,9 and 951,28: Use of the term "extinction coefficient" is a bit confusing here, because it differs from the "extinction coefficient" used in basic radiative transfer equations. Here, it represents the reduction in flux within a scattering medium. I suggest briefly clarifying this to avoid confusion.

Response: *Text will be changed to "...measurements of light extinction coefficient (reduction in flux within a scattering medium, optical wavelengths 400–800 nm) and albedo.."*

and we note that the original Grenfell and Maykut (1977) paper describes the calculation of extinction coefficient as follows:

"To calculate extinction coefficients from measured irradiances, a model is needed to describe how absorption and scattering affect the radiation field within the ice. The approach most commonly used is to apply the Bouguer-Lambert law which assumes that irradiance decreases exponentially through a homogeneous material of infinite optical thickness. This assumption, however, is not strictly true in the lower part of a sea-ice cover because of differences in scattering between the ice and the underlying ocean.

The effects of the lower boundary were taken into account by applying a two-stream photometric model which, except for the boundary conditions, followed the formulation of Dunkle and Bevans (1956)."

Referee comment: 951,24-25: Please fix the wording in this sentence.

Response: *Fixed. Text will now read. "Table 1 lists the sky conditions, asymmetry factor...and solar zenith angle for each sea ice/snow pack modeled."*

Referee comment: 951,27: Are there necessarily unique combinations of scattering and absorption mass cross-sections that yield an optimal fit with measured albedo and extinction coefficient? Please include a sentence or two about this, and how it relates to the uncertainty depicted in Figure 2 and described in section 4.4.

Response: *The following text will be added. "The unique solutions found by the above method are a result of using light penetration data and reflectivity data for the same sea ice or snow pack. The unique solution is demonstrated in Lee-Taylor and Madronich (2002) in their figure 1, where the intersection of two curves on a plot of, σ_{scatt} against, σ_{abs} (one curve representing constant albedo and the other curve representing constant e-folding depth) is the unique solution. The intersection and thus values of σ_{scatt} and σ_{abs} may be sensitive to the initial fit to the reflectivity and e-folding depth data, propagating the uncertainty results in the error bars to be demonstrated later in fig. 2."*

Referee comment: Also, could the fit with measurements be influenced at all by variability in the scattering asymmetry parameter (g), which was held constant?

Response: *The following text will be added to clarify:*

"The asymmetry parameter was held constant in this study at a value of 0.95 for the sea ice and 0.89 for snow. It is not always possible to find a unique solution for σ_{scatt}, σ_{abs} and g. Adopting the approach of Lee-Taylor and Madronich, (2002), g, was held constant and σ_{scatt} and σ_{abs} varied. France et al. (2012) undertook a sensitivity study of changing g between reasonable limits based on the work of Wiscombe and Warren

(1980) and found the value of σscatt and σabs+ to be relatively insensitive to the value of g for a snowpack in Barrow, Alaska. Repeating a similar study to the France et al. (2012) study yields figure 2 in this response.

Referee comment: 954,20: "each sea ice/snow" -> "each sea ice/snow combination"?

Response: *text will now read*

"...mass ratio of black carbon in each sea ice or snow pack can be estimated..."

Referee comment: 956,5: "increase observed" - increase of what?

Response: *text will now read*

"could explain the increase in absorption cross-section with wavelength."

Referee comment: 956,3-17: Doherty et al (2010) concluded that about 40% of the light absorption in their Arctic snow and sea-ice samples was caused by non-BC species.

Response: *The following text will be added. "...in the snow and sea ice studied. Further evidence from Doherty et al (2010) concluded that 40% of the light absorption in their filtered snow and sea ice samples was due to species other than black carbon."*

Referee comment: 957,20: "... implies a large value of the scattering cross-section will result in black carbon having less effect on surface albedo." - OK, but this is not entirely consistent with the data cited from Light et al. (1998) and Grenfell et al. (2002). For example, Light applied higher scattering cross-sections than Grenfell and those used for first-year ice in this study, and yet Light et al calculated a larger albedo reduction from BC than either study. This suggests that other factors or assumptions also play key roles in determining the albedo sensitivity to additional BC. Please comment on this.

Response: *The following text will be added: "...for the multi-year sea ice. The results presented here suggest that a large value of the scattering cross-section will result in*

black carbon having less effect on albedo. Warren (1982) reports a more scattering medium has a smaller grain size, and therefore a photon may experience more transitions between air and ice (the most efficient place for photons to be scattered). Warren (1982) continues to explain that a photon will only be absorbed as it passes through the ice, where it can be absorbed by the ice matrix or black carbon. However, Light et al. (1998) use large scattering cross-sections (relative to those used in this study) and see a relatively large change in albedo with increasing black carbon, suggesting other factors may play a key role in determining the albedo response of sea ice. Different studies distribute the black carbon in different positions in the sea ice which limits comparability between studies; Grenfell et al. (2002) place black carbon in a surface 1 cm layer, Light et al. (1998) evenly distributed black carbon throughout the sea ice, and in the work presented here black carbon is situated in a 5 cm surface layer."

Referee comment: 958,11: Please fix this sentence.

Response: *Sentence will now read:*

"The snow or sea ice is described as "optically thick" when increasing its thickness does not result in a change in surface reflectivity"

Referee comment: 960,12-15: "These values of uncertainty were calculated through making small changes to the fit of the albedo and extinction coefficient data from Grenfell and Maykut (1977), and judged by eye, to ascertain how small changes affect the derived scattering and absorption value." - This description of uncertainty determination needs clarification. Can it be stated that the uncertainty bars represent reasonable ranges of absorption cross-section that can produce an optimal fit with observed albedo and extinction coefficient, while holding all other variables (e.g., scattering asymmetry parameter) constant? Please clarify, and perhaps elaborate on the approach used to quantify uncertainty.

Response: *The text will now read "The uncertainty bars on figure 2 represent the range of values of the absorption cross-section that are derived from an optimal fit* *of the albedo and extinction coefficient data from Grenfell and Maykut (1977), while holding scattering asymmetry parameter and density constant."*

Interactive comment on The Cryosphere Discuss., 7, 943, 2013.

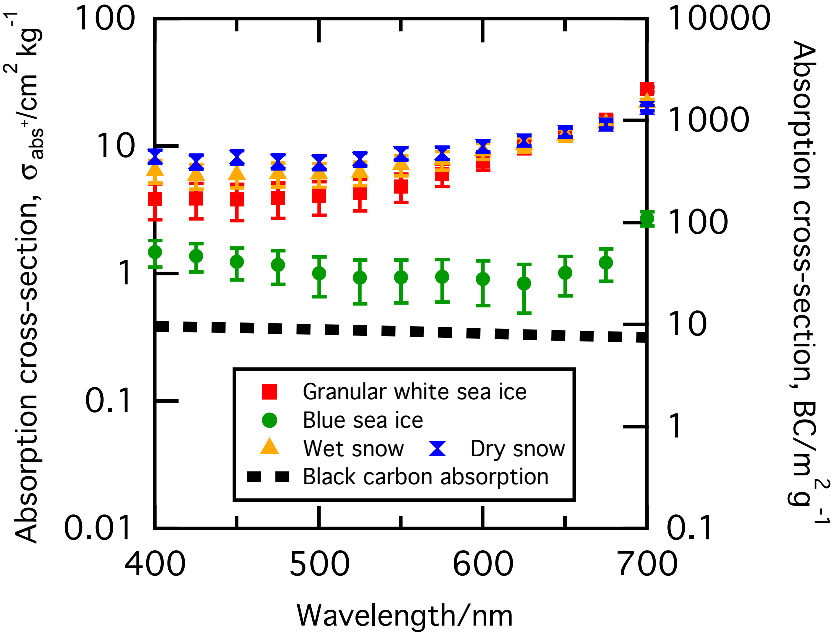

Fig. 1. Addition of black carbon absorption cross-section to figure 2

Asymmetry Parameter, g	Blue sea ice, λ=550 nm		Granular white sea ice, λ=550 nm	
	σ_{scatt} /m^2 kg^{-1}	σ^{+}_{abs} /cm^2 kg^{-1}	σ_{scatt} /m^2 kg^{-1}	σ^{+}_{abs} /cm^2 kg^{-1}
0.945	0.027	1.037	0.665	4.272
0.95	0.03	1.037	0.726	4.272
0.955	0.034	1.035	0.814	4.272

Fig. 2. Sensitivity of derived scattering and absorption cross-section values to variation in asymmetry parameter, g