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Interactive comment on "The effect of snow/sea ice type on the response of albedo and light penetration depth (e-folding depth) to increasing black carbon" *by* A. A. Marks and M. D. King

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We thank the referee for their comments. Our answers and corrections are below.

Referee comment: This is a well-written paper that should be accepted after minor revisions. This paper uses the TUV-snow model to investigate relationships between black carbon concentrations and the albedos and e-folding depths of various snow and sea ice types. The various types of snow and sea ice are specified using scattering coefficients and asymmetry parameters in line with observations for each surface type. Changes in black carbon influence the albedo and e-folding depths of each surface type to varying degrees. Changes in albedo due to variations in black carbon are

different depending on sea ice and snow type. However, changes in e-folding depths due to variations in black carbon are not dependent on snow or sea ice type. It would be informative to include estimates of snow grain size for each snow type if possible. Also, it would be interesting to note why snow and sea ice have distinct spectral profiles for albedos and e-folding depths. There are multiple types of snow and sea ice types considered, but it appears that there are some common patterns

Response: *Typical snow grain sizes for all snow types will be added to table 1 (included here as figure 1). The following text will be added to explain the spectral profile of snow and sea ice "The variation of albedo and e-folding depths with visible wavelengths is controlled by the scattering and absorption of photons in the snowpack. At visible wavelengths the absorption cross-section of ice is very small (Brandt and Warren, 2008) and thus light absorbing impurities have a large effect on the albedo and e-folding depth. Warren and Wiscombe (1982a,b) demonstrate and describe these effects for albedo in detail. France et al. (2012) and Marks and King (2013) demonstrate that the effect of light absorbing impurities on albedo and e-folding depth is large enough to be able to deduce the absorption spectrum of the light absorbing impurities from the measurements of albedo and e-folding depth of snow and sea ice respectively."*

Referee comment: Abstract: Line 11-15: It's not clear why the relative change in albedo between melting snow and cold snow is compared or why the relative change in albedo between melting sea ice and multi-year sea ice is compared. These comparisons became clearer after reading the paper, but adding a sentence before these comparisons in the abstract that puts these comparisons in context would be beneficial. Otherwise it could seem that random snow and ice types are being compared.

Response: *The following clarifying sentences will be added to the abstract "The snow and sea ice types are effectively defined by a scattering cross-section, density and asymmetry parameter. The relative change in albedo and e-folding depth of each of the three snow and three sea ice types with increasing mass ratio of black carbon is* *considered relative to a base case of 1 ng g^{-1} of black carbon. The relative response of each snow and sea ice type considered is then compared to examine how different snow and sea ice types respond relatively to each other. The relative change in albedo..."*

Referee comment: Body: p. 1025, line 7: Include the wavelength bands over which BC is responsible for 85% of absorption.

Response: *Wavelength range will be added in the following sentence "in snow/sea ice (over a wavelength range of 400–700 nm) ..."*

Referee comment: p. 1025, line 12: Since this statement will become dated, I wonder if there is a better way to estimate the date of the next IPCC report. If not, it's probably best to remove the sentence.

Response: *The sentence will be deleted*

Referee comment: p. 1025, line 18: add "light-absorbing" before impurities for consistency.

Response: *"light-absorbing" will be added before all cases of "impurities".*

Referee comment: p. 1026, top of page: It would be good to give the reader a brief reminder of why large grains lead to lower albedos. This topic comes up frequently during the paper, so it would be good to put a sentence or two in the introduction that provides a clear explanation

Response: *The following text will be added to the introduction "...with a more coarse grained snow showing a greater relative decrease in albedo. Warren (1982) suggests for a clean snow photons are typically scattered at the air-ice interface and may be absorbed whilst passed through the ice. The longer the path length through the ice the more likely a photon is to be absorbed. Thus the albedo for a large grained snowpack is smaller as a path-length of a photon through ice is larger between scattering events. The penetration of the photon deeper into the snowpack is also greater for a large*

grained snowpack. The increased penetration of the photon into the snowpack will increase the probability of the photon may be absorbed by a black carbon impurity within the snowpack. And thus the albedo of a coarse grained snowpack may be more sensitive to light absorbing impurities than a fine grained snowpack. Figure S4..."

Referee comment: p. 1029, line 9-11: There are polluted places in the world where BC values can reach these high values [Wang et al., 2013]. Please consider removing this statement

Response: *The text will be revised to read "...considered large, although Wang et al. (2013) show that in polluted areas black carbon can reach values up to 1220 ng g^{-1}. Thus the values of 512 and 1024 ng g^{-1} have also been included for completeness..."*

Referee comment: p. 1029, 13-14: it would be helpful to mention the mass absorption efficiency values that were used in this study at some point during the paper

Response: *A graph of the absorption cross-section of black carbon with wavelength used in the paper will be added (attached as figure 2).*

Referee comment: p. 1029, line 22: This sentence needs rewording, or perhaps should be split into two sentences. You could say something like "the e-folding depth and albedos were calculated using snow and sea ice of a variety of thicknesses: 0.5 m, 1 m, and 10 m. Additional simulations were performed using thicknesses of 0.25 m for sea ice and 0.1 m for snow"

Response: *Sentence will be changed as suggested above.*

Referee comment: p. 1030, line 25: Why is a base case of 1 ng/g chosen?

Response: *Lowest values recorded in snowpacks are about 1 ng g^{-1}* at Dome C, Antarctica by Warren and Clarke (1990). The following sentence will be added to the paper to reflect this "A base value of 1 ng g^{-1} is used for the mass ratio of black carbon; representing the lowest values of mass ratio of black carbon recorded (at Dome C, Antarctica by Warren and Clarke (1990))".

Referee comment: p. 1031, line 15: Figure 2a also shows sea-ice, not just snow, but the sea ice cases aren't talked about until later in the paper. It would be good to mention that sea ice is also shown in Figure 2a here, even if it isn't discussed until later.

Response: *The presence of sea ice in figure 2a will be mentioned with the following sentence added "for the three snowpacks (the relative change for the three sea ice types are also included in figure 2a and will be discussed later). The lines..."*

Referee comment: p. 1031, line 18: How exactly were these mid-range albedos and e-folding depths? By eye? Please describe the process and also provide values for each snow and sea ice type

Response: *The following descriptive text will be added and the values will be entered in an additional table. "The albedo and e-folding depths reported in figure 2 are the central value of albedo and e-folding depth for each snow and sea ice type and black carbon mass-ratio plotted in figures 1, 3, 6 and 7."*

Referee comment: p. 1032, equation 3: Why S? S should be given a proper name. S in theory could be used for any BC base-case concentration (not just 1). It would be useful to note that, because this relationship is a great way to relate changes in BC to albedos/e-folding depths in different types of snow.

Response: *"S" describes a ratio of the relative change in albedo of melting snow to the relative change of cold polar snow for a specific black carbon mass-ratio increase, "S" will be changed to "Relative change factor".*

Referee comment: p. 1032, line 8: Please add a clarifying statement that better explains why the sensitivity is only a weak function of mass-ratio.

Response: *The following text will be added "...approximations. To date the exact reason for the very weak dependence of the relative change factor on mass ratio of black carbon is not known. It does not appear to be an artifact of the model (i.e. a rounding or interpolation error) and unfortunately the field data is not of high enough*

quality to check the weak function is a real effect. However inspection of figure 2 demonstrates that the reason is probably due to the function form of the relative change in albedo versus black carbon mass ratio is displaced in mass ratio of black carbon for the different type of sea ice; and is most prominent at large values of mass ratio of black carbon. The displacement is probably related to the transition of absorption being dominated by ice to being dominated by black carbon as explained by Reay et al. (2012). Accurate..."

Referee comment: p. 1032, line 11: The word "light" isn't needed.

Response: *"Light" will be deleted*

Referee comment: p. 1032, line 17: Please elaborate on the pronounced effect

Response: *The following will be added "pronounced effect owing to the larger value of the absorption cross-section of ice at a wavelength of 700 nm."*

Referee comment: p. 1035, lines 7-10: Why is the change in albedo less pronounced for the melting sea ice compared to the melting snow?

Response: *The following text will be added "A melting snow has a larger scattering cross-section than a melting sea ice, thus the albedo of a melting snow is less responsive to additions of black carbon."*

Referee comment: p. 1035, line 20: How is the change in density related in magnitude to the change in snow grain size? Do changes in grain size influence the e-folding depth more than changes in density?

Response: *Our study doesn't use grain size, however the scattering cross-section used in our study is proportional to 1/(grain size). Changes in the scattering cross-section have a significantly larger effect than changes in density on the e-folding depth response. The following clarifying sentence will be added to the paper "The study presented does not use grain size as a variable but instead uses the scattering cross-section with values derived from field studies. Kokhanovsky and Zege (2004)* *have linked scattering cross-sections to grain size for albedo and Libois et al (2013) (amongst others) have recently discussed grain size and shape with respect to e-folding depths."*

Referee comment: Figure 2: Adding equation 3 or the equations on 1030, line 26 somewhere in the figure would be helpful so that the reader doesn't need to flip back to the equation when trying to think about the percent change in albedo and e-folding depths. Also, specifying the mid-range albedo and e-folding depth on the figure or in the caption would be helpful

Response: *The equations will be added to the figure captions and the mid-range albedo and e-folding depths.*

Referee comment: Figure 4: In the caption, when comparing the BC sensitivity, which type of snow of semi-finite thickness are being comparing to the thin, melting snow? In some cases here, (e.g. comparing the 10 cm melting snow to the 10 m cold snow), the sensitivity of the melting snow appears larger

Response: *The following comment will be added to the caption labelling the three panels in figures 4 and 8 "the left figure is melting snow, the central figure is windpacked snow and the right hand figure is cold polar snow." And the following additional information will be provided in figures 5 and 9 "the left figure is melting sea ice, the central figure is first year sea ice and the right hand figure is multi-year sea ice."*

Referee comment: Figure 9: The snow *e*-folding depths look realistic (Figure 8), but the sea-ice *e*-folding depths are really large. Are these values realistic? Also, have there been any measurements of black carbon in sea ice? If so, what are the typical values? I would assume that the main light-absorbers in sea ice are organics. If there are any measurements of these species, perhaps estimates of the equivalent black carbon values in sea ice using the technique you describe earlier in the paper could be provided.

Response: *The sea ice e-folding depths are calculated for a sea ice which contains no impurities other than black carbon, thus are realistic for this scenario, although in nature other impurities may be present e.g. sediment, algae. Marks and King (2013) demonstrated the spectrum of light absorbing impurities in sea ice (deduced from real measurements) could be consistent with a significant mass-ratio of black carbon (11–48 ng g^{-1}), whilst black carbon was responsible for the majority of light absorbing impurities there was evidence for other light absorbing impurities in sea ice owing to the spectral shape. The following sentence will be added regarding measurements of black carbon in sea ice "Doherty et al. (2010) report measurements of black carbon in sea ice of 4 to 67 ng g^{-1}. The figures presented in our paper show the absorption cross-section of the impurity and the equivalent mass-ratio of black carbon. The absorption cross-section of impurity could be converted to a mass-ratio of any known absorbing impurity if the absorption cross-section is known."*

Referee comment: p. 1037, line 25: spelling of "scattering"

Response: *Spelling will be corrected*

Referee comment: p. 1038, line 5: Missing a parenthesis

Response: *Parenthesis will be added*

Referee comment: Section 4.4: This is a great way to link this work to the bigger picture

Response: *Thank you*

Interactive comment on The Cryosphere Discuss., 8, 1023, 2014.

Snow/sea ice type	Scattering cross-section (m^2 kg^{-1})	Density (kg m^{-3})	Asymmetry parameter (*g*)	Indicative grain size range (mm)
Cold polar snow	15–25	200–600	0.89	0.1--0.5 mm
Windpacked snow	5–10	200–600	0.89	0.5--2mm
Melting snow	0.5–2	200–600	0.89	2--5 mm
Frozen multi-year sea ice	0.5–1	700–950	0.98	--
Frozen first-year sea ice	0.1–0.2	700–950	0.98	--
Melting sea ice	0.01–0.05	700–950	0.98	--

Table 1- Properties of snow and sea ice types studied. Optical and physical properties are based on work by Grenfell and Maykut (1977); Perovich (1990); Timco and Frederking (1996); Perovich (1996); Gerland et al. (1999); Fisher et al. (2005); King et al. (2005); France (2008); France et al. (2011); Marks and King (2013); Simpson et al. (2002). Approximate grain size for each snow type is also included for information only; grain size is not included in the model.

Fig. 1. Revised table 1 to include approximate range of grain sizes for each snow type.

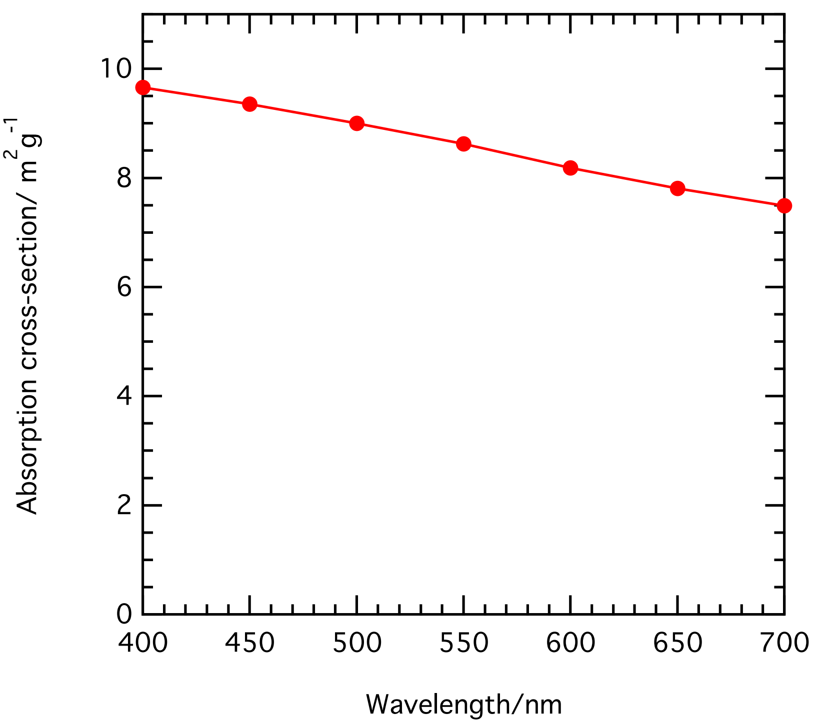

Fig. 2. Black carbon absorption cross-section used in this work which will be added to the paper