Response to Anonymous Referee #1 on tc-2021-372

1. Reviewer comment '*I find the title somewhat misleading, as the authors really have not quantified the climatic impact of oil pollution*'.
- Author response: title changed to '*Quantifying the effects of background concentrations of crude oil pollution on sea ice albedo*'.
2. Reviewer comment '*I don't believe that the optical descriptions given here for first-year, multiyear, and melting sea ice are realistic or representative in the context of this study. It is well established that the scattering coefficients for sea ice display significant variability, including between ice types, within a single ice column, and for the same ice type at different times and locations.*'.
- Author response: It is difficult to reply accurately to this comment as no comparison to data or references are provided by the reviewer.
- The authors are aware that scattering cross sections for sea ice vary within the ice column, with seasons and between geographic locations. We present a new figure in the Uncertainties section of the paper using a range of scattering sections from literature (Grenfell and Maykut, 1977; Perovich, 1990; Timco and Frederking, 1996; Perovich, 1996; Gerland et al, 1999) for typical thickness sea ices. This graph also shows that whilst there is variability in the albedo response of each type of sea ice, the conclusions put forward in this manuscript are valid:

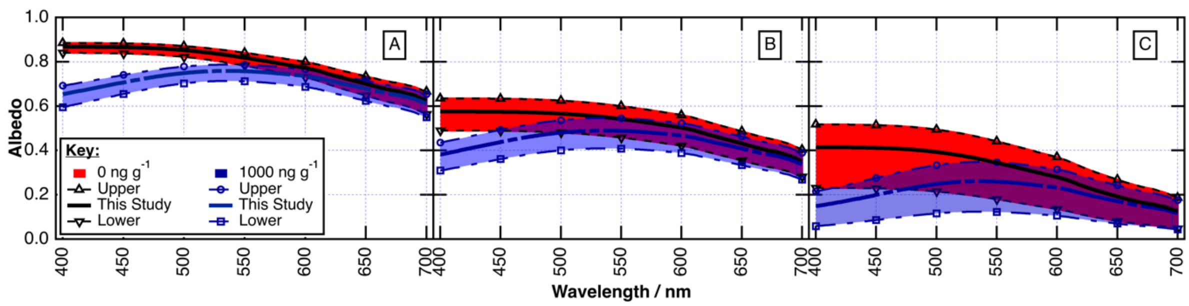

Fig. 8. Wavelength dependent albedo of multi-year (A), first-year (B), and melting sea ice (C). Shown here is the variability in albedo for each type of sea ice based on scattering cross sections described in literature (Grenfell and Maykut, 1977; Perovich, 1990; Timco and Frederking, 1996; Perovich, 1996; Gerland et al, 1999), ranging from 0.5–1 $m^2\ kg^{-1}$ for multi-year sea ice; 0.1–2 $m^2\ kg^{-1}$ for first-year sea ice; and 0.01–0.05 $m^2\ kg^{-1}$ for melting sea ice. Shown in red are the data with no oil pollution present and shown in blue are the data with 1000 ng g^{-1} of *Romashkino* oil present. The thicker lines show the values of typical ice used in this study. The melting sea ice and multi-year sea ice are 2.5 m thick; the first-year sea ice is 0.8 m thick, and the background concentration of black carbon is set to 5.5 ng g^{-1}.

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- Whilst we cannot know which scattering cross section or albedo values the reviewer is comparing to, we would like to make clear for the reader/reviewer that our study does the following:
- (1) lists monochromatic albedo which must be integrated to compare to broadband albedo. Reported broadband albedo values are thus lower.
- (2) Focuses on three different types of sea ice which are assigned a quasi-infinite thickness as sea ice thickness and type vary so much. The quasi-infinite thickness allows a fair 'like-for-like' comparison between optical properties; the three types of

ice are simple examples to explore the variation in scattering cross sections as opposed to being rigid prototypes. The three different types of sea ice are based on the loci of their scattering cross sections.

- (3) The work is an exploration, possibly the first of how oil optical properties may affect sea ice and so the mass ratio of black carbon has been kept at a pristine level for quasi-infinite cases.
- (4) The variation of scattering cross sections within the ice column has not been explored as this is the first exploratory study to determine if oil is a concern for sea ice albedo. Further detailed models with a plethora of ice types and possibly dynamics are now all possible, but this initial study demonstrating the effect is important so that others can choose to explore these effects further. It should be stated that there has been significant interest in this unpublished manuscript from environmental and petrochemical organisations.
- We have added the following text to the manuscript:
- Edited caption in Methodology: '***Table 1****. TUV-snow model sea ice input parameters derived from literature (Grenfell and Maykut, 1977; Perovich, 1990; Timco and Frederking, 1996; Perovich, 1996; Gerland et al, 1999) and previously used in other studies (e.g. King et al, 2005; France 2008; France et al 2011; Marks and King 2013; Marks et al, 2014).*'
- Added to Uncertainties section: '*Throughout this study the mid-range/typical values for sea ice have been selected and are reported in Table 1. To assess any uncertainties that may arise from the variability of scattering cross sections reported in literature (Grenfell and Maykut, 1977; Perovich, 1990; Timco and Frederking, 1996; Perovich, 1996; Gerland et al, 1999) Fig. 8 is additionally presented and indicates the response of realistic types of sea ices with both lower and higher scattering cross sections.*'

3. Reviewer comment: '*I'm a bit confused by the FY, MY, melting classifications. If Arctic sea ice isn't melting, it is likely snow covered. Do the authors intend for this study to treat bare, non-melting FY, MY ice? And, if the snow is implicitly included, then the dynamics of snow-oil interactions need to be accounted for.*'.

- Author response: We have done a general study for the effect of oil pollution on bare sea ice. Sea ice is frequently snow covered so this study, similar to the study of Light et al, 1998, may only be valid for areas of sea ice that experience snow melt or removal of snow by wind. Whilst this study focuses on the Arctic owing to the development of shipping routes and enormous hydrocarbon reserves in the region, these results are also relevant for non-polar sea ice and the Antarctic.
- The reviewer has raised two minor issues here: (a) First-year, multi-year, and melting sea ice classification; and (b) snow cover on sea ice.
- (a) Our first-year, multi-year, and melting sea ice classifications are a way of exploring the variation in scattering cross sections of sea ice as described in response to point 2 above. We now explicitly state in the Uncertainties section that these are the mid-range/typical values selected from literature.
- (b) We have added the following text to the Uncertainties section: '*Sea ice is frequently covered with snow and sea ice tends only to be free of snow where it is removed by katabatic winds or during the melting season (Weeks, 2010).*'
- However, studies (Marks and King, 2013) have previously reported that an overlying snowpack of 2–5 cm is sufficient to mask light absorbing impurities in sea ice and so

it was not necessary to consider snow cover in this work as it would mask our results. Unlike black carbon pollution in snow and sea ice, which is deposited from the atmosphere, the incorporation of background quantities of oil pollution into the sea ice matrix is postulated to come from the ocean. We have not considered the movement of oil from the sea ice matrix to snowpack in this work as it is an area of research and probably only relevant at much higher concentrations of oil.

- For clarity, the following has been added to the Methodology: '*Snow has not been considered in this study in order to independently assess the effect that oil pollution has on the albedo of the different types of sea ice*'.

4. Reviewer comment: '*L183: how do authors justify 201 layers?*'

- Author response: Previous works (Marks, 2017) have demonstrated that a large number of layers are required at the interface, and 201 layers was a good compromise between computational time and precision.
- The following text has been added to the Methodology: '*Marks (2017) found it important to have a large number of layers at the interface so 201 layers offers a good compromise between computational time and precision.*'

5. Reviewer comment: '*L200 (Eq1): What is the prime symbol for?*'

- Author response: it was a comma and has been removed for clarity.

6. Reviewer comment: *'L212: why bother modelling atmosphere here? Seems extraneous'*

- Author response: In this paper we report diffuse sky conditions to keep the work manageable. Our initial efforts included the effects of solar zenith angle and sky conditions (e.g. cloud, aerosol, ozone column etc.) but the work became too large for a single paper and the atmosphere radiative-transfer detracted from the sea ice radiative-transfer.

7. Reviewer comment: *'L299*: *"The oil is most absorbing at 400 nm, where ice is the least absorbing…" Perhaps this is true, but this is the cause, not a result.'*

- Author response: we think there may be a misunderstanding here, we have taken the optical properties and done a Mie calculation on them – this is a result and helps the reader understand the results more clearly.
- We are describing the absorption efficiency of an oil droplet (similar size to the wavelength of light) because that is different depending on the size (see Fig. 3) to the absorption cross section.
- For clarity, we have changed the text to now read: '*The Mie calculation demonstrates the oil droplet is most absorbing at 400 nm where the ice is least absorbing.'*

8. Reviewer comment: *'L313: "the effect of oil significantly decreases as wavelength increases over the region studied and the oil becomes less absorbing whilst the ice becomes more absorbing." Same as previous comment, this is a physical cause, not a result.'*

- Author response: this statement resides from the fact that we have done a Mie calculation and is therefore a result.
- For clarity, we have changed to the text to now read: '*the Mie calculation shows the effect of oil significantly decreases as wavelength increases and the ice becomes more absorbing.*'

9. Reviewer comment: *'L328: "The three types of sea ice have different unpolluted albedos: melting sea ice 0.72, first-year sea ice 0.87, and multi-year sea ice 0.94 at a*

wavelength of 400 nm respectively, owing to their different scattering cross sections (Perovich, 1996; Marks and King, 2014)." I think this overstates the differences between these three ice types if indeed it is intended that all are snow free.'

- Author response: the ice is snow free as now clearly stated in the Methodology: '*Snow has not been considered in this study in order to independently assess the effect that oil pollution has on the albedo of the different types of sea ice.*'
- This comment is a repeat of the issues responded to above in point 2 and our explanations and edits are again valid here.
- Please note these are the maximum monochrome albedo values of each type of sea ice taken at a wavelength of 400 nm and that these sea ice's have been made quasi-infinite in order to independently compare the effects of oil pollution on sea ice albedo.

10. Reviewer comment: *'L606: "As these data shows, this decline in perennial types of sea ice renders the Arctic much more vulnerable to increased oil pollution in the region..." I don't think this conclusion is supported by this study. For example, the high scattering prevalent in the surface layers of multiyear ice, and the larger thickness of this layer in thicker ice is not accounted for in this study. Also, there is no attempt to simulate how oil droplets respond to summer freshwater flushing that is a key factor that distinguishes FY ice from MY ice.'*

- Author response: we have edited the text to read '*As these data shows, this decline in perennial types of sea may render the Arctic more vulnerable to increased oil pollution in the region.*'
- We have done the first study to show that background concentration levels of oil in sea ice are important – the model is a radiative transfer model only and allows for the effect of oil pollution to be determined and for the basis to be set for more complex work in the future utilising more sophisticated models.
- We have added a line in the Uncertainties section '*This manuscript shows that background concentrations of oil pollution may have an important effect on sea ice albedo and will hopefully lay the groundwork for more sophisticated modelling studies to explore the effects such as oil movement within the sea ice column in greater detail.*'
- Martin (1979) explained that once oil reaches the ice surface it will be reintroduced to the ocean in a weathered or emulsified form and potentially be available to be re-incorporated in newly forming ice – we considered this and the fact that oil droplets will rise in the ice column as brine channels broaden in the spring/summer. It is not clear how it would be possible to model the effects of flushing, so we have not attempted to do so in this manuscript.
- We have alluded to this in the text and added the following line to the Mie calculations section: '*Martin (1979) also found that in summer oil on surface leads to melt-pond formation owing to the absorbed solar energy and once on the surface the oil will be reintroduced to the ocean in a weathered or emulsified form, by melting through the ice or flowing of the sides.*'

11. Reviewer comment: *'L621: "Therefore, it appears that the type of oil has the biggest effect on how responsive sea ice is to increasing mass ratios of oil as opposed to the type of sea ice and in contrast with the findings of a comparable study into the effects of mineral dust on sea ice albedo (Lamare et al., 2016)." I don't understand what this means. Is it saying that there is larger variability in oil inherent optical*

properties than in the optical properties of mineral dust? That may be so, but it is not a result or a conclusion.'

- Author response: we have edited the text to make it clearer: '*Therefore, it appears that the type of oil has the biggest effect on how responsive sea ice is to increasing mass ratios of oil owing to the large variability in oil optical properties. This differs from a similar study (Lamare et al, 2016) which concluded that the optical properties of sea ice played a more important role on the response of sea ice albedo than the type of pollutant (e.g. windblown aerosols).*'
- This is a discussion point, not a result or a conclusion and is in the Discussion section (4).

12. Reviewer comment: *'L627: "First-year and particularly melting sea ice are more responsive to oil pollution than multi-year sea ice, so these trends indicate that sea ice albedo in the Arctic may become more vulnerable to background levels of oil 630 pollution as the ice becomes progressively thinner and younger." I find this conclusion unsubstantiated, because I don't think differences in the optical properties of FY / MY ice types is treated in a realistic way here. This simplification may be well justified for the purposes of a sensitivity study such as carried out here, but I think it's a stretch to draw conclusions such as stated here from this type of sensitivity exercise.'*

- Author response: we have demonstrated in our comments to point 2 above that the optical properties of first-year and multi-year sea ice used in this manuscript indeed are valid and based on measurements made by experts.
- We have edited the text to make it clearer: '*First-year and particularly melting sea ice may be more responsive to oil pollution than multi-year sea ice, so these trends indicate that sea ice albedo in the Arctic may become more vulnerable to background levels of oil pollution as the relative amount of these types of ice dominate in the Arctic.*'