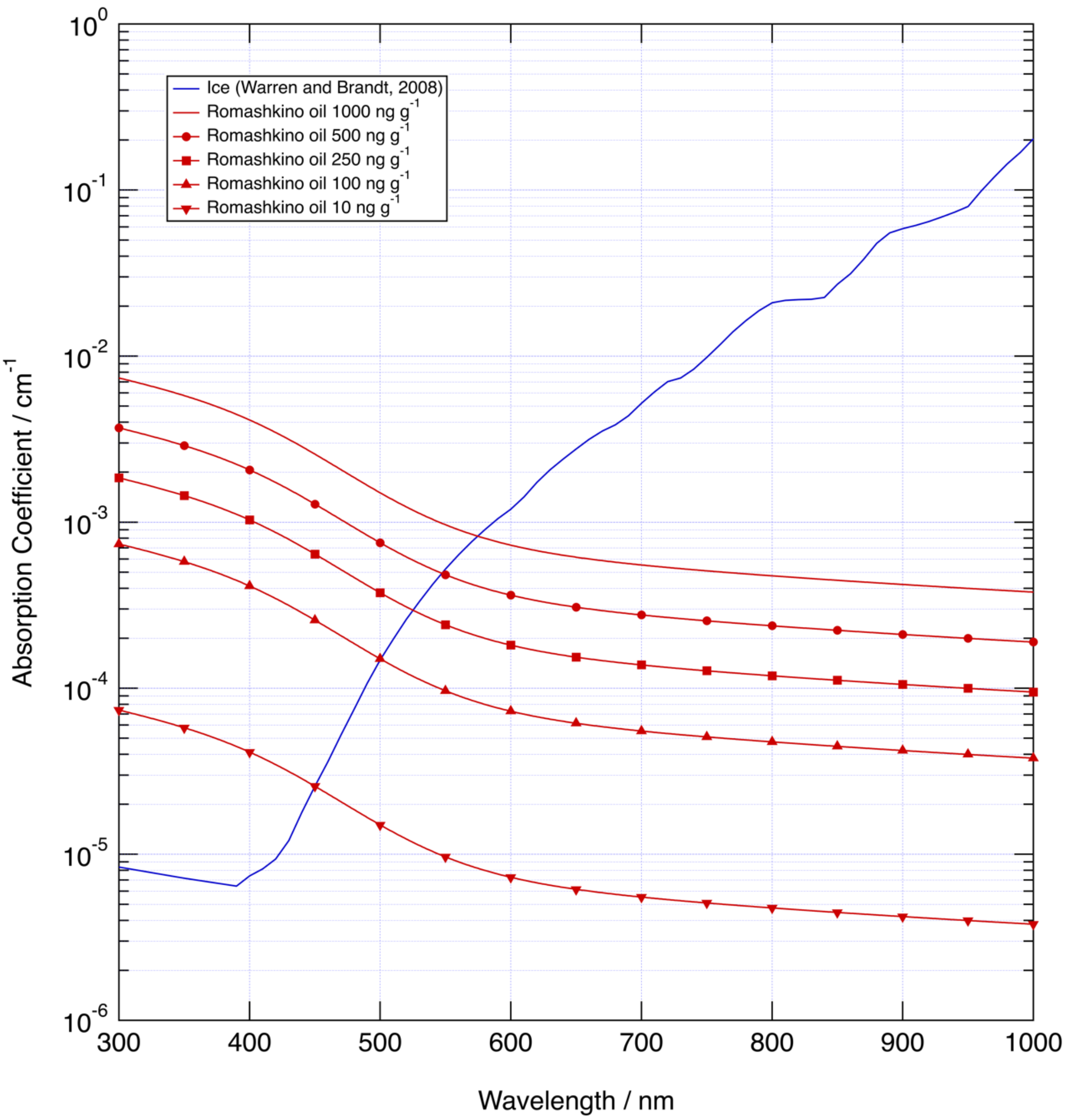
Response to Anonymous Referee #2 on tc-2021-372

1. The authors would like to thank the reviewer for their positive comments and the recommendation that this manuscript should be published.
2. Reviewer comment: '*There is a misalignment between the title of the article and certain statements (see detailed comments below) and the actual purpose of the proposed work. Indeed, the climatic impact of crude oil pollution is not addressed in this sensitivity study. I would recommend that the authors rephrase the title of the manuscript and correct the statement line 641.*'

- Author response: The title has been changed to '*Quantifying the effects of background concentrations of crude oil pollution on sea ice albedo.*'
- The reviewer raises a valid point, the full climatic potential has not been realised by our paper as we only explore albedo. We have therefore removed the word climatic from line 641.

3. Reviewer comment: '*The impacts of crude oil droplets dispersed in sea ice are investigated in the visible wavelengths (400-700 nm). Could the authors please expand on the reasons for this wavelength range? Is it a limitation of the model or a deliberate choice? Most observation tools (ground-based instruments, drone or aircraft mounted sensors, Earth Observation satellite) cover a larger spectrum, generally from the visible to the shortwave infra-red. Furthermore, climate models (e.g. CMIP models) consider the longwave radiative balance to monitor the Earth's energy balance. Although longwave radiation is most likely out of scope for this study, it is surprising that such a small range of wavelengths is being considered here. Extending the range to 2500 nm would allow direct comparisons with observations.*'

- Author response: The selected wavelengths are a deliberate choice by the authors as we are only measuring over the wavelength window where oil has an effect on the albedo of sea ice.
- To clarify this for the reviewer we have attached a figure below comparing the absorption coefficients of oil taken from Warren and Brandt (2008) to background levels of Romashkino oil between 10–1000 ng g^{-1}:



- **Fig. A1.** Wavelength dependent absorption coefficients of ice measured by Warren and Brandt (2008) and Romashkino oil at increasing background mass ratios (10–1000 ng g-1).
- At a wavelength of 580 nm the absorption coefficient of a mass ratio of 1000 ng g^{-1} of Romashkino oil is equal to the absorption of ice. At higher wavelengths the absorption of ice is greater than that of the oil. At lower mass ratios of oil, the absorption coefficient is equal to ice at shorter wavelengths.
- This effect is illustrated in Fig. 1 of the paper where oil can be seen to have a decreasing effect on albedo as the wavelength increases. Similarly, the peak in albedo moves to shorter wavelengths as mass ratios of oil decrease as the absorption coefficient of oil decreases with increasing wavelength in the range explored here (400–700 nm) whilst the absorption coefficient of ice increases at longer wavelengths.
- At 700 nm the absorption of solar photons is dominated by ice as shown by the intersection in Fig. A1, so longer wavelengths are not considered in the present study.

- The reviewer is correct to point out that remote sensing tools measure in the infrared range of the spectrum, but we hope that Fig. A1 coupled with Fig. 1 in the paper show that the absorption in this region is mostly due to the ice, not due to added to oil. Therefore, we have not explored further than 700 nm as the albedo at longer wavelengths are controlled by the absorption of the ice.
- For clarity in the text, we have edited the following line in Section 2.1: *'This study considers the wavelength range 400–700 nm as the absorption coefficient of oil decreases with increasing wavelength whereas the absorption coefficient of ice increases with wavelength, thus at wavelengths longer than 700 nm the absorption of solar photons is dominated by ice.'*

4. Reviewer comment: '*The authors state that "the effects that oil pollution has upon sea ice albedo have not previously been considered in literature". Although this statement holds, the authors disregard the existing corpus of works that investigate the effects of oil pollution on sea ice reflectance (e.g. 1-5 in the reference section below). Despite the quantities being different, albedo can be derived from reflectance using a BRDF model, and it is widely accepted that reflectance may be used as an approximation for albedo. A short review of the existing studies would be desirable in the introduction.*'

- Author response: The reviewer is correct to mention albedo can be calculated from BRDF and we would like to thank them for highlighting these papers which are new to the paper (barring [2] Liu et al (2018)), and these have now been included in the paper.
- We have now edited the following line in section 1: *'studies have looked into the hyperspectral features of oil-polluted sea ice (Praks et al, 2004; Ivanov et al, 2005; Liu et al, 2016, 2018; Chao et al., 2017); it is possible to calculate the albedo from bidirectional reflection distribution function (BDRF), however these are not comparable to this study as background mass ratios of oil are examined here.'*

5. Reviewer comment: '*In this study the authors have chosen to distribute the oil evenly throughout the sea ice. While this may be realistic in certain conditions (particularly for low oil concentrations), how plausible is this to occur at higher loadings (1000 ng g-1)? In the discussion (line 496) the authors describe the different scenarios of how oil entrains itself into sea ice. From these comments, it is clear that layering of the oil is a common situation encountered in sea ice. The model used allows the definition of layers throughout the ice pack: rather than address the relationship between black carbon and oil loadings, would it not have been of value to consider the effects of oil located in specific (e.g. surface, or subsurface) layers?.*'

- Author response: The reviewer is correct to mention that the model can do layers, however, in previous studies where layering was explored (e.g. Marks and King, 2013; Lamare et al, 2016; Marks et al, 2017) this was owing to the fact that there was sufficient prior knowledge of how aerosols (e.g. black carbon/dust) deposited from above are found in snow and ice. To accurately model these layers, we require more experimental data about how background mass ratios of oil are incorporated in layers in the ice before it is feasible to model it. It is also likely that unlike aerosol layers in the snow or ice, an oil layer would not be static. The parameter space needed to consider the number, thickness, depth of all these layers and thickness of three different types of realistic and quasi-infinite ice is huge. To cover this parameter space (wavelength dependence, droplet size, mass ratio of droplets, ice thickness, and position of layer) would be a much larger study requiring further knowledge of the behaviour of background oil within ice and which would benefit from an associated field or lab-based study.

- We have added the following text to Section 1: '*The TUV-snow model is capable of considering layers of pollutant in the ice; however, until there is greater knowledge of the thickness, type and location of these layers for background mass ratios of oil, it is beyond the scope of the present work.*'

6. Reviewer comment: '*In link to the paragraph above, the concentrations of the oil would deserve more clarifications. Indeed, the article focusses on "microscopic sized background concentrations of oil" (line 509) but in the introduction it is mentioned that after the Deepwater Horizon incident, mass ratios of 100 ng g-1 were found. Can mass ratios of 1000 ng g-1 still be considered as "background"?.*'

- Author response: The authors mention the DWH mass ratio of 100 ng g^{-1} as this was tracked in Berenshtein et al (2020) to travel from the Mississippi Canyon to the Carolinas via the Loop Current, a distance exceeding 1500 km, indicating concentrations of oil can remain high over a very long range.
- Oil concentrations from several ppb to ppm are common in regions of intense shipping, marine transportation, and offshore oilfields (Haule and Feda, 2016) and other studies have examined the optical properties of oil in the marine realm at concentrations of 1 ppm (i.e. 1000 ng g^{-1}) (Otremba, 2007).
- Whilst 1000 ng g^{-1} may be considered high for background oil concentrations for areas of the Arctic Ocean that are currently pristine, they are valuable for straightforward parameterisation of this study which the reviewer has described as of value to the scientific community.
- We have added the following line to Section 4.2: '*The mass ratio of 1000 ng g^{-1} of oil in ice is possibly a large value for diffuse background pollution but is included to provide a significant upper limit to the effect of background oil pollution on sea ice.*'

7. Reviewer comment: '*More information about the relationship between the oil droplet size and the mass ratios would be important to better understand which scenarios in the paper are most plausible. Have the authors investigated if there is a relationship between droplet size and mass ratios between 1 and 1000 ng g-1 or is it likely to find all sizes within the loading range?*'

- Author response: The authors could not find the requisite answer to this question. In this study we have explored a large envelope of a realistic range of droplet sizes to cover all reasonable eventualities. Some of the high mass ratios with large sizes may be unlikely, however we have included them here for completeness and to provide an upper limit.
- Moreover, there is a lack of a large corpus of results for the smaller sizes, as is highlighted in and described extensively in Section 1 (L 128-147)

8. Reviewer comment: '*Section 4.6 on the implications of the study is quite light and could be fleshed out more. It would be insightful to read the authors thoughts on the implications in terms of how the sea ice melting rates and extent in summer will be*

affected by oil pollution. How does the increased oil pollution impact the energy balance of the Arctic, and are the effects sufficient to be considered in General Climate Models?'

- Author response: The authors have been asked to remove the climatic implications from both our title and text by both reviewers and we therefore feel it inappropriate to make climatic predictions.

9. Reviewer comment: '*Lastly, as a side note, I would suggest that the authors make the input data available through an open repository, which would benefit the modelling community greatly (e.g. use of the parametrisations of crude oil in climate models) and allow for further intercomparisons of modelling approaches.*'

- Author response: All data will be made available on Zenodo once the manuscript is accepted for publication.
- The following text has been added after Section 5: '*Data availability. All data have been published using Zenodo and can be accessed at: DOI.10.5281/zenodo.6514952.*'

Detailed comments

10. Reviewer comment: *'l46: What do the authors mean by: "The wavelength integrated and spectral albedos for different types of sea ice have previously been considered [...]: this study focuses on three types of sea ice: melting, first-year, and multi-year sea ice." It is not clear if the authors are referring to the literature or if they are stating that they have considered a wide variety of sea ice types before settling for the three mentioned.'*

- Author response: The authors are referring to the literature where the values used in the study have been selected from.
- To make it clearer for the reviewer and the reader, we have changed the text to the following: '*The wavelength integrated and spectral albedos for different types of sea ice have previously been considered in literature (Grenfell and Maykut, 1977; Perovich, 1990; Timco and Frederking, 1996; Perovich, 1996; Gerland et al, 1999); utilising these optical properties this study focuses on three types of sea ice: melting, first-year, and multi-year sea ice*.'

11. Reviewer comment: '*Table 1: One would expect the density of first-year, multi-year and melting sea ice to be different owing to differences in structure (brine channels, air bubbles...). The reference cited by the authors [Marks and King, 2014] states that the density of sea ice ranges 700–950 kg m-3. How do the authors justify the same fixed value for all sea ice types?'*

- Author response: The reviewer is correct, typical densities of the three ices tend to range between 700–950 kg m^{-3} (Grenfell and Maykut, 1977; Perovich, 1990; Timco and Frederking, 1996; Perovich, 1996; Gerland et al, 1999), however, these have been approximated to 800 kg m^{-3} to be directly comparable to Lamare et al (2016).
- Variation in scattering cross section caused by natural variation of density is much smaller than the natural variation in scattering cross section as shown in the new Fig. 8, produced to answer a question from Reviewer 1 and for the paper, and presented again below. The following line has been added to Section 4.7 to demonstrate this: '*There is a natural variation in sea ice density between 700–950 kg m^{-3}* (*Grenfell and*

Maykut, 1977; Perovich, 1990; Timco and Frederking, 1996; Perovich, 1996; Gerland et al, 1999) which can be propagated to a variation in scattering cross section of approximately a factor of 0.88 and 1.19 of the original values for the lowest and highest reported densities, respectively. These ranges are much smaller than the natural variation in the scattering of sea ice, as shown in Fig. 8. The variation due to density of ice in this study is not considered important.'

- The variation in density is small and would only affect the scattering of the light in our calculations. The authors would like to stress that the change in scattering cross section of the ice types, the thickness of the ice, the changing concentration of oils, the different types of oil, and the different droplet size are the fundamental controllers of albedo in this study.
- The effect of a very low (700 kg m^{-3}) or large (950 kg m^{-3}) value for density can be estimated because a change in density of 700/800 would be the equivalent to an error in scattering cross section of approximately 0.88, and 950/800 would be approximately 1.19. This is within the error limit that has been presented for Reviewer 1 and added to the paper as Fig. 8 indicating that the effect is much smaller than the natural variation in scattering due to other conditions, so we do not need to consider it in this study.
- To make this clear to the reader, the following line has been added to Section 2.1: '*The density of sea ice has been fixed in this study to be comparable to previous work (Lamare et al, 2016), however sea ice density can range between extremes of 700–950 kg m^{-3} (Grenfell and Maykut, 1977; Perovich, 1990; Timco and Frederking, 1996; Perovich, 1996; Gerland et al, 1999).'*

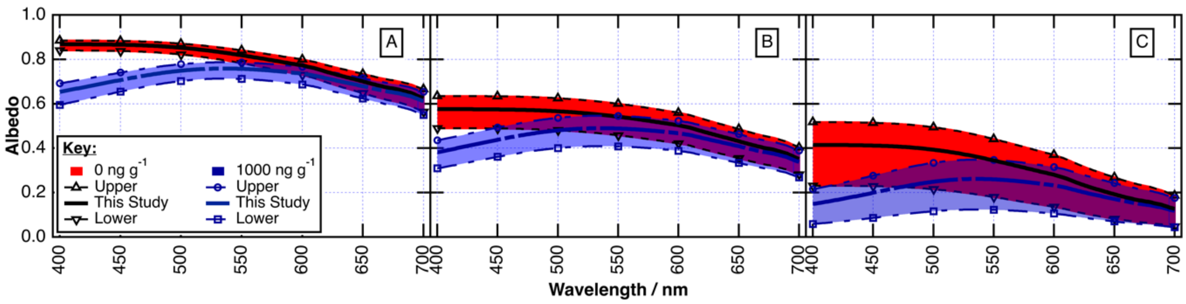


Fig. 8. Wavelength dependent albedo of multi-year (A), first-year (B), and melting sea ice (C). Shown here is the variability in albedo for each type of sea ice based on scattering cross sections described in literature (Grenfell and Maykut, 1977; Perovich, 1990; Timco and Frederking, 1996; Perovich, 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}.

12. Reviewer comment: 'Table 2: On what basis were the number of layers (201) and the increments chosen for the model?'

- Author response: Previous works (Marks, 2017) have demonstrated that a large number of layers are required at the interface between air and ice, and 201 layers was a good compromise between computational time and precision. Running the

model with fewer and more layers gave the same results. Previous calculations have increased the number of layers to give a constant answer.
- 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.*'

13. Reviewer comment: '*l236: In this paragraph the authors describe the optical properties of the two types of crude oil used in the study. Although it is stated that "Whilst both crude oils have a variety of uses, including as marine engine fuels, Romashkino can be considered a typical marine engine Heavy Fuel Oil", the reasons for selecting Romashkino and Petrobaltic oil is not sufficiently clear to the reader, who has to wait until line 578 to understand that "both Romashkino and Petrobaltic can be regarded as the upper and lower respective brackets of the effect that oil pollution can have on sea ice albedo". Furthermore, it would be useful to understand if these oil types are only representative of pollution that may occur from shipping activities, or can also be used to understand the impacts of oil spills from drilling activities.*'
- Author response: We would like to highlight the sentence which immediately precedes the one raised above: L 237 '*Otremba established that, for the oils capable of forming a surface film, Romashkino crude oil has the largest imaginary refractive index and absorption coefficient values whereas Petrobaltic crude oil has the smallest values, with other oils bracketed by these parameters (Otremba, 2000).*'
- The aim of this study is an exploration of how oil can affect sea ice and according to Otremba (2000) these oils succinctly envelope the upper and lower optical properties of typical oils. It is feasible for both types of oil, and everything in between, to be in the marine realm owing to the various ways in which oil is released (e.g. subsurface release, oil spill etc.), the densities of the oil, and is justified in Otremba (2000). The focus here is on the presence of background mass ratios of oil and is not prescriptive of the method or release into the environment.

14. Reviewer comment: '*l275: There seems to be a repetition in the first and second sentences. In the second sentence, the author state the same elements as in the first sentence but with melting and multi-year sea ice in addition. Please fix or clarify.*'
- Author response: The text is correct as it is a repetition of the study, however it has now been reworded: '*Albedos of quasi-infinite first-year sea ice doped with different mass ratios of both Petrobaltic and Romashkino from 0–1000 ng g^{-1} (0, 5, 10, 25, 100, 150, 200, 250, 300, 350, 400, 450, 500, and 1000 ng g^{-1}) are calculated as a function of wavelength. The study presented here is then repeated for quasi-infinite melting, first-year, and multi-year sea ice.*'

15. Reviewer comment: '*l279: In the sentence concerning the effect of oil droplet size, it would be useful to explicitly state the sea ice type considered.*'
- Author response: the text has been changed and now reads: '*The effect of oil droplet size (in the range 0.05–5.0 μm) are then considered for a single wavelength (400 nm) for the oil with largest absorption cross section (Romashkino) and for quasi-infinite sea ice with the largest penetration depth to light (melting sea ice) (Marks and King, 2014).*'

16. Reviewer comment: '*Figure 1: I suggest using a Y axis ranging from 0.3 to 0.9, and putting the legend outside the figure for more clarity, if this is allowed by editing rules.*'
- Author response: The authors believe it is more valuable to have the same x-axis for all figures to allow easy comparison. The raw data will be made available to allow accurate reading of any data.

17. Reviewer comment: '*Section 3.3 Could the authors specify why melting sea ice was chosen for the analysis of the effects of oil droplet size on albedo? Are the implications similar for other types of sea ice?*.'
- Author response: The melting sea ice was chosen as it has the largest penetration depth to light (Marks and King, 2014) and is justified in point 15 above.
- The implications are similar for the other types of sea ice, however melting sea ice is liable to have the least conservative effect and we therefore found it most useful to explore the significance of droplet size.
- We have added the following sentence to Section 3.3: '*Melting sea ice was selected as it is liable to have the least conservative effect owing to it having the largest light penetration depth of the three types of sea ice.*'
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18. Reviewer comment: '*Section 3.4: A reference to ΔA/Δm used in Figure 5 is expected in the text.*'
- Author response: The text in Section 3.4 has been edited to now read: '*The upper row of Fig. 5 (A, C, and E) indicate albedo versus increasing mass ratios of Romashkino oil, whereas the lower row (B, D, and F) is a metric for the sensitivity of an ice to oil in the presence of black carbon, where sensitivity is the rate of change in albedo with increasing mass ratios of Romashkino oil (i.e. dA/dM).*'

19. Reviewer comment: '*l627: "Arctic multi-year and first-year sea ice are declining at 17.5% and 13.5% respectively..." is not clear. Please rephrase.*'
- Author response: The text has been edited to now read: '*Arctic multi-year and first-year sea ice extent are declining at 17.5% and 13.5% per decade respectively*'.

20. Reviewer comment: '*l641: "[...] this is the first instance that the climatic effect of oil pollution on sea ice has been considered." This sentence is misleading and implies the use of a climate model or conclusions on the large scale impact of oil pollution in the Arctic which is not the case here. Please rephrase.*'
- Author response: The text has been edited to now read: '*this is the first instance that the background effect of oil pollution on sea ice albedo has been considered.*'

21. Reviewer comment: '*l659: "[...] the findings of this study may only be valid during the ablation season when snow cover has melted or been removed by wind." In this case why consider different types of sea ice? I believe the value of this paper lies in the sensitivity study considering a variety of optical and physical parameters. I suggest to add that this may be the case in practise and that the authors restate the main purpose of the study..*'
- Author response: As suggested by the reviewer, we have added the following text to the end of Section 4.7 to restate the purpose: '*The paper presented here is a*

sensitivity study considering a wide variety of optical and physical parameters for the oil pollution of sea ice. This is an exploratory study and will hopefully act as a foundation for more sophisticated studies coupled with field and lab-based experiments to follow.'