Author response to tc-2019-285-RC2

Takehiko Nose on behalf of all authors

We sincerely appreciate the critique and insightful comments that will improve this manuscript. Below outlines our response to each of the critical point raised by the reviewer. The document structure corresponds to that of tc-2019-285-RC2 except for the first section. Please also refer to our response to Reviewer#1 as some major changes were made to address Reviewer#1's comments.

Overview of major changes

We begin with an overview of major changes in the revised manuscript to address both reviewers' comment regarding readability of the paper. The change of section titles is shown in bold text (if changed).

Abstract The abstract has been rewritten to more clearly emphasise the focus of the study and its findings.

Section 2.3 The description of WAVEWATCH III ® (WW3) has been modified in a way that it is focused on the core idea of the paper: wave-ice interactions. The readability is improved by using equations and compact notations, thereby demonstrating clearly the link between sea ice concentration (SIC) and wave-ice models.

Section 3 Sea ice concentration: definition, characteristics, and the use in wave-ice models
The presentation of this section is one of the major changes in the revised version. We have rewritten this section to discuss the concept of SIC from a wave-ice modelling perspective. Despite different scales and objectives, the SIC is being used to moderate the attenuation rate of waves in the MIZ without the model having any consideration to the sea ice field heterogeneity, i.e., subgrid scale physics. We discuss the implication of the length scale of satellite retrieved SIC to the SIC and wave-ice model formulation.
Section 3.2 is shortened and moved to the beginning of Section 5 to give an overview of how satellite retrieved SIC varies on a regional scale so that the transition to the wave hindcast analysis of the region is more fluent.
Original Figures 3 and 4 are removed as they were deemed redundant.

Section 4 Δc_i effects on wave modelling at the observation sites
Note Δc_i is denoted as the SIC uncertainty in the text.

Section 5 Δc_i and wave modelling in the refreezing Chukchi Sea

Section 5.1 On- and off-ice wave evolution in the refreezing Chukchi Sea MIZs

Section 5.2 Relative significance of Δc_i compared with wave-ice interaction parameterisation uncertainty
We tested the robustness of the results based on sensitivity analyses that tested sea ice thickness (SIT) and the inclusion of scattering. The study findings remain unchanged.

Section 6 Conclusions and discussions
This section is shortened considerably and includes discussions on the study outcome.

General comments

Reviewer comment R#2-1 The manuscript examines the impact of observational uncertainty in sea ice concentration on numerical modelling of ocean surface waves in sea ice, using Wavewatch III. The most interesting finding, in my opinion, is that the effect of this uncertainty on wave modelling is large, and larger than the differences between various wave-ice interaction source terms currently included in WW3.

In general, I find the results to be well supported by thorough analysis. The manuscript is a little hard to follow in places (some instances of this noted below in 'presentational comments'). As currently presented, my sense is that this work is of interest to a narrow section of the community (i.e. those working on spectral models of wave-ice interactions) and may be better suited to a more targeted journal. However, this could be addressed by revising the text to stress the aspects that could be interesting to a more general audience e.g. the differences between SIC products and their accuracy near the ice edge; that the sea ice coverage may be more important in determining ocean surface waves in ice than a detailed understanding of wave-ice interaction physics; the level to which waves in the open ocean are influenced by sea ice.

Author response We are pleased the significance of the SIC uncertainty on wave-ice models has been conveyed to the reviewer. Regarding the suggested approach to broaden the audience (*"e.g. the differences between SIC products and their accuracy near the ice edge; that the sea ice coverage may be more important in determining ocean surface waves in ice than a detailed understanding of wave-ice interaction physics; the level to which waves in the open ocean are influenced by sea ice"*), our analysis aims to convey that wave-ice model tuning may not be as effective at this time when the knowledge of the true SIC field is too uncertain; however, our work was not intended to suggest that SIC forcing accuracy takes precedence over the detailed understanding of wave-ice interaction physics. Our view is that advancing the knowledge of wave-ice interactions and its implementation in WW3 (or other wave model platforms) constitute the foundation to improving the predictability of ocean waves in ice-covered waters.

The research of ocean waves are becoming an important polar region research topic; waves feedback to the dynamics of atmosphere, ocean, and sea ice, and as such, we believe the manuscript contents are of interest to a general audience of The Cryosphere (TC). The recent acceptance of a coupled ice-ocean-wave model paper [Boutin et al., 2019] in TC reflects the increasing interest of the audience to the topic of ocean waves. We also cited the coupled wave-ice model references in the text to address R#2-10, which should help attract a wider audience.

Major comments

Reviewer#2 comment R#2-2 'Analysis of significant wave height uncertainty distributions for SIC forcing and wave-ice interaction source terms reveals that they are both sizeable; however, the study concludes the more dominant uncertainty source of modelling wave-ice interactions is the accuracy of satellite retrieved SIC estimates that are used as model forcing.' The authors need to clarify that uncertainty in wave-ice interaction terms is an estimate based only on the various wave-ice interaction terms included in WW3, which as the authors note later in the manuscript are based on a limited number of field observations. It does not sample all possible wave-ice interaction terms, nor does it sample different parameter values.

Author response Abstract has been rewritten as mentioned in the overview of major changes. The new abstract reads as below.

Author's changes in manuscript Ocean waves are known to decay exponentially when they interact with sea ice. Wave-ice models implemented in a spectral wave model, e.g., WAVEWATCH III ® (WW3), derive the attenuation coefficient based on several different model ice types, i.e., how the model treats sea ice. In the marginal ice zone (MIZ) with SIC < 1, the wave attenuation is moderated by SIC: this implies that the subgrid scale physics is missing, and the accuracy of SIC plays an important role in the predictability. Satellite retrieved SIC data (or a sea ice model that assimilates them) are often used to force wave-ice models, but these data are known to have uncertainty. Six satellite retrieved SIC products, based on four algorithms applied to SSMIS and AMSR2 data, were used in the WW3 hindcast experiment to study the effect of SIC uncertainty ΔSIC on modelling MIZ waves during the 2018 R/V Mirai observational campaign in the refreezing Chukchi Sea. The results show that ΔSIC can cause wave prediction discrepancies in ice cover. There is evidence that bivariate uncertainty data (model significant wave heights and SIC forcing) are correlated, although off-ice wave growth is more complicated due to the cumulative effect of ΔSIC along an MIZ fetch. Further, we found that the effect of ΔSIC can be large enough, such that it overwhelms the choice of model ice types, i.e., wave-ice interaction parameterisations. Despite these parameterisations being derived from different concepts and missing the subgrid scale physics relating to sea ice field heterogeneity, the accuracy of satellite retrieved SIC used as model forcing is the primary error source of modelling MIZ waves in the refreezing ocean.

Reviewer comment R#2-3 It is well-known that SIC satellite observations underestimate concentrations for low thicknesses, less than 35 cm (Ivanova et al. 2015). This should be stated in the Introduction. I think the newer result here is how varied the satellite products are for these low thicknesses. This should be made clearer in the text.

Author response The long-known deficiency of satellite derived SIC accuracy in thin ice was indeed missing. We have incorporated the comment in Section 1 Introduction.

Author's changes in manuscript . . . To date, there is no robust validation of any algorithm, so users are urged to understand strengths and weaknesses of the algorithms when using and interpreting the data [Ivanova et al., 2015, Comiso et al., 2017]. The long-known SIC discrepancies imply there is uncertainty in the knowledge of true sea ice coverage [Notz, 2014]. The uncertainty is potentially greater for MIZs in the refreezing ocean as satellite derived SIC estimates are known to underestimate thin ice less than 35 cm [Heygster et al., 2014, Ivanova et al., 2015].

Reviewer comment R#2-4 Sec 2.3 This section needs more explanation to make it suitable for a more general audience - i.e. those not familiar with WW3 wave-ice interaction terms. What is the IS0 switch?

Author response We have modified Section 2.3 to be more readable to a broader audience. Please see the overview of major changes. The passage relating to the major change of this section is given below.

Author's changes in manuscript . . . The sum of these source terms s is expressed based on the following default scaling in ice-covered waters:

$$s = (1 - c_i)(s_{\text{wind}} + s_{\text{dissipation}}) + c_i s_{\text{ice}} + s_{\text{non-linear interactions}}.$$

Specifically to this study, c_i relates to the satellite retrieved SIC and s_{ice} to the ice type, i.e., how the model treats sea ice. The effect of sea ice on waves are represented via the modified dispersion relation $\sigma = \sigma(\bar{k})$ where $|\bar{k}| = k = k_r + ik_i$. The real part k_r is the physical wavenumber and alters the propagation speed of waves in a sea ice field (analogous to effects of shoaling and refraction by bathymetry), and the imaginary part k_i is the exponential decay coefficient. k_i is introduced in the model as $s_{\text{ice}} = -2c_g k_i N$ for fully ice-covered sea, i.e., c_i=1, and the solution to $\frac{dN}{dt} = s_{\text{ice}}$ is $N_0 e^{-2c_g k_i t}$. There are five options for treating sea ice in WW3 denoted as IC1–5; c_i provides the scaling in the linkage between s_{ice} and ICX as

$$\frac{dN}{dt} = c_i s_{\text{ice}} = -2c_i c_g k_i(f, p_1, ..., p_n)N$$

where $p_1, ..., p_n$ are the sea ice properties, e.g., effective shear modulus and effective viscosity. Therefore, the rate of attenuation depends on the wave period and sea ice properties, which is moderated by c_i, i.e., $N_0 e^{-2c_i c_g k_i t}$.

The wave-ice models implemented in WW3 that calculate k_r to model k_i are as follows: IC2 calculates dissipation due to basal friction in the boundary layer below an ice sheet, which is modelled as a continuous thin elastic plate based on the work of Liu and Mollo-Christensen [1988]; IC3 treats sea ice as a visco-elastic layer based on Wang and Shen [2010], which calculates the internal stress of the ice cover based on storage and dissipation; and IC5 is a visco-elastic beam model based on Mosig et al. [2015]. The dispersion relation of these models are provided in Appendix B. Ardhuin et al. [2018], Boutin et al. [2018] (IC2) and Rogers et al. [2016], Cheng et al. [2017] (IC3) describe the progress of these s_{ice} parameterisations using the refreezing Beaufort Sea data of Thomson et al. [2018]. These wave-ice models can be combined with an energy-conservative scattering attenuation model denoted as IS1 and IS2 [Meylan and Masson, 2006, Dumont et al., 2011, Williams et al., 2013, Ardhuin et al., 2018, Boutin et al., 2018].

Reviewer comment R#2-5 What is the estimated of spatial domain of the sea-truth concentration observations? Are these comparable to the resolution of the satellite products?

Author response Here, we infer the comment pertains to Section 3.1. This section has been rewritten to address Reviewer#1's comments (refer to R#1-1, R#1-2, and R#1-19 in our response to the reviewer#1). Please also refer to the overview of major changes. Section 3 now reads as below.

Author's changes in manuscript WMO [2014] defines SIC as "the ratio expressed in tenths describing the amount of the sea surface covered by ice as a fraction of the whole area being considered". The so-called "area considered" presumably varies for different objectives. Length scale of $O(10)$ km may be adequate for sea ice extent climatology, but for wave-ice interactions, the wave provides a scale in a phase-resolved sense. Satellite derived SIC represents the fraction of ice-covered water over a large area, sufficiently large enough that the SIC represents a property of a continuum. In reality, the sea ice in the MIZ is granular, and ice floes jam due to horizontal convergence by Langmuir circulation, internal waves, and wind variability, resulting in a formation of features such as ice bands and wind streaks—with which waves likely interact distinctively.
On 14 November 2018 during the MIZ transect observation, R/V Mirai encountered moderate on-ice waves with an H_{m0} up to around 2.00 m propagating towards the ice edge (this H_{m0} estimate is consistent from both the shipboard wave data described in Appendix A and hindcast models as discussed later). Figure 2 presents a series of snapshot images of the sea ice field during the encounter. R/V Mirai traversed over 10 km in the MIZ from the ice edge, and each image area extends at least over 1 km conservatively (using the crude distance to horizon calculation). These images depict the heterogeneous sea ice field, both in distribution and ice types, that waves propagate when they enter an MIZ. Because WW3 wave-ice interaction models are scaled according to $\frac{dN}{dt} = c_i s_{\mathrm{ice}}$ (Equation 4), the subgrid scale physics is completely missing. It is plausible the subgrid scale distribution of SIC and ice types can be treated in a stochastic manner to provide meaningful mean values to the grid-scale model. On the other hand, c_i also affects the WW3 wave-ice model by means of scaling (Equation 4). Figure 2 shows SIC data from eight satellite retrieved products described in Section 2.2 during the event. The SIC estimates interpolated at the R/V Mirai positions largely deviate among the products, characterising the uncertainty of the satellite retrieved SIC. Moreover, the entire time series of the MIZ transect observation depicts Δc_i is persistent (Figures A4 to A6 of Appendix D). Hereafter, we show how large the effect of Δc_i on modelling MIZ waves can be, so much so that it overwhelms the choice of s_{ice}, e.g., ICX.

Reviewer comment R#2-6 Sec 3.2 - why are only three products considered here? Conclusions on which products perform best (or worst) for this region would be useful and of broader interest to the cryospheric community.

Author response The three products were selected to convey the magnitude of uncertainty. Since the uncertainty was defined as $\Delta c_i = max(c_i) - min(c_i)$, three products are sufficient to convey this point. Showing all eight products clutters the figure and potentially distract readers from the main point.

In addition, the revised manuscript is presented such that the focus is apparent, which is the wave-ice models and SIC forcing and not about the SIC data. We anticipate this will be apparent when the revised manuscript is read. Nevertheless, regarding ranking the product performance, we agree such a conclusion would be a significant contribution. We have attempted to rank the SIC products, but the result is inconclusive primarily due to the number of days comprehensive mosaic can be produced and inconsistent variability of SIC estimates. We expect such an analysis warrants a separate dedicated study to produce noteworthy outcomes, especially considering the previous intercomparison studies, such as Ivanova et al. [2015] and Comiso et al. [2017], concluded there is no one product that is superior. They state that the choice of SIC products are largely dictated by the SIC data application, and we concur with this statement based on our field observation and analysis conducted.

Minor comments

Reviewer comment R#2-7 : L22. 'which are greater in the Arctic regions.' As compared to what?

Author response We made a change to this passage (bold text) as below.

Author's changes in manuscript. . . From a practical view point, this downward trend of sea ice decline opens trans-Arctic shipping routes connecting Europe and Asia for longer times of the year; potential global economic benefits of non-ice breakers accessing routes like Northern Sea Route and North West Passage are substantial [Stephenson et al., 2013, Bekkers et al., 2018]. **The increasing vessel traffic implies that adequate prediction capabilities will become crucial to assist ships in polar waters to circumnavigate hazards such as high winds and waves, collision with perennial sea ice, and sea-spray icing; however, Jung et al. [2016] describe that the existing polar prediction systems need to be urgently enhanced to effectively manage the risks and opportunities associated with growing human activities, and the Polar Prediction Project (PPP) has contributed to advancing the predictive capabilities. While wave forecasting in polar oceans is still in its early years, the need for advancing wave forecast capacity will only grow in the emerging Arctic Ocean.** This paper focuses on the effect of SIC uncertainty on third-generation spectral wave model simulations in and near a MIZ.

Reviewer comment R#2-8 : L23. 'sustainable developments of the Arctic Ocean' - this statement sounds strange.

Author response Please see author response to R#2-7.

Reviewer comment R#2-9 : L28. 'dispersion relation'→'the dispersion relation'.

Author response Corrected.

Reviewer comment R#2-10: L32. Other recent work on wave-ice interactions could be cited here: Zhang et al. 2019 (https://doi.org/10.1016/j.ocemod.2019.101532), Roach et al. 2019 (https://doi.org/10.1029/2019MS001836).

Author response This passage pertains specifically to the standalone WW3 wave-ice interaction source term developments, so the suggested references are unrelated. We added new sentences at the end of the paragraph as shown in the bold text below. This way, we can relate the study to a broader audience, which also helps to address R#2-1.

Author's changes in manuscript . . . Standalone contemporary spectral wave models simulate wave-ice interactions using sea ice as forcing; in this space, the intensive field measurements of the Arctic Sea State and Boundary Layer Physics Program [Thomson et al., 2018] have made a solid contribution to the recent advance of The WAVEWATCH III ® Development Group (WW3DG) [2019] wave-ice interaction parameterisation. Rogers et al. [2016], Cheng et al. [2017], Ardhuin et al. [2018], Boutin et al. [2018] describe the development and optimisation of the latest WW3 parameterisations for wave evolution in sea ice cover. Despite the progress, Squire [2018], Thomson et al. [2018] qualify accurately quantifying the wave decay and connecting the associated mechanisms over a large domain still remain a challenge because sea ice fields are notoriously heterogeneous; therefore, the wave-ice interaction source term is a source of uncertainty when simulating wave evolution in MIZs. **Recent**

developments of coupled wave-ice-ocean models on a pan-Arctic scale [Boutin et al., 2019, Roach et al., 2019, Zhang et al., 2020] reflect the growing interest in the surface wave's role in the atmosphere, ocean, and sea ice dynamics: perhaps this indicates advancing the wave-ice interaction physics is becoming a more pertinent issue to broader scientific communities.

Reviewer comment R#2-11 : L37. 'Besides the model interior' What does this mean?

Author response We are referring to the inner part of numerical models. We added "wave-ice interaction parameterisations" as an example.

Reviewer comment R#2-12: L37. 'like SIC'→'in products such as SIC'?

Author response Changed as suggested.

Reviewer comment R#2-13: L69. 'generally'→'generally between'.

Author response Corrected.

Reviewer comment R#2-14: L70. 'Albeit the MIZ coverage..' - this sentence is unclear.

Author response We have attempted to make it clearer.

Author's changes in manuscript Although the MIZ coverage was less expansive, daily observation of the sea ice conditions at the same geographical locations for an extended period is rare if not unique because of exhaustive ship time required.

Reviewer comment R#2-15: L82. 'mostly same'→'mostly the same'.

Author response Corrected.

Reviewer comment R#2-16 : L96. remove 'exhaustive' (this is an opinion).

Author response "exhaustive" changed to "large".

Reviewer comment R#2-17 : L102. 'most frequent'→'most frequently'.

Author response Changed as suggested.

Reviewer comment R#2-18 : L102. 'leading algorithms' leading in what? Perhaps you mean the most commonly used?.

Author response We realised the phrase is unnecessary, so it is removed.

Reviewer comment R#2-19 : L152. 'sanity checked' inappropriate language for a publication.

Author response Changed to "tested".

Reviewer comment R#2-20 : L153. 'leading packages' again, leading in what way? Most commonly used? Most skill?.

Author response Changed to "commonly used".

Reviewer comment R#2-21 : L211. change to 'SSTs exceeded 0oC'.

Author response Corrected.

R#2-22 : L211. At what depth were the shipboard SSTs measured? Are they affected by the ship itself?.

Author response The technical details of the instruments were given in Appendix A, which was introduced in L76 of the original version: "-1 m below the sea surface with further 5 m inlet to the gauge" (L458). We are not aware of any ship effects on the SST measurement. During the cruise, we note that sea ice, even grease ice, was observed only when shipboard SSTs were less than around -1.5 °C. Accordingly, the gauge was sufficiently accurate for this discussion.

Reviewer comment R#2-23 : **L212.** No s after MIZ.

Author response "s" removed.

Reviewer comment R#2-24 : **L218.** 'forseeable'→'visible'.

Author response Corrected the elementary error: thank you.

Reviewer comment R#2-25 : **L223.** 'The sea ice tends to cluster, so it appears dense where the ice exists.' - reword.

Author response Please see author's response to R#2-5.

Reviewer comment R#2-26 : **L230.** 'depict the'→'show that the' ?

Author response Changed as suggested.

Reviewer comment R#2-27 : **L264.** What does 'best practice wave models' mean? Perhaps replace with 'commonly used'?

Author response Changed to "high quality".

Reviewer comment R#2-28 : **L266.** 'a bit over' - informal language.

Author response Changed to "slightly".

Reviewer comment R#2-29 : **L277.** 'as uncertainty generally increased in the MIZs.' - unclear. No s after MIZ.

Author response "in the MIZs" removed as it was unnecessary.

Reviewer comment R#2-30 : **L299.** remove the rest of the sentence after 'ongoing work' - not necessary.

Author response Removed the sentence as it was unnecessary.

Reviewer comment R#2-31 : **L323.** add 'that' - 'demonstrated that'.

Author response Added "that".

Reviewer comment R#2-32 : **L338.** 'like a'→'as a'.

Author response Changed as suggested.

Reviewer comment R#2-33 : **L339.** 'effects. . .are' (not is).

Author response Corrected.

Reviewer comment R#2-34 : **L443.** Reword.

Author response The sentence is removed as it was unnecessary.

Thank you kindly for your review and consideration.

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