

## **Oil droplets are severely overlooked in risk assessments**

Corresponding Author: Dr Håvard G. Frøysa

**This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.**

**Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.**

Version 0:

Decision Letter:

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Dear Dr Frøysa,

Your manuscript titled "Oil droplets are severely overlooked in risk assessments" has now been seen by 3 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:

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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Alice Drinkwater, PhD  
Associate Editor  
Communications Earth & Environment  
Consulting Editor  
Communications Sustainability

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<http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf>.

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<http://www.nature.com/authors/policies/availability.html>.

## REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

"Oil droplets are severely overlooked in risk assessments"

Authors: Håvard G. Frøysa, Raymond Nepstad, Elin Sørhus, Carey E. Donald, Sonnich Meier, Frode B. Vikebø

Overall assessment: Goals and hypotheses of the paper are clearly stated. The authors make a point in saying oil droplets are understudied and under-evaluated in spill events, with which I completely agree. The paper does a great job at simulating and recreating oil spill conditions from a spill event in Norway 2001. The average exposure to crude oil, in relation to the early days of life and its position in the water column of an egg is nicely described. Comparisons of the

dissipation and exposure of the dissolved fraction and oil droplets are clear and insightful. Simulations show that eggs are exposed to higher concentrations of oil droplets than the dissolved oil fraction. When considering oil droplets, exposure times are much higher than previously simulated data on the dissolved fraction.

The conclusions are novel, since oil droplets are not usually considered as a crude oil source for plankton, but as moving parcels of soon to be dissolved oil. The manuscript is nicely written, and the model is clearly described.

Since I believe there is a gap in oil droplet research and would and that the scientific community would benefit from this current addition, I recommend publication of this paper, but I would like the authors to address the following points.

Major comments:

Line 79-81: My main comment is regarding the assumption that all droplets that contact the egg will remain until hatching. Wouldn't that overestimate the role of oil droplets, since some would not stick, and most importantly, some could detach from the egg from external forces like turbulence, collision, etc? If it is not possible to implement in the current model, I think this caveat should be developed further in the discussion, and the possibility of droplet detachment should be assessed. Would it be possible to run the simulation using different values of stickiness ( $\alpha$ ), perhaps to show the extreme scenarios, i.e., all droplets are retained vs. half of less?

Line 239: Most planktonic and benthic filter feeders, e.g., copepods, larvaceans, barnacles, sabellid worms, will encounter, capture oil droplets via setae, setules, mucus nets, and potentially ingest. Implications of the proposed model for this functional group should be assessed, or at least discussed. Most crustacean filtering appendages are hydrophobic, which helps capture lipid based particles, and unfortunately crude oil droplets. The argument could be made that even if the fish egg does not encounter a lot of oil droplets during the spill event, it could potentially ingest them as a larval fish from predation of zooplankton who did ingest droplets. Would predation events or trophic transfer be possible to implement in the model if you were to consider larval fish as well?

Line 253: While it is true that oil droplets and dissolved oil have different compositions, the composition of the droplet itself changes rapidly over the course of the first few weeks of an oil spill, a timeframe critical for this particular model since egg hatching rate is around 2 weeks. These weathering processes will increase crude oil droplets density, viscosity and will shift the particle size distribution to bigger droplets in the water column. Increased density will lower rise velocity and potentially affect the collision rate of the model. I would like to see if the model would benefit from a progressive change in these parameters, emulating weathering processes. The discussion would minimally benefit from acknowledging these and how the model would be affected.

Jordan and Payne (1980), Fate and Weathering of Petroleum Spills in the Marine Environment gives a thorough overview of the different weathering processes oil slicks and droplets undergo in the initial stages of the spill events.

Increased density and viscosity of the oil through weathering will in turn also affect droplet detachment probability from the egg/filtering structure. While I understand this might be out of scope for this particular effort, it could be worth mentioning in the discussion to reach other spheres of the literature, i.e., zooplankton structural biology, fluid mechanics.

Line 281: Surfactants decrease the free-stream velocity needed for oil droplets to detach from filtering appendages. While the surface chemistry and wettability of the egg is different than crustacean structures, this could mean less droplets are retained by the egg, depending on water column turbulence. Letendre et al., (2023) studied the effect of surfactants on oil droplet detachment conditions.

Minor comments:

Line 64: by a factor "of" 10

Line 75: Adding the size classes, or size limits could benefit the reader here.

Figure 4: What is the main contributor of the large vertical variation in egg position? Is this due to the hydrography of the area? Is this something we could expect at a different spill location?

An important yet understudied mechanism in oil droplet fate is the shift in oil droplet size distribution due to zooplankton interaction. This could be mentioned in the discussion. Uttieri et al., (2019) describes this mechanism in detail.

Line 284: Hansen et al., (2016) and Bobra et al., (1989) compare chemically and mechanically dispersed crude oil droplets and their respective effects on copepods and daphnids.

Line 334 : Have you tried using the oil droplet to egg size ratio instead of the absolute metrics?

Thank you for the opportunity to read and comment on your manuscript. I will address any questions you may have.

Regards,  
Francis Letendre

Reviewer #2 (Remarks to the Author):

This manuscript innovatively constructed a framework for quantifying the interaction between oil droplets and fish eggs and applied it to numerical models, making up for the deficiency in previous risk assessment that only dissolved oil was considered. It provided a new perspective and method for studying the impact of Marine oil pollution on organisms and demonstrated certain innovation in research ideas and methods. It is suitable for publication after minor revisions.

1. In the model of the manuscript, it is assumed that all the oil droplets adhere to the fish eggs until they hatch, which is different from the actual situation. It is recommended that a more realistic adhesion probability model be added, and reasonable adhesion probabilities should be determined by combining laboratory research or field observation data, to improve the accuracy of the model.
2. Although the manuscript mentions the comparison between the experimental data and the simulation results, the experimental conditions mentioned have a large difference from the actual marine environment, and the experimental data are limited. It is recommended to conduct experiments under different environmental conditions to obtain more data, further verify the reliability of the model in different scenarios and narrow the gap between the simulation and the actual situation.
3. When determining the size classes of oil droplets, relying solely on partial simulation data may have limitations. It is recommended to comprehensively consider more actual observational data or different simulation results to classify the size classes, ensuring that they can more accurately reflect the actual distribution of oil droplets and avoiding the influence of unreasonable size class division on the research conclusions.
4. When discussing the impact of oil droplets on fish eggs, the manuscript mainly focuses on the effect of oil droplets directly adhering to fish eggs. However, it lacks an in-depth exploration of the interactions between oil droplets and other environmental factors (such as marine microorganisms, extracellular polymers of microorganisms, etc.) and their comprehensive impacts on fish eggs. It is recommended to supplement relevant content to improve the analysis of influencing factors.
5. In the manuscript, a model is constructed with Northeast Atlantic haddock as an example. Although it has a certain representativeness, there are significant differences in the ecological environment and biological characteristics of different species in different sea areas. It is recommended to further explore the applicability of the model when it is applied to other species and geographical regions and clarify the applicable scope and limitations of the model.
6. In the results section of the manuscript, there is relatively little analysis of the uncertainties of the simulation results. Considering the uncertainties of the model input parameters and the complexity of the environment, the content of uncertainty analysis should be added to provide more comprehensive support for the research conclusions.
7. The manuscript mainly studies the impact of oil droplets on fish eggs from a macroscopic perspective, lacking in-depth analysis from a microscopic level (such as molecular biological mechanisms). It is recommended to combine modern biological technologies and further explore the toxic mechanisms of oil droplets on fish eggs from microscopic aspects like gene expression and cellular damage, which can enhance the depth and value of the research.

Reviewer #3 (Remarks to the Author):

The paper is well written and easy to comprehend. The authors have developed a framework to quantify the exposure of dissolved and droplet oil on fish eggs in the ocean. Using numerical simulations, the authors demonstrate that oil droplets cover a much larger domain at much higher concentrations than dissolved oil, leading to greater accumulation of oil on fish eggs. The authors suggest that considering oil droplets, in addition to dissolved oil, could provide better impact assessments of oil spills. The numerical simulation results support the claims. Given the numerical simulation nature of the work, the inclusion of experimental tank and field measurements and/or references would strengthen the validity of the claims made. Line 58: Fig. 1 shows ~1 mm fish eggs and adhered oil droplets with varying dimensions (mostly droplets smaller than egg dimensions).

1. Was Fig.1 part of the experiments performed for this study or adopted from other papers?
  2. Was the water in the oil exposure chamber static or turbulent?
  3. Was the buoyant rising or turbulent mixing the dominant cause for oil droplet collision in this experiment?
  4. Can similar tank experiments be done at different turbulence levels to experimentally determine and/or validate the collision rates defined in line 369 and measure oil accumulation? The 4 km horizontal resolution of the ocean model used in the simulation may be inadequate to describe smaller-scale turbulence and the interaction of oil droplets and fish eggs.
  5. Figure S6: Egg abundance is higher near the surface, and likely larger oil droplets and oil slicks will also be present at/near the surface. How do fish eggs adhere to oil droplets larger than 100  $\mu\text{m}$  and oil slicks? How does ignoring oil droplets larger than 100  $\mu\text{m}$  and oil slicks affect the oil exposure simulation?
- Line 156, Figure 4: In the simulation, both the fish eggs and oil droplets are buoyant particles with positive rise velocity. After a certain time, all the fish eggs and oil droplets would reach the ocean surface.
1. What happens to the fish eggs and oil droplets once they reach the ocean surface, likely contaminated with oil slicks? Adhesion of fish eggs to oil slicks or larger oil droplets (>100  $\mu\text{m}$ ) could change their buoyancy, and fish eggs may stick to the ocean surface for a longer period of time. Zooplankton have been found to stick to the water surface containing a thin layer of oil slicks (impaired swimming) during exposure to dissolved oil in a static chamber containing crude oil-water

mixture (Gurung et al.(2024). *Limnol Oceanogr*, 69: S42-S53. <https://doi.org/10.1002/lno.12489>).

2. What causes the fish eggs to move back to deeper water from the ocean surface? Do oil droplets also move from the ocean surface to deeper water, or are the oil droplets lost once they reach the ocean surface? Oceanic processes like wave breaking and wind-driven Langmuir circulation can create downwelling currents, causing re-entrainment of buoyant particles from the surface to deeper water, increasing retention of buoyant particles like oil droplets and fish eggs. But such phenomena are not mentioned in the manuscript.

3. How does the rise velocity of fish eggs compare to the downward velocity of fish eggs from the ocean surface to deeper water?

4. In Figure 4, the left top and left middle figures show dissolved oil and droplet oil concentration; there are short periods of very low concentration shown by a rapid drop in the concentration over time tracing. Why are there regions with such low oil concentration even when the egg reaches near the oil release site? Is this due to the downward vertical motion of eggs during those time periods? What's causing the downward vertical motion of eggs? Does the same downward vertical forcing cause downward vertical motion of oil droplets, increasing the concentration of oil droplets along the water depth?

Line 139: As seen in Figure 3 and Figure 4, the region contaminated by oil droplets is larger than that by the dissolved oil. Rather than stating that the simulation shows the result, what physical phenomenon would cause this difference in coverage area?

Line 251: Please provide references on experimental work on oil droplet behavior in tank experiments and field measurements.

Line 210: Discussion on sensitivity analysis showing how variations in model input parameters affect results can be included.

Line 282: Use of dispersant creates smaller oil droplets that can reach lower depths of water column and can retain for longer period of time. This also increases oil concentration at deeper water for longer time and the effect of dispersants on oil droplet exposure is likely non-trivial.

Line 298: Accumulated oil mass in the simulation is 200 times ( $\sim 40 \mu\text{g}$  vs  $\sim 0.2 \mu\text{g}$ ) the experimental value. Could the simulation be overestimating the accumulated oil mass?

Line 369: Do the collision rates consider the effect of the distance between the nearest oil droplets? If the distance between the oil droplets is greater than the  $\text{Li}$  (Line 330), eggs may pass between the oil droplets without colliding with the oil droplets that are not present in their path.

Line 444: Larger oil droplets ( $>100 \mu\text{m}$ ) could be present in the water column due to wave breaking and downwelling currents of Langmuir circulation (Gurung et al. (2022), *Limnol Oceanogr Methods*, 20: 633-655.

<https://doi.org/10.1002/lom3.10510>). Disregarding larger droplets ( $>100 \mu\text{m}$ ) may underestimate the magnitude of the collision rate and oil accumulation.

Line 408: Oil droplet entrainment in Stommel retention zones created by Langmuir circulation could increase oil droplet concentration and collision rate at greater depths. Also, the trajectories of buoyant particles may follow helical vortices during Langmuir circulation instead of a purely vertical trajectory due to buoyancy. This may affect collision rates and oil accumulation. Does the ocean model consider the effect of Langmuir circulation?

Minor points:

Title:

1. 'Oil droplets' is a broad term. Oil droplets from spilled crude oil or processed fossil fuel could be more specific.

2. 'Risk assessments' is a broad term. The paper uses a simulation for fish eggs. The findings of the manuscript would apply to the environmental risk to fish eggs.

In this manuscript, the mechanism of oil droplets contamination is through adhesion to the fish eggs surface. If there are oil droplets in water, then it can adhere to any other particles including sediment suspension (forming oil particle aggregates), zooplanktons and larger animals. The contamination of oil droplets could thus be even larger than that shown by the fish egg simulations.

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Version 1:

Decision Letter:

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Dear Dr Frøysa,

Your manuscript titled "Oil droplets are severely overlooked in risk assessments" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Best regards,

Alice Drinkwater, PhD  
Associate Editor  
Communications Earth & Environment  
Consulting Editor  
Communications Sustainability

#### REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have addressed all of my comments. I recommend this paper for publication.

Reviewer #2 (Remarks to the Author):

Authors have substantially revised their paper to address my previous concerns and improved their presentation. I believe the revised paper is suitable for publication in communications earth & environment.

Reviewer #3 (Remarks to the Author):

The authors have attempted to address the comments previously provided in the revised manuscript. I would like to commend the authors for this work. Presenting an explicit sensitivity analysis (if possible) may have been helpful.

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href="http://www.nature.com/authors">www.nature.com/authors</a> for information about policies, services and author benefits\*\*

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“Oil droplets are severely overlooked in risk assessments”

Authors: Håvard G. Frøysa, Raymond Nepstad, Elin Sørhus, Carey E. Donald, Sonnich Meier, Frode B. Vikebø

Overall assessment: Goals and hypotheses of the paper are clearly stated. The authors make a point in saying oil droplets are understudied and under-evaluated in spill events, with which I completely agree. The paper does a great job at simulating and recreating oil spill conditions from a spill event in Norway 2001. The average exposure to crude oil, in relation to the early days of life and its position in the water column of an egg is nicely described. Comparisons of the dissipation and exposure of the dissolved fraction and oil droplets are clear and insightful.

Simulations show that eggs are exposed to higher concentrations of oil droplets than the dissolved oil fraction. When considering oil droplets, exposure times are much higher than previously simulated data on the dissolved fraction.

The conclusions are novel, since oil droplets are not usually considered as a crude oil source for plankton, but as moving parcels of soon to be dissolved oil. The manuscript is nicely written, and the model is clearly described.

Since I believe there is a gap in oil droplet research and would and that the scientific community would benefit from this current addition, I recommend publication of this paper, but I would like the authors to address the following points.

Major comments:

Line 79-81: My main comment is regarding the assumption that all droplets that contact the egg will remain until hatching. Wouldn't that overestimate the role of oil droplets, since some would not stick, and most importantly, some could detach from the egg from external forces like turbulence, collision, etc? If it is not possible to implement in the current model, I think this caveat should be developed further in the discussion, and the possibility of droplet detachment should be assessed. Would it be possible to run the simulation using different values of stickiness ( $\alpha$ ), perhaps to show the extreme scenarios, i.e., all droplets are retained vs. half of less?

Line 239: Most planktonic and benthic filter feeders, e.g., copepods, larvaceans, barnacles, sabellid worms, will encounter, capture oil droplets via setae, setules, mucus nets, and potentially ingest. Implications of the proposed model for this functional group should be assessed, or at least discussed. Most crustacean filtering appendages are hydrophobic, which helps capture lipid based particles, and unfortunately crude oil droplets. The argument could be made that even if the fish egg does not encounter a lot of oil droplets during the spill event, it could potentially ingest them as a larval fish from predation of zooplankton who did ingest droplets. Would predation events or trophic

transfer be possible to implement in the model if you were to consider larval fish as well?

Line 253: While it is true that oil droplets and dissolved oil have different compositions, the composition of the droplet itself changes rapidly over the course of the first few weeks of an oil spill, a timeframe critical for this particular model since egg hatching rate is around 2 weeks. These weathering processes will increase crude oil droplets density, viscosity and will shift the particle size distribution to bigger droplets in the water column. Increased density will lower rise velocity and potentially affect the collision rate of the model. I would like to see if the model would benefit from a progressive change in these parameters, emulating weathering processes. The discussion would minimally benefit from acknowledging these and how the model would be affected.

Jordan and Payne (1980), *Fate and Weathering of Petroleum Spills in the Marine Environment* gives a thorough overview of the different weathering processes oil slicks and droplets undergo in the initial stages of the spill events.

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#### Minor comments:

Line 64: by a factor “of” 10

Line 75: Adding the size classes, or size limits could benefit the reader here.

Figure 4: What is the main contributor of the large vertical variation in egg position? Is this due to the hydrography of the area? Is this something we could expect at a different spill location?

An important yet understudied mechanism in oil droplet fate is the shift in oil droplet size distribution due to zooplankton interaction. This could be mentioned in the discussion. Uttieri et al., (2019) describes this mechanism in detail.

Line 284: Hansen et al., (2016) and Bobra et al., (1989) compare chemically and mechanically dispersed crude oil droplets and their respective effects on copepods and daphnids.

Line 334 : Have you tried using the oil droplet to egg size ratio instead of the absolute metrics?

Thank you for the opportunity to read and comment on your manuscript. I will address any questions you may have.

Regards,

Francis Letendre

Authors have substantially revised their paper to address my previous concerns and improved their presentation. I believe the revised paper is suitable for publication in communications earth & environment.

## Reviewer 1:

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### **Response:**

*Thank you. We have addressed your comments. Please see the detailed responses.*

## **Major comments:**

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### **Response:**

*Good comment. We have explicitly addressed this in L.299-313 in the discussion and L.372-374 in the methods. In addition, we have now added new text under Material and methods: 1.1.1 Accumulation of oil droplets on fish eggs the following sentence at L.374:*

***“As stated towards the end of the Discussion, this parameter is species and stage specific and need to be addressed experimentally to determine the correct values.»***

*It would be possible to apply any (fixed) value of  $\alpha$  in the simulations. However, as we lack good experimental values, we prefer to keep it fixed at one such that all droplets stick. Essentially, we then only model the collision process and not the adhesion or uptake/effects. It is correct that this will likely overestimate the accumulation, or at least*

*give an upper limit, for the oil exposure. However, as a first step to assess the effect of oil droplets we find it beneficial to apply this assumption to quantify the possible exposure.*

Line 239: Most planktonic and benthic filter feeders, e.g., copepods, larvaceans, barnacles, sabellid worms, will encounter, capture oil droplets via setae, setules, mucus nets, and potentially ingest. Implications of the proposed model for this functional group should be assessed, or at least discussed. Most crustacean filtering appendages are hydrophobic, which helps capture lipid based particles, and unfortunately crude oil droplets. The argument could be made that even if the fish egg does not encounter a lot of oil droplets during the spill event, it could potentially ingest them as a larval fish from predation of zooplankton who did ingest droplets. Would predation events or trophic transfer be possible to implement in the model if you were to consider larval fish as well?

**Response:**

*Good point. We have explicitly focused this manuscript on the direct effect of oil droplets on marine species, here fish eggs, in addition to the dissolved oil as this is typically lacking from risk assessments. But you are correct that oil droplets, and dissolved oil for that matter, also might indirectly affect marine species through contaminant prey. We have now added a sentence at L. 234 to make this clear:*

*“It may also be integrated with additional features such as indirect exposure through fish larvae feeding on zooplankton (Carroll et al, 2018) that may have ingested oil droplets (Nordtug et al. 2015).»*

Line 253: While it is true that oil droplets and dissolved oil have different compositions, the composition of the droplet itself changes rapidly over the course of the first few weeks of an oil spill, a timeframe critical for this particular model since egg hatching rate is around 2 weeks. These weathering processes will increase crude oil droplets density, viscosity and will shift the particle size distribution to bigger droplets in the water column. Increased density will lower rise velocity and potentially affect the collision rate of the model. I would like to see if the model would benefit from a progressive change in these parameters, emulating weathering processes. The discussion would minimally benefit from acknowledging these and how the model would be affected.

**Response:**

*The oil spill and fate model already includes weathering of oil when calculating mass concentration of droplets so that the processes mentioned above are already included. We have elaborated this in L.451 that now reads:*

*“Oil is modelled using a multi-phase particle based model [64, 65, 66, 67] that uses forcing from the ocean model and include environmental weathering processes of the oil.»*

*As of now we use a fixed size spectrum and density to calculate the droplet number concentrations from the mass concentration. This is mainly due to computational considerations, and it would in theory be possible to have temporal and spatial variation in the size and composition of droplets. However, the effect of using a fixed size spectrum and density is negligible for the results of accumulated mass presented here. This is now added in L.295 of the discussion:*

*“For the calculation of accumulated mass, however, the exact size distribution and buoyancy of droplets are insignificant. This is because collision rates are dominated by the rise velocity of the egg and thus almost constant across droplet sizes (section 1 in the SI).”*

Jordan and Payne (1980), Fate and Weathering of Petroleum Spills in the Marine Environment gives a thorough overview of the different weathering processes oil slicks and droplets undergo in the initial stages of the spill events.

Increased density and viscosity of the oil through weathering will in turn also affect droplet detachment probability from the egg/filtering structure. While I understand this might be out of scope for this particular effort, it could be worth mentioning in the discussion to reach other spheres of the literature, i.e., zooplankton structural biology, fluid mechanics.

**Response:**

Correct. As described in the response above, weathering is included in the oil model which is made more explicit in the updated manuscript in L.451 that now reads:

*“Oil is modelled using a multi-phase particle based model (refs) that uses forcing from the ocean model **and include environmental weathering processes of the oil.**»*

Still, there is work to be done experimentally to also understand how “stickiness” may change, which we acknowledge in the end of the discussion:

*“Also, whether an oil droplet adheres if encountering marine life depends on various aspects such as the speed and angle at encounter, shape and size of contact area, adhesivity of marine life in question, and the density of objects colliding.”*

We have also added in the conclusion of the discussion that various oil component compositions should be considered in future experiments:

*“Additionally, one needs to address uptake rates of oil droplets **with various oil component compositions** adhered to the egg surface experimentally and numerically.”*

Line 281: Surfactants decrease the free-stream velocity needed for oil droplets to detach from

filtering appendages. While the surface chemistry and wettability of the egg is different than crustacean structures, this could mean less droplets are retained by the egg, depending on water column turbulence. Letendre et al., (2023) studied the effect of surfactants on oil droplet detachment conditions.

**Response:**

*Our understanding is that surfactants lower the surface tension between different phases such as oil and water, thereby reducing the energy required for them to mix (dissolve). Dispersants are specific surfactants designed to prevent aggregations. In L.285-298 we have addressed the impacts that dispersants might have with respect to aggregations of oil droplets on adhesive marine life and we question if smaller droplets that may have increased contact rates attach to eggs similarly to larger droplets. We have also updated the text slightly and added a reference to Letendre et al. (2023):*

*“However, changing the number and sizes of droplets could affect the mass **and size distribution** of oil accumulated on eggs (Letendre et al., 2023).”*

**Minor comments:**

Line 64: by a factor “of” 10

**Response:**

*Fixed.*

Line 75: Adding the size classes, or size limits could benefit the reader here.

**Response:**

*Added reference to Table 1 and 2.*

Figure 4: What is the main contributor of the large vertical variation in egg position? Is this due to the hydrography of the area? Is this something we could expect at a different spill location? An important yet understudied mechanism in oil droplet fate is the shift in oil droplet size distribution due to zooplankton interaction. This could be mentioned in the discussion. Uttieri et al., (2019) describes this mechanism in detail.

**Response:**

*A vertical distribution of eggs similar to this is expected also at other locations for positively buoyant pelagic eggs such as haddock ones. For more on this, see Sundby et al. (2015) on The Principles of Buoyancy in Marine Fish Eggs and Their Vertical Distributions across the World Oceans.*

*We have included a comment on zooplankton manipulation of the oil droplet size spectrum and a reference to Uttieri et al. (2019) in the discussion:*

*“In addition, there may be other processes that alter the distribution of oil droplet size such as zooplankton manipulation (Uttieri, 2019).”*

Line 284: Hansen et al., (2016) and Bobra et al., (1989) compare chemically and mechanically dispersed crude oil droplets and their respective effects on copepods and daphnids.

**Response:**

*We have included references to the two suggested manuscripts. The updated text is:*

*“Despite previous reports that dispersants have limited effects on exposure rates of fish early life stages to oil when considering dissolved oil [6], it is not clear if this is true also when addressing oil **droplets as studies are limited and typically address copepods or daphnids (Hansen et al. (2016) and Bobra et al. (1989)).**”*

Line 334: Have you tried using the oil droplet to egg size ratio instead of the absolute metrics?

**Response:**

*In order to calculate rise velocities using Stoke’s law it is necessary to use absolute size values. This is a non-linear calculation, so the resulting velocities and differences will not be well defined, either in absolute or relative values, for a given relative size ratio.*

Thank you for the opportunity to read and comment on your manuscript. I will address any questions you may have.

**Response:**

*Thank you for great comments and suggestions.*

## **Reviewer 2:**

This manuscript innovatively constructed a framework for quantifying the interaction between oil droplets and fish eggs and applied it to numerical models, making up for the deficiency in previous risk assessment that only dissolved oil was considered. It provided a new perspective and method for studying the impact of Marine oil pollution on organisms and demonstrated certain innovation in research ideas and methods. It is suitable for publication after minor revisions.

**Response:**

*Thank you.*

1. In the model of the manuscript, it is assumed that all the oil droplets adhere to the fish eggs until they hatch, which is different from the actual situation. It is recommended that a more realistic adhesion probability model be added, and reasonable adhesion probabilities should be determined by combining laboratory research or field observation data, to improve the accuracy of the model.

**Response:**

Agree. See the reply to the first major comment by reviewer 1 repeated here. We have explicitly addressed this in L.299-313 in the discussion and L.372-374 in the methods. In addition, we have now added new text under Material and methods: 1.1.1 Accumulation of oil droplets on fish eggs the following sentence at L.374:

*“As stated towards the end of the Discussion, this parameter is species and stage specific and need to be addressed experimentally to determine the correct values.”*

*It would be possible to apply any (fixed) value of  $\alpha$  in the simulations. However, as we lack good experimental values, we prefer to keep it fixed at one such that all droplets stick. Essentially, we then only model the collision process and not the adhesion or uptake/effects. It is correct that this will overestimate the accumulation, or at least give an upper limit, for the oil exposure. However, as a first step to assess the effect of oil droplets we find it beneficial to apply this assumption to quantify the possible exposure.*

2. Although the manuscript mentions the comparison between the experimental data and the simulation results, the experimental conditions mentioned have a large difference from the actual marine environment, and the experimental data are limited. It is recommended to conduct experiments under different environmental conditions to obtain more data, further verify the reliability of the model in different scenarios and narrow the gap between the simulation and the actual situation.

**Response:**

We agree that the relevant experimental data available is limited and address this in the manuscript at L. 21, L.253 and the entire paragraph starting at L.299. Specifically, L.313 points at the different conditions in experimental setup and the field and L.321 calls for more experiments that address these challenges:

*“Based on our findings, we strongly recommend experimental investigations of these mechanisms and oil droplet impacts on various species and stages to improve realisms in oil spill impact assessment models. Additionally, one needs to address uptake rates of oil droplets with various oil component compositions adhered to the egg surface experimentally and numerically.”*

*At the same time, experiments are very expensive to perform and any experiment performed in the laboratory will have differences from the actual marine environment. Nonetheless, for these reasons experiments should be carefully planned in a way that provides as much information as possible for numerical models such as the one here.*

3. When determining the size classes of oil droplets, relying solely on partial simulation data may have limitations. It is recommended to comprehensively consider more actual observational data or different simulation results to classify the size classes, ensuring that they can more accurately reflect the actual distribution of oil droplets and avoiding the influence of unreasonable size class division on the research conclusions.

**Response:**

*We agree that it would be ideal to have more experimental data on this. However, field experiments measuring oil droplet sizes are very scarce. The DeepSpill experiment [1] is one, and data from there has been used for developing and testing [2] the OSCAR oil model used here. Comprehensive scaled down lab experiments of blow-outs and surface entrainment have been conducted and used for OSCAR development, e.g. [3,4]. Also, during the recent oil on water exercise, the wave-entrained oil droplet sizes under an oil slick was measured with the SilCam, but these have not been published yet.*

*Of course, the type of oil and various environmental factors will greatly influence the droplet size spectrum, but only within a certain range. For example, too large droplets are unstable and will break up and/or surface quickly. Also, the presented values for accumulated oil are very stable with regards to the droplet size spectrum, as addressed in several of the other responses and in the manuscript.*

**Refs:**

- [1] <https://www.sciencedirect.com/science/article/pii/S1353256102001238>
- [2] <https://www.sciencedirect.com/science/article/pii/S0964569121000375>
- [3] <https://www.sciencedirect.com/science/article/pii/S0025326X1300194X>
- [4] <https://www.sciencedirect.com/science/article/pii/S0025326X15001162>

4. When discussing the impact of oil droplets on fish eggs, the manuscript mainly focuses on the effect of oil droplets directly adhering to fish eggs. However, it lacks an in-depth exploration of the interactions between oil droplets and other environmental factors (such as marine microorganisms, extracellular polymers of microorganisms, etc.) and their comprehensive impacts on fish eggs. It is recommended to supplement relevant content to improve the analysis of influencing factors.

**Response:**

*This is a good comment by the reviewer, and we agree that there are many additional factors that could affect the oil droplet exposure of fish eggs and the resulting toxicological effects. The presented modelling framework could be extended with additional modules for plankton and microorganisms interacting with the individual oil droplets and eggs. However, our main goal for this manuscript is to inform based on combined observations and modelling that oil droplets play a significant role in the exposure of fish eggs and should be included in impact assessments of oil spills in addition to dissolved oil. It is thus beyond the scope of this manuscript to include all additional factors as the ones suggested by the reviewer, but they may be part of future work by building on the model framework presented here.*

5. In the manuscript, a model is constructed with Northeast Atlantic haddock as an example. Although it has a certain representativeness, there are significant differences in the ecological environment and biological characteristics of different species in different sea areas. It is recommended to further explore the applicability of the model when it is applied to other species and geographical regions and clarify the applicable scope and limitations of the model.

**Response:**

*This is an important comment. The model framework is generic, and parameters used may be replaced to adapt to other species and environments. It is, however, beyond the scope of this manuscript to demonstrate its use for multiple environments and species. Nonetheless, the functions are described and the code is made available such that it is possible for others to use the model for other species and locations. This is stated in line 233:*

*“The framework is generic and may be applied to other species and geographical regions by entering scenario-specific information.”*

6. In the results section of the manuscript, there is relatively little analysis of the uncertainties of the simulation results. Considering the uncertainties of the model input parameters and the complexity of the environment, the content of uncertainty analysis should be added to provide more comprehensive support for the research conclusions.

**Response:**

*All such simulations inherently possess a significant degree of uncertainty, but the model system used here is well established and used in several previous publications (see refs). In addition, each module (ocean, oil, egg) of the model is also each used independently in an even higher number of publications. Thus, the established model system is considered mature and well documented.*

*The new numerical part in this manuscript is the collision module. For this module, there are three main uncertainties:*

- **Size spectrum of the oil droplets:**

*Addressed in several other responses and in the new text of the manuscript in L.295 of the discussion:*

*“For the calculation of accumulated mass, however, the exact size distribution and buoyancy of droplets are insignificant. This is because collision rates are dominated by the rise velocity of the egg and thus almost constant across droplet sizes (section 1 in the SI).”*

- **“Stickiness parameter”  $\alpha$ :**

*Addressed in several other responses and the last paragraph of the discussion:*

*“Also, whether an oil droplet adheres if encountering marine life depends on various aspects such as the speed and angle at encounter, shape and size of contact area, adhesivity of marine life in question, and the density of objects colliding. Based on our findings, we strongly recommend experimental investigations of these mechanisms (...).”*

- **Turbulent mixing:**

*Addressed in the last paragraph of the discussion.*

**Refs:**

- [1] <https://www.sciencedirect.com/science/article/pii/S0025326X17309153>
- [2] <https://www.frontiersin.org/journals/marine-science/articles/10.3389/fmars.2021.767191/full>
- [3] <https://www.sciencedirect.com/science/article/pii/S0025326X2200889X>
- [4] <https://www.sciencedirect.com/science/article/pii/S0048969723055766>

7. The manuscript mainly studies the impact of oil droplets on fish eggs from a macroscopic perspective, lacking in-depth analysis from a microscopic level (such as molecular biological mechanisms). It is recommended to combine modern biological technologies and further explore the toxic mechanisms of oil droplets on fish eggs from microscopic aspects like gene expression and cellular damage, which can enhance the depth and value of the research.

**Response:**

*This is a great suggestion, but beyond the scope of this manuscript. Here, we establish that oil droplets constitute a significant exposure, which should motivate follow up studies on the actual mechanisms and toxic effects of this exposure as stated in L.323:*

*“Additionally, one needs to address uptake rates of oil droplets adhered to the egg surface experimentally and numerically.»*

**Reviewer 3:**

The paper is well written and easy to comprehend. The authors have developed a framework to quantify the exposure of dissolved and droplet oil on fish eggs in the ocean. Using numerical simulations, the authors demonstrate that oil droplets cover a much larger domain at much higher concentrations than dissolved oil, leading to greater accumulation of oil on fish eggs. The authors suggest that considering oil droplets, in addition to dissolved oil, could provide better impact assessments of oil spills. The numerical simulation results support the claims. Given the numerical simulation nature of the work, the inclusion of experimental tank and field measurements and/or references would strengthen the validity of the claims made.

**Response:**

*Thank you. We agree that lab and field experiments are important to support and improve the numerical simulations, which we address in the last paragraph of the discussion.*

Line 58: Fig. 1 shows ~1 mm fish eggs and adhered oil droplets with varying dimensions (mostly droplets smaller than egg dimensions).

1. Was Fig.1 part of the experiments performed for this study or adopted from other papers?
2. Was the water in the oil exposure chamber static or turbulent?
3. Was the buoyant rising or turbulent mixing the dominant cause for oil droplet collision in this experiment?

**Response:**

The pictures in Fig.1 are not presented previously though they belong to a previously described experiment (Sørhus et al., 2021). It is included here to show that droplets adhere to fish eggs and motivate the study. In the previous tank experiments the water was circulating but the turbulence was likely much less than what is found in the field. As such it cannot realistically inform of the relative importance of buoyant rising and turbulent mixing for adhesion of oil droplets to eggs in the field.

**Ref:**

<https://www.sciencedirect.com/science/article/pii/S0048969720374271>

4. Can similar tank experiments be done at different turbulence levels to experimentally determine and/or validate the collision rates defined in line 369 and measure oil accumulation? The 4 km horizontal resolution of the ocean model used in the simulation may be inadequate to describe smaller-scale turbulence and the interaction of oil droplets and fish eggs.

**Response:**

We agree that such studies would be very useful, as stated at the end of the discussion:

*“Based on our findings, we strongly recommend experimental investigations of these mechanisms and oil droplet impacts on various species and stages to improve realism in oil spill impact assessment models. Additionally, one needs to address uptake rates of oil droplets with various oil component compositions adhered to the egg surface experimentally and numerically.”*

It is, however, to our knowledge very difficult to reproduce a realistic exposure scenario including both oil exposure and turbulence. As stated in the discussion:

*“Remember, however, that turbulence existing in the field is notoriously difficult to replicate in experimental tanks and numerical experiments.”*

Thus, experimental studies typically only address some of the relevant physical processes. Still, there are some studies on encounter rates of prey (see refs to Pecseli et al. in manuscript). These studies are relevant, but the process of droplets adhering to eggs is even more complicated than grazing in the regard that there is no active process where a predator eats all the prey within a given volume. As mentioned in the discussion, collision and adhesion also depend on several other factors:

*“Also, whether an oil droplet adheres if encountering marine life depends on various aspects such as the speed and angle at encounter, shape and size of contact area, adhesivity of marine life in question, and the density of objects colliding.”*

While it should be noted that the oil model used has a higher resolution than the ocean model with 1.5 km horizontal resolution, we agree that the 4 km horizontal resolution of the ocean model is inadequate to address small scale turbulence accurately. This is acknowledged in the manuscript in the passage also cited above:

*“Remember, however, that turbulence existing in the field is notoriously difficult to replicate in experimental tanks and numerical experiments.”*

*Independent of this, analytical considerations in the supplementary information show that for all reasonable turbulence values the rise velocity of the egg will still be the dominating factor for the collision rate. Thus, even though the turbulence may not be accurately represented in the collision algorithm, this is not believed to significantly affect the calculation of accumulated mass.*

5. Figure S6: Egg abundance is higher near the surface, and likely larger oil droplets and oil slicks will also be present at/near the surface. How do fish eggs adhere to oil droplets larger than 100 µm and oil slicks? How does ignoring oil droplets larger than 100 µm and oil slicks affect the oil exposure simulation?

**Response:**

*Our understanding is that this comment relates the vertical distribution of Figure S6 to the experimental picture of Figure 1. However, figure S6 is from the simulation, which is unrelated from the experimental picture. Please see the responses to the following comments regarding oil slicks in the model.*

Line 156, Figure 4: In the simulation, both the fish eggs and oil droplets are buoyant particles with positive rise velocity. After a certain time, all the fish eggs and oil droplets would reach the ocean surface.

**Response:**

*There is a dynamic balance between turbulent mixing and buoyancy that results in an exponential decrease of eggs and droplets with depth, as described in L.68. We have updated L.117 to make this clearer:*

*“Vertical positioning of eggs is updated dynamically according to individual buoyancies resulting in an exponential depth distribution (Thygesen and Ådlandsvik, 2008).”*

1. What happens to the fish eggs and oil droplets once they reach the ocean surface, likely contaminated with oil slicks? Adhesion of fish eggs to oil slicks or larger oil droplets (>100 µm) could change their buoyancy, and fish eggs may stick to the ocean surface for a longer period of time. Zooplankton have been found to stick to the water surface containing a thin layer of oil slicks (impaired swimming) during exposure to dissolved oil in a static chamber containing crude oil-water mixture (Gurung et al.(2024). *Limnol Oceanogr*, 69: S42-S53. <https://doi.org/10.1002/lno.12489>).

**Response:**

*We agree that larger droplets that adhere to the egg may have a significant effect on the buoyancy of the egg. They may thus reach the surface easier and potentially also get stuck there. For this reason, we have updated the paragraph on buoyancy in the discussion:*

*“(…) Hence, the effect of adhered oil on the buoyancy can be expected to be within the range of natural variability of eggs **for the droplet sizes considered here**. However, if **larger droplets are present and adhere to the egg such that its density decreases significantly**, eggs would rest higher in the water column and*

*potentially be exposed to more UV radiation which enhances toxicity [21]. Eggs reaching the ocean surface may also be exposed to and potentially get stuck within oil slicks.”*

2. What causes the fish eggs to move back to deeper water from the ocean surface? Do oil droplets also move from the ocean surface to deeper water, or are the oil droplets lost once they reach the ocean surface? Oceanic processes like wave breaking and wind-driven Langmuir circulation can create downwelling currents, causing re-entrainment of buoyant particles from the surface to deeper water, increasing retention of buoyant particles like oil droplets and fish eggs. But such phenomena are not mentioned in the manuscript.

**Response:**

*L.68 informs of how the dynamic balance between buoyancy and turbulent mixing cause eggs and droplets to exponentially decrease with depth. From a technical perspective, the vertical position of the egg is implemented as a discrete random walk with a specific time step where the next vertical position is either one step up, remain in the current position, or one step down with a probability for each possibility given by its buoyancy.*

3. How does the rise velocity of fish eggs compare to the downward velocity of fish eggs from the ocean surface to deeper water?

**Response:**

*From a technical point of view, in each time step of the numerical model the egg is moved to its new position according to a random walk. Then, at this resulting position oil droplet concentrations and rise velocities for egg and droplets are calculated. Thus, there is no downward velocity present in the model. From a physical perspective, moving a water volume containing droplets and eggs down as a unit does not create collisions, so the rise velocity could be interpreted as relative to the surroundings even though the net movement might be downwards.*

4. In Figure 4, the left top and left middle figures show dissolved oil and droplet oil concentration; there are short periods of very low concentration shown by a rapid drop in the concentration over time tracing. Why are there regions with such low oil concentration even when the egg reaches near the oil release site? Is this due to the downward vertical motion of eggs during those time periods? What's causing the downward vertical motion of eggs? Does the same downward vertical forcing cause downward vertical motion of oil droplets, increasing the concentration of oil droplets along the water depth?

**Response:**

*Both eggs and oil are modelled in 3D, so that egg and oil need to overlap in all 3 dimensions for eggs to be exposed to high oil concentrations. Thus, eggs may be close to oil but upstream, thereby experiencing low ambient oil concentrations. Also, even though eggs and oil droplets are modelled in similar ways using the same physical forcing, their positions are calculated independently in the model. As these calculations involve random movements reflecting natural turbulent and diffusive processes, this could be a*

source of some of the oil exposure fluctuations shown for the eggs. Also, the oil spill is represented by a final number of particles in a particle tracking model and can therefore be patchy, typically in areas of low concentrations. However, as we have used a relatively high number of oil and individual egg particles, the overall exposure statistics are robust.

Line 139: As seen in Figure 3 and Figure 4, the region contaminated by oil droplets is larger than that by the dissolved oil. Rather than stating that the simulation shows the result, what physical phenomenon would cause this difference in coverage area?

**Response:**

*The larger region is mainly due to applying the same concentration cutoff for oil droplets and dissolved oil in Figure 3. If a lower threshold had been applied to the dissolved oil, its spatial extent would increase as there typically is (a low concentration of) dissolved oil present where there are oil droplets. One contributing factor to this is that dissolved oil is biodegraded faster than droplet oil. However, very low (relative) concentrations are more prone to numerical noise. Thus, we choose to apply the same concentration threshold for both panels of the plot even though concentrations for droplets typically are greater than for dissolved oil. To correspond better with the results, we have updated the abstract:*

*“(…) shows that droplets **for a given concentration** cover a much larger domain than dissolved oil.”*

*We have also updated L.132 in the results that now reads:*

*“**For a given concentration threshold** the oil droplets cover a larger area than the dissolved oil, (…).”*

Line 251: Please provide references on experimental work on oil droplet behavior in tank experiments and field measurements.

**Response:**

*We have now included two references here:*

*“(…) the dynamics of oil droplet exposure is more complex to replicate in an experiment **even though there exist some studies like Sørhus et al. (2015) and Hansen et al. (2018).**”*

Line 210: Discussion on sensitivity analysis showing how variations in model input parameters affect results can be included.

**Response:**

*Please see the response to comment #6 of reviewer number 2 regarding uncertainties.*

Line 282: Use of dispersant creates smaller oil droplets that can reach lower depths of water column and can retain for longer period of time. This also increases oil concentration at deeper water for longer time and the effect of dispersants on oil droplet exposure is likely non-trivial.

**Response:**

*Agree. We discuss this in the paragraph starting at L.285 and conclude similarly as you.*

Line 298: Accumulated oil mass in the simulation is 200 times (~40 µg vs ~0.2 µg) the experimental value. Could the simulation be overestimating the accumulated oil mass?

**Response:**

*As discussed in the paragraph referred to by the reviewer, the knowledge about adhesion and accumulation is limited. Especially turbulent mixing and the “stickiness parameter”  $\alpha$  provide uncertainty. In total, it is certainly likely that the calculation overestimates the amount of adhered oil, but this does not alter our main message that oil droplets should be considered in impact assessment, and is consistent with our concluding suggestion in L.321:*

*“Based on our findings, we strongly recommend experimental investigations of these mechanisms and oil droplet impacts on various species and stages to improve realism in oil spill impact assessment models.”*

Line 369: Do the collision rates consider the effect of the distance between the nearest oil droplets? If the distance between the oil droplets is greater than the  $\lambda_i$  (Line 330), eggs may pass between the oil droplets without colliding with the oil droplets that are not present in their path.

**Response:**

*The algorithm does not consider the minimum distance explicitly, only implicitly through the number concentration of droplets. Thus, the collision rates should be interpreted as an average collision rate assuming a uniform distribution within the grid cells. However, for the durations, length scales and concentrations considered here, this assumption/interpretation is not considered to be problematic.*

Line 444: Larger oil droplets (>100 µm) could be present in the water column due to wave breaking and downwelling currents of Langmuir circulation (Gurung et al. (2022), *Limnol Oceanogr Methods*, 20: 633-655. <https://doi.org/10.1002/lom3.10510>). Disregarding larger droplets (>100 µm) may underestimate the magnitude of the collision rate and oil accumulation.

**Response:**

*We agree that larger droplets could affect the results presented here, but additional exposure from larger droplets would only strengthen our message that droplets should be considered in impact assessments of oil spills in addition to dissolved oil. However, we have now added some text about larger droplets in L.280 of the discussion:*

*“(…) if larger droplets are present and adhere to the egg such that its density decreases significantly, eggs would rest higher in the water column and potentially be exposed to more UV radiation which enhances toxicity [21]. Eggs reaching the ocean surface may also be exposed to and potentially get stuck within oil slicks.”*

Line 408: Oil droplet entrainment in Stommel retention zones created by Langmuir circulation could increase oil droplet concentration and collision rate at greater depths. Also, the trajectories of buoyant particles may follow helical vortices during Langmuir circulation instead of a purely vertical trajectory due to buoyancy. This may affect collision rates and oil accumulation. Does the ocean model consider the effect of Langmuir circulation?

**Response:**

*Langmuir circulation cell effects are not included in the oil model used here. It could be important in some cases, in particular close to the surface, but is not considered to be critical here as few eggs are located very close to the surface (Figure 4 and Figure S6).*

**Minor points:**

Title:

1. 'Oil droplets' is a broad term. Oil droplets from spilled crude oil or processed fossil fuel could be more specific.

**Response:**

*We agree that this would have been more specific, but at the same time we prefer the title to be as short as possible in accordance with the author guidelines of the journal. However, we have included the term in line 72 of the introduction that now reads:*

*“Specifically, we present an algorithm to model the accumulation of oil droplets from crude oil on individual fish eggs due to turbulent mixing and differences in rise velocities between eggs and droplets.”*

2. 'Risk assessments' is a broad term. The paper uses a simulation for fish eggs. The findings of the manuscript would apply to the environmental risk to fish eggs. In this manuscript, the mechanism of oil droplets contamination is through adhesion to the fish eggs surface. If there are oil droplets in water, then it can adhere to any other particles including sediment suspension (forming oil particle aggregates), zooplanktons and larger animals. The contamination of oil droplets could thus be even larger than that shown by the fish egg simulations.

**Response:**

*We completely agree with the reviewer. Even though the manuscript focuses on fish eggs, effects on other species are mentioned several places including L.221 and L.322 in the discussion:*

*“However, when quantifying exposure of vulnerable marine species and life stages to oil for impact assessment, typically, only the dissolved oil is considered.”*

*“Based on our findings, we strongly recommend experimental investigations of these mechanisms and oil droplet impacts on various species and stages to improve realisms in oil spill impact assessment models.”*