

Spring Phenology of the Arctic Ocean Shelf Production System

Corresponding Author: Dr Mats Huserbråten

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

Version 0:

Decision Letter:

**** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors ****

Dear Dr Huserbråten,

Please allow us to apologize again for sending this delayed decision on your manuscript titled "Spring Phenology of the Arctic Ocean Shelf Production System". It has now been seen by 2 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,

Jose Luis Iriarte Machuca, PhD
Editorial Board Member
Communications Earth & Environment

Mengjie Wang

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and also in our style and formatting guide <https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf> Communications Earth & Environment formatting guide .

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Please refer to our data policies at <http://www.nature.com/authors/policies/availability.html>.

REVIEWER COMMENTS:

Reviewer #2 (Remarks to the Author):

Spring Phenology of the Arctic Ocean Shelf Production System

General about the paper:

The current study uses a numeric biophysical model to further explore the seasonality of the key components of the Arctic marine ecosystems. It provides a closer look at the seasonal phenological co-development and interaction between the

physical processes and key biological players as ice-associated algae, a copepod, and Polar cod fish.

The paper is very well written, the methods and the support for the choice of methods is well explained. In my opinion, the paper just need a minor revision, where the authors need to better highlight the strengths and novelties of their research , and thus, the contribution of this paper to a vast literature on phenology of the Arctic ecosystems.

Below, I provide more details to help the authors address this issue, and make a few minor corrections.

Abstract

Lines 12-18. Here you mention only briefly that you have used a biophysical model and what the model showed. My question is: didn't we know it from before that ice algae growth begins in early May and intensifies in late May and so on? I understand that your model mimicked the real ecosystem so well that its results match the reality, then please, highlight it here in the Abstract. What I think you miss is to add sentences saying that the model's results matched the theory (and you don't need to describe all the phenological details right here), and then how the model results contributed something new, how they were informative given that there are quite a few papers on arctic phenology already published?

Lines 23-24. You say your finding offer insights into how climate-drive changes may disrupt the ecosystems. And this is the crucial result of your whole research. So what are these insights? Can you give an example or two, here, in the Abstract?

I hope I explained myself well, I simply think that you can improve the Abstract so that it becomes more eye-catching (many readers look only at the Abstract, you know).

Introduction

Lines 66-70. This is a passage about the physical oceanography of the Barents Sea, which I know is important for the ecosystem's biological processes as well. But I miss the connection, or a transition from the facts about oceanic currents (down to the line 66) and *C. glacialis* distribution. You mention it later in the sentence, but I think the logical flow will be better if you add something like "the oceanic water transport has a direct impact on the extent of key zooplankton species—*C. glacialis*", and then you may explain what this impact is.

Line 69. I think the verb "deflected" should be in the present tense as "deflects" to be parallel with a verb "exports".

Line 72. As far as I recall, composite adjectives are written with a hyphen, to make "ice-covered pelagic production". Otherwise, it may be misread as ice has covered the production of the Arctic ocean. I have seen the same mistake multiple times through the paper, please, check for the other occurrences of "ice covered".

Line 77." Under ice" primary production should be written as "under-ice". You can see in Google scholar that other papers use "under-ice" for the same meaning as in your paper. For instance:
<https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015JC011183>

Line 90. Shouldn't it be "individual-based model"?

Line 93." Ecologically important copepod" in place of "ecological important".

Line 94. The months are written in capital letters in English, so it should be March, not march.

Line 102. "As an example of the Arctic Ocean ..."

Material and methods

Line 133: "the -u and -v components"... You may explain what are these components, since the paper will be read also by ecologists that know little about circulation models.

Line 151: you say that "to hypothesize that spawning may be triggered ..." but then you insert a reference to Søreide et al. So, that spawning is triggered by the first sunlight is your hypothesis or the one Søreide et al. has proposed? Please, clarify.

Line 164: YOY Polar cod in BESS. I have not seen the explanation of what is YOY and BESS earlier in the paper, would you add an explanation here?

Line 170: a reference to Ben Laurel – should be round parentheses here?

Line 240: "stage-specific" with a hyphen. Check also the other occasions of this phrase.

Lines 245-248. Here you explain the results of the binomial GLM. First, what was the effect of 1 degree temperature change on the odds of CV (the log of beta)? This log of beta parameter is the temperature effect, but you don't report it here. You mention the 26% decline in CV proportion but how have you arrived at that number? You may estimate the probability of CV for each given temperature using the model equation (and then, I assume, you interpret probability as proportion), but how you estimated a decline in the probability/proportion? Please, check this section and add beta parameter. Check also

that 26% decline in biomass is correct. This seems like a huge change in CV biomass for 1 degree change in temperature.

Line 291. "The pre-adult CV" not C5 since you used CV throughout the text.

Results

Line 334: "When growth rate accelerated noticeably". Say rather by how much, in units, the growth rate has accelerated.

Discussion

In my opinion, the Discussion is very well written and summarize well the work done by the authors.

Line 420: "toward the end of May". You often do not write the article "the" in the similar phrases, please, check the whole text.

I would also advise the authors to edit just a little the last passage, starting on the line 479. There you highlight the ecological results of the paper, but you say nothing about the method (the biophysical model that you have applied). You may add a phrase or a small paragraph featuring the model you have used in the paper. Based on the performance of this comprehensive model, what would you conclude about this model as a research tool for marine ecologists? Should they try to develop a similar model, while adjusting and improving something? In the other words, is your model a promising research approach for marine ecology? If yes, then add this detail to your conclusions, and you will further strengthen your paper.

Reviewer #3 (Remarks to the Author):

Spring Phenology of the Arctic Ocean Shelf Production System
Mats Huserbråten^{1*}, Frode Vikebø¹

Overall evaluation

This manuscript is well written and valuable, as it addresses the ice associated production, and related development of polar cod larvae in the Arctic Barents Sea. The adult polar cod (*Boreogadus saida*) has been a key forage fish of Northeast arctic cod (*Gadus morhua*) in the past. The Barents Sea is experiencing unprecedented warming and related loss of sea ice and the decrease of many key fish stocks, including polar cod. Hence, this study is timely. I recommend publishing the model driven study in *Communications Earth & Environment*. The manuscript is accepted with minor changes.

Reviewer: Padmini Dalpadado

General comments

Some structuring of the manuscript is needed. Under the Material and method section, explanations given on the different model layers are imbalanced e.g. a couple of sentences on the 1st layer (physical drives) followed by a lengthy 2nd layer on the primary production. Furthermore, I suggest adding subheadings particularly to the lengthy section addressing "biological models", for the reader to easily follow. The following subheadings are proposed: "ice algae development; predicting *Calanus glacialis* biomass; Egg production, mortality and vertical positioning of *C. glacialis*; Polar cod egg incubation, drift and swimming capabilities of larvae"

In the introduction there should be a short paragraph on climatic changes in the marginal ice zone ecosystem and its impact on the higher trophic levels, including polar cod and cod. The authors should include recent references on: algal species *Nitzschia frigida* (Hegseth and von Quilfeldt (2022), the importance of ice algae for *Calanus glacialis* (Daase et al. 2013) and *C. glacialis* as key prey for polar cod (Dalpadado et al. 2024). Also see Årthun et al (2015) for transport mechanisms, likely impacting *C. glacialis*. Full references are given below.

The results and discussion section are concise and well written.

Please note that the supplementary material was NOT available for the review process. These should be submitted for the final evaluation as soon as possible.

Specific minor comments:

L11- add a sentence that open water primary production has increased while ice algae productions has decreased
<https://doi.org/10.1016/j.pocean.2020.102320>

L13- add "Arctic" before copepod

L15-17- Rephrase the sentence – using “intensifies” and “peaks”
 L50-51– Important to state that polar cod larvae and adults feed on *C. glacialis* (see my remarks under “general comments”)
 Line 84-add “phytoplankton, zooplankton, larval fish” after the three trophic levels
 L96-add “high” before Arctic
 L98-add “NI-NVI” and “CI-CV” after nauplii and copepodite respectively
 L130- IMB -Individual Based Models
 L154-156- Atlantic herring has a more southerly distribution than capelin and feeds mostly on *C. finmarchicus*. Young (nursery grounds) of herring are mostly restricted to the southern Barents Sea. You should address the predation pressure from capelin on *C. glacialis* more in depth with relevant references. Capelin has migrated very close to the ice-edge in recent years e.g. 2023
 L158-correct “ice-covered”
 L162- add “e.g. Northeast Atlantic cod *Gadus morhua*”
 L242- More information on the years Vardø Nord transect Data were obtained
 L243-244-add “plankton net hauls”, add “180µm mesh size”, add “copepodite” in appropriate places
 L244- was used as “a” response
 L354-*C. glacialis* in italics
 L355-add “E”, “NI-NII”, “CV” after egg, nauplii and copepodite respectively
 L413-add “YOY” after young of the year
 L45-460- though timing and displacement of *C. glacialis* are discussed in detail not much is mentioned about the decrease in *C. glacialis* nor the polar cod due to decrease in ice except the GAM model results discussed in 245-252. These results should be highlighted in the abstract.

Other minor comments – correct throughout the MS

Change “Polar cod” to “polar cod”

Spell out all abbreviations used in the article

Introduce the nauplii (NI-NVI) and copepodite (CI-CVI) stages at the beginning

Make clear the layers used in the model are clearly presented

References:

Hegseth, E.N. and von Quillfeldt, C., 2022. The sub-ice algal communities of the Barents Sea pack ice: Temporal and spatial distribution of biomass and species. *Journal of Marine Science and Engineering*, 10(2), p.164. <https://doi.org/10.3390/jmse10020164>

Daase, M., Falk-Petersen, S., Varpe, Ø., Darnis, G., Søreide, J.E., Wold, A., Leu, E., Berge, J., Philippe, B. and Fortier, L., 2013. Timing of reproductive events in the marine copepod *Calanus glacialis*: a pan-Arctic perspective. *Canadian journal of fisheries and aquatic sciences*, 70(6), pp.871-884. <https://doi.org/10.1139/cjfas-2012-0401>

Dalpadado, P., Prokopchuk, I.P., Bogstad, B., Skaret, G., Ingvaldsen, R.B., Dolgov, A.V., Boyko, A.S., Rey, A., Ono, K., Bagøien, E. and Huse, G., 2024. Zooplankton link climate to capelin and polar cod in the Barents Sea. *Progress in Oceanography*, 226, p.103302. <https://doi.org/10.1016/j.pocean.2024.103302>

Årthun, M., Brakstad, A., Dörr, J., Johnson, H.L., Mans, C., Semper, S. and Våge, K., 2025. Atlantification drives recent strengthening of the Arctic overturning circulation. *Science Advances*, 11(28), p.eadu1794. DOI: 10.1126/sciadv.adu1794

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Version 1:

Decision Letter:

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Dear Dr Huserbråten,

Your manuscript titled "Spring Phenology of the Arctic Ocean Shelf Production System" 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 address the remaining concerns of our reviewers. At the same time we ask that you 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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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Mengjie Wang
Associate Editor, Communications Earth & Environment
Consulting Editor, Communications Sustainability
Bluesky: @commsearth.nature.com; @commssustain.nature.com

José Luis Iriarte Machuca, PhD
Editorial Board Member
Communications Earth & Environment

REVIEWERS' COMMENTS:

Reviewer #2 (Remarks to the Author):

The manuscript was already very well written before the first review, and now, small flaws were corrected. Also, the Abstract is much stronger now and highlights the strengths of this study.

I think that the authors of the paper have done a great job revising the manuscript, and the manuscript can be accepted without further corrections.

Reviewer #3 (Remarks to the Author):

Spring Phenology of the Arctic Ocean Shelf Production System
Mats Huserbråten^{1*}, Frode Vikebø¹

Reviewer: Padmini Dalpadado

Evaluation

The authors have addressed all comments well, in a systematic manner. The ability of their model to recreate observed production and recruitment patterns including climate driven changes are clearly highlighted in the revised abstract. Recommend the manuscript to be accepted for publication in Communications Earth & Environment.

The below given minor edits should be in place before publishing. The line numbers refer to the version with revisions.

Line 8: Propose to change to "The shelf areas of the Arctic Ocean"

Line 11: Add "," after knowledge gaps

Line 15: Change to "northern"

Line 305: Change to "Vardø Nord"

Line 318-322: "Propose shortening: "." after (AME); Start the next with "The calculated values provide..."

Line 472: State that zooplankton samples are from the Vardø Nord

Line 648: Change to "ability" and "recreate"

Figure 3B: Names of places - increase font size, change colour

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REVIEWER COMMENTS:

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Spring Phenology of the Arctic Ocean Shelf Production System

General about the paper:

The current study uses a numeric biophysical model to further explore the seasonality of the key components of the Arctic marine ecosystems. It provides a closer look at the seasonal phenological co-development and interaction between the physical processes and key biological players as ice-associated algae, a copepod, and Polar cod fish.

The paper is very well written, the methods and the support for the choice of methods is well explained. In my opinion, the paper just need a minor revision, where the authors need to better highlight the strengths and novelties of their research , and thus, the contribution of this paper to a vast literature on phenology of the Arctic ecosystems.

Below, I provide more details to help the authors address this issue, and make a few minor corrections.

REPLY TO GENERAL REMARKS: We thank Reviewer #2 for their positive feedback and constructive suggestions, which have helped strengthen the manuscript greatly. We agree that highlighting the novelties and contributions of our biophysical model is important, and we have revised the Abstract, Introduction, and Discussion accordingly. Below, we address each comment point-by-point.

Abstract

Lines 12-18. Here you mention only briefly that you have used a biophysical model and what the model showed. My question is: didn't we know it from before that ice algae growth begins in early May and intensifies in late May and so on? I understand that your model mimicked the real ecosystem so well that its results match the reality, then please, highlight it here in the Abstract. What I think you miss is to add sentences saying that the model's results matched the theory (and you don't need to describe all the phenological details right here), and then how the model results contributed something new, how they were informative given that there are quite a few papers on arctic phenology already published?

Lines 23-24. You say your finding offer insights into how climate-drive changes may disrupt the ecosystems. And this is the crucial result of your whole research. So what are these insights? Can you give an example or two, here, in the Abstract?

I hope I explained myself well, I simply think that you can improve the Abstract so

that it becomes more eye-catching (many readers look only at the Abstract, you know).

REPLY TO CRITIQUE OF ABSTRACT (COMBINED REPLY TO BOTH

COMMENTS): Due to the combined need to substantially reduce word count and addressing the valid criticism of the previous draft, the abstract has now been completely re-written. Hopefully this revision has addressed Reviewer #2's concerns with regards to generalization of results (rather than listing of specifics), better highlight potentially new knowledge generated (rather than "listing" of results), and briefly explaining impact via examples.

Introduction

Lines 66-70. This is a passage about the physical oceanography of the Barents Sea, which I know is important for the ecosystem's biological processes as well. But I miss the connection, or a transition from the facts about oceanic currents (down to the line 66) and *C. glacialis* distribution. You mention it later in the sentence, but I think the logical flow will be better if you add something like "the oceanic water transport has a direct impact on the extent of key zooplankton species—*C. galcialis*", and then you may explain what this impact is.

REPLY: Duly noted, this section has been revised now tying circulation patterns to *C. glacialis* distributions, see lines 67-69.

Line 69. I think the verb "deflected" should be in the present tense as "deflects" to be parallel with a verb "exports".

REPLY: The verb has been changed to present tense, see line 71

Line 72. As far as I recall, composite adjectives are written with a hyphen, to make "ice-covered pelagic production". Otherwise, it may be misread as ice has covered the production of the Arctic ocean. I have seen the same mistake multiple times through the paper, please, check for the other occurrences of "ice covered".

REPLY: Thanks for the comment, all the composite adjectives should now be written with a hyphen.

Line 77. "Under ice" primary production should be written as "under-ice". You can see in Google scholar that other papers use "under-ice" for the same meaning as in your paper. For instance:

<https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015JC011183>

REPLY: All apparent composite adjectives should now be written with a hyphen

Line 90. Shouldn't it be "individual-based model"?

REPLY: Yes, this has now been changed, see line 103

Line 93. "Ecologically important copepod" in place of "ecological important".

REPLY: Yes, this has now been changed, see line 106

Line 94. The months are written in capital letters in English, so it should be March, not march.

REPLY: Yes, this has now been changed, see line 107

Line 102. "As an example of the Arctic Ocean ..."

REPLY: "... as an example ..." has been added, see line 122

Material and methods

Line 133: "the -u and -v components"... You may explain what are these components, since the paper will be read also by ecologists that know little about circulation models.

REPLY: Thanks for the comment, an explanation has now been added, see line 159

Line 151: you say that "to hypothesize that spawning may be triggered ..." but then you insert a reference to Søreide et al. So, that spawning is triggered by the first sunlight is your hypothesis or the one Søreide et al. has proposed? Please, clarify.

REPLY: It was indeed we who explicitly hypothesised that the appearance of light ($>0 \text{ Wm}^{-2}$) under the ice might trigger spawning. Thus the reference to Søreide et al. 2010 has been moved to the previous sentence reviewing timing of spawning in *C. glacialis*. Also, thanks to input from Reviewer #3, we now have backed our spawning hypothesis with a reference (Daase et al. 2013) that also discuss the importance of first light (albeit indirectly through the start of ice algae growth, as we understand the text) see line 190-194.

Line 164: YOY Polar cod in BESS. I have not seen the explanation of what is YOY and BESS earlier in the paper, would you add an explanation here?

REPLY: The Barents Sea Ecosystem Survey (BESS) is already explained in line 176—but the concept Young Of the Year, i.e., juveniles younger than one year is now explained here, see line 207.

Line 170: a reference to Ben Laurel – should be round parentheses here?

REPLY: Yes, see lines 226-227

Line 240: “stage-specific” with a hyphen. Check also the other occasions of this phrase.

REPLY: Yes, “stage specific” has now been replaced with “stage-specific” throughout the manuscript.

Lines 245-248. Here you explain the results of the binomial GLM. First, what was the effect of 1 degree temperature change on the odds of CV (the log of beta)? This log of beta parameter is the temperature effect, but you don't report it here.

You mention the 26% decline in CV proportion but how have you arrived at that number? You may estimate the probability of CV for each given temperature using the model equation (and then, I assume, you interpret probability as proportion), but how you estimated a decline in the probability/proportion? Please, check this section and add beta parameter. Check also that 26% decline in biomass is correct. This seems like a huge change in CV biomass for 1 degree change in temperature.

REPLY: Thank you for your careful review of the binomial GLM results and for requesting more details on the temperature effect on the proportion of pre-adult CV *C. glacialis* in samples and how we derived the 26% decline. The number stemmed from an approximation of the *maximum* marginal effect ($\beta * p * (1-p)$), or $-1.025 \times 0.25 \approx -0.256$, evaluated at a baseline probability $p = 0.5$ (midpoint) where the logistic slope is steepest. For context we have now also included the the average marginal effect (AME), which provides an interpretable average change in the predicted proportion per 1°C increase in temperature across all observations. This was computed with the *marginaleffects* package in R (function `avg_slopes()`), yielding an AME of -0.062 (SE = 0.012, $z = -5.14$, $p < 0.001$; 95% CI: -0.085 to -0.038). In other words, for each 1°C increase in temperature, the proportion of pre-adult CV stages declines by approximately 6.2 percentage points, on average.

For completeness, we also report:

- The temperature coefficient ($\beta = -1.025$, SE = 0.252, $z = -4.07$, $p < 0.001$), representing the change in log-odds per 1°C.
- The odds ratio: $\exp(\beta) \approx 0.36$, meaning the odds of observing a CV stage are reduced to about 36% of their prior value for each 1°C increase.

Considering that Reviewer #3 wanted these results front and center as examples of temperature effect on Arctic zooplankton distribution in the abstract (see Reviewer #3 comments on L450-460 below), the added model diagnostics/results/parameters from the GLM now hopefully gives the reader a fuller picture of the model and underlying data; hopefully Reviewer #2 see the added value too.

Moreover, with respect to the comment on the perceived high maximum marginal effect of 26% evaluated at the mid-point of the logistical curve (as opposed to the

6.2% average along the whole gradient) this might be a direct artifact of the Polar front traversing the Barents Sea. This front represent a sharp transition zone from “Atlantic” water masses to the south, and “Arctic” water masses to the north and east, allowing typical habitat to *C. glacialis* to the north, but generally unfavorable habitat to the south.

Line 291. “The pre-adult CV” not C5 since you used CV throughout the text.

REPLY: C5 now changed with CV, see line 385

Results

Line 334: “When growth rate accelerated noticeably”. Say rather by how much, in units, the growth rate has accelerated.

REPLY: We now have have added specific numbers: “when growth rate accelerated noticeably beyond ca. 0.3 divisions per day”, see line 437

Discussion

In my opinion, the Discussion is very well written and summarize well the work done by the authors.

Line 420: “toward the end of May”. You often do not write the article “the” in the similar phrases, please, check the whole text.

REPLY: Agree, article “the” was removed from “toward the end of May”—at the same time it is hard to evaluate the extent of the use of “the” in similar context elsewhere in the manuscript, please be specific.

I would also advise the authors to edit just a little the last passage, starting on the line 479. There you highlight the ecological results of the paper, but you say nothing about the method (the biophysical model that you have applied).

You may add a phrase or a small paragraph featuring the model you have used in the paper. Based on the performance of this comprehensive model, what would you conclude about this model as a research tool for marine ecologists? Should they try to develop a similar model, while adjusting and improving something? In the other words, is your model a promising research approach for marine ecology? If yes, then add this detail to your conclusions, and you will further strengthen your paper.

REPLY: Thank you for this thoughtful comment—a short paragraph summarizing the performance, future promise, and further improvements that can be made to our biophysical model, see lines 637-645.

Reviewer #3 (Remarks to the Author):

Spring Phenology of the Arctic Ocean Shelf Production System
Mats Huserbråten^{1*}, Frode Vikebø¹

Overall evaluation

This manuscript is well written and valuable, as it addresses the ice associated production, and related development of polar cod larvae in the Arctic Barents Sea. The adult polar cod (*Boreogadus saida*) has been a key forage fish of Northeast arctic cod (*Gadus morhua*) in the past. The Barents Sea is experiencing unprecedented warming and related loss of sea ice and the decrease of many key fish stocks, including polar cod. Hence, this study is timely. I recommend publishing the model driven study in Communications Earth & Environment. The manuscript is accepted with minor changes.

Reviewer: Padmini Dalpadado

General comments

Some structuring of the manuscript is needed. Under the Material and method section, explanations given on the different model layers are imbalanced e.g. a couple of sentences on the 1st layer (physical drives) followed by a lengthy 2nd layer on the primary production. Furthermore, I suggest adding subheadings particularly to the lengthy section addressing “biological models”, for the reader to easily follow. The following subheadings are proposed: “ice algae development; predicting *Calanus glacialis* biomass; Egg production, mortality and vertical positioning of *C. glacialis*; Polar cod egg incubation, drift and swimming capabilities of larvae”

In the introduction there should be a short paragraph on climatic changes in the marginal ice zone ecosystem and its impact on the higher trophic levels, including polar cod and cod. The authors should include recent references on: algal species *Nitzschia frigida* (Hegseth and von Quilfeldt (2022)), the importance of ice algae for *Calanus glacialis* (Daase et al. 2013) and *C. glacialis* as key prey for polar cod (Dalpadado et al. 2024). Also see Årthun et al (2015) for transport mechanisms, likely impacting *C. glacialis*. Full references are given below.

The results and discussion section are concise and well written.

Please note that the supplementary material was NOT available for the review process. These should be submitted for the final evaluation as soon as possible.

REPLY TO GENERAL REMARKS: Thanks for the great comments made by Dr. Dalpadado, primarily focusing on improving the structure of the methods and providing more referenced information about the study system/species in the introduction. As recommended we now have: (1) broken up the “Model outline and

rationale” section into several logical paragraphs, each describing the four layers of the model (see lines 147-230), as well as added subheadings in M&M where suggested (although with slightly different wording, see lines 287, 298, 344, 364, and 393); and (2) added the recommended section of a small review on ecological consequences of contemporary warming with references in introduction (see lines 73-76) and other relevant sections describing ice algae (see line 106) and *C. glacialis* (see line 114). With regards to Årthun et al. (2025) describing the recent increase in overturning circulation along the northern Barents Sea shelf break, the ecological effect of this is yet to be seen—at least we see no further mechanistic effects than increased flow along the shelf break, potentially increasing the export of biomass along the shelf; an effect that (at least theoretically) should already be captured by our ocean model and drift models (e.g., as presented in Figure 3B, although this phenomena have yet to be cross-checked if present in our regional ROMS setup covering the same time period).

Specific minor comments:

L11- add a sentence that open water primary production has increased while ice algae productions has decreased <https://doi.org/10.1016/j.pocean.2020.102320>

L13- add “Arctic” before copepod

L15-17- Rephrase the sentence – using “intensifies” and “peaks”

REPLY to remarks on L11-17: These remarks were made on the previous version of the abstract and are no longer valid as the Abstract has been rewritten completely. Yet still addressing core intent of comment on L11, Dalpadado et al. 2020 (ref linked to supplied DOI) has been added to Introduction where we review the climate effects on northern Barents Sea ecosystem (line 76) and a sentence pointing to the change in productivity patterns has been added to revised Abstract (lines 20-21).

L50-51– Important to state that polar cod larvae and adults feed on *C. glacialis* (see my remarks under “general comments”)

REPLY: Agree, a reference to Dalpadado et al. (2024) that describe the feeding of juvenile and adult polar cod on *C. glacialis* has now been included in the Introduction, see lines 118-119.

Line 84-add “phytoplankton, zooplankton, larval fish” after the three trophic levels

REPLY: These three words have been added to the sentence, see line 96.

L96-add “high” before Arctic

REPLY: Done, see line 115.

L98-add "NI-NVI" and "CI-CV" after nauplii and copepodite respectively

REPLY: Done, see line 117.

L130- IMB -Individual Based Models

REPLY: The acronym "IBMs" is already established in introduction, see line 103.

L154-156- Atlantic herring has a more southerly distribution than capelin and feeds mostly on *C. finmarchicus*. Young (nursery grounds) of herring are mostly restricted to the southern Barents Sea. You should address the predation pressure from capelin on *C. glacialis* more in depth with relevant references. Capelin has migrated very close to the ice-edge in recent years e.g. 2023

REPLY: Agree, we have now removed herring as potential major predator to *C. glacialis* in the northern Barents Sea and instead mentioned older polar cod as a potential predator (in addition to capelin) and added a reference to Dalpadado et al. (2024) describing the feeding habits of the juvenile and adult capelin and polar cod (lines 194-196).

L158-correct "ice-covered"

REPLY: Corrected throughout the MS

L162- add "e.g. Northeast Atlantic cod *Gadus morhua*"

REPLY: Not clear what the reviewer means by this, adding the Northeast Atlantic cod *Gadus morhua* as an example of the vertical behaviour of Polar cod larvae? While there are similarities, there is enough empirical data published in the literature on polar/arctic cod egg and larval behavior to construct a coherent individual-based model (see lines 393-429)

L242- More information on the years Vardø Nord transect Data were obtained

REPLY: Collection period (2000-2022) has been added, see lines 302-303.

L243-244-add "plankton net hauls", add "180µm mesh size", add "copepodite" in appropriate places

REPLY: These words has been added where appropriate, see lines 307-308.

L244- was used as “a” response

REPLY: “a” has been added, see line 308.

L354-C. glacialis in italics

REPLY: Edited, see line 313.

L355-add “E”, “NI-NII”, “CV” after egg, nauplii and copepodite respectively

REPLY: Added, see line XX

L413-add “YOY” after young of the year

REPLY: Added “YOY”, see line 536.

L450-460- though timing and displacement of C. glacialis are discussed in detail not much is mentioned about the decrease in C. glacialis nor the polar cod due to decrease in ice except the GAM model results discussed in 245-252. These results should be highlighted in the abstract.

REPLY: Agree—a sentence and reference to the decrease of polar cod in the Arctic Ocean/Barents Sea has now been added in the relevant part of the discussion (see lines 587-588). Moreover, in combination with Reviewer #2’s request of more concrete examples of “how climate-drive changes may disrupt the ecosystems” in Abstract and the results from the GLM having been more thoroughly presented in M&M and in Results, we feel that some highlights from the GLM can justifiably be added to the Abstract (see lines 18-21).

Other minor comments – correct throughout the MS

Change “Polar cod” to “polar cod”

Spell out all abbreviations used in the article

Introduce the nauplii (NI-NVI) and copepodite (CI-CVI) stages at the beginning

Make clear the layers used in the model are clearly presented

REPLY: Addressing other minor comments that need to be corrected throughout:

“Polar cod” is changed with “polar cod” throughout.

All abbreviations used should be spelled out now.

Nauplii (NI-NVI) and copepodite (CI-CVI) stages are introduced in the introduction (see line 117).

Based on revisions to the structure of the methods the four layers that the biophysical model consists of should now be more clearly presented.

References:

Hegseth, E.N. and von Quillfeldt, C., 2022. The sub-ice algal communities of the Barents Sea pack ice: Temporal and spatial distribution of biomass and species. *Journal of Marine Science and Engineering*, 10(2), p.164.

<https://doi.org/10.3390/jmse10020164>

Daase, M., Falk-Petersen, S., Varpe, Ø., Darnis, G., Søreide, J.E., Wold, A., Leu, E., Berge, J., Philippe, B. and Fortier, L., 2013. Timing of reproductive events in the marine copepod *Calanus glacialis*: a pan-Arctic perspective. *Canadian journal of fisheries and aquatic sciences*, 70(6), pp.871-884. <https://doi.org/10.1139/cjfas-2012-0401>

Dalpadado, P., Prokopchuk, I.P., Bogstad, B., Skaret, G., Ingvaldsen, R.B., Dolgov, A.V., Boyko, A.S., Rey, A., Ono, K., Bagøien, E. and Huse, G., 2024. Zooplankton link climate to capelin and polar cod in the Barents Sea. *Progress in Oceanography*, 226, p.103302. <https://doi.org/10.1016/j.pocean.2024.103302>

Årthun, M., Brakstad, A., Dörr, J., Johnson, H.L., Mans, C., Semper, S. and Våge, K., 2025. Atlantification drives recent strengthening of the Arctic overturning circulation. *Science Advances*, 11(28), p.eadu1794. DOI: 10.1126/sciadv.adu1794