nature portfolio

Peer Review File

Cumulative hydrodynamic impacts of offshore wind farms on North Sea currents and surface temperatures

Corresponding Author: Dr Nils Christiansen

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

Version 0:

Decision Letter:

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Dear Dr Christiansen,

Your manuscript titled "Cumulative hydrodynamic impacts of offshore wind and tidal wakes" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised substantial concerns that must be addressed. In light of these comments, extensive revisions will be required before we can further consider the manuscript for publication. We would, however, be interested in considering a revised version that fully addresses these serious concerns.

Specifically, we require the following thresholds be met:
-demonstrate the cumulative hydrodynamic impacts of offshore wind and tidal wakes
-perform model calibration and validation, particularly for tidal currents.

We hope you will find the reviewers' comments useful as you decide how to proceed. If additional work allows you to either incorporate or refute these criticisms, we will be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file or provide a list of the changes to the manuscript with your responses to the reviewers.

When resubmitting, please provide a point-by-point response to the reviewers' comments. Please submit your 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.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will 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.

We are committed to providing a fair and constructive peer-review process. Please do not 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 reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank

you for the opportunity to review your work.

Best regards,

Olusegun Dada, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0001-8020-3323

Alice Drinkwater, PhD
Associate Editor
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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This manuscript presents a modeling study on the cumulative hydrodynamic impacts of offshore wind (OSW) and tidal wakes. The topic is highly relevant to the ocean energy and coastal science community and aligns well with the scope of Communications Earth & Environment. The study's objectives, research approach, and discussion of results are generally clear. However, there are several concerns on the methodology and the numerical experiments that must be addressed before the manuscript can be considered for publication.
1. The current title does not clearly convey that the study investigates cumulative impacts on ocean physics from offshore wind farm development, such as changes in tidal currents and sea surface temperature (SST). Please revise the title to reflect this focus.
2. SCHISM was used to simulate both natural ocean conditions (control scenario) and wind farm scenarios. However, there is no validation of tidal elevations and currents, which is essential. Please include tidal current validation. The SST and SSS validation was performed at only one station (FINO1); are additional datasets available? Furthermore, please consider validating temperature and salinity profiles, as stratification and mixing strongly influence turbulence and tidal wake dynamics.
3. Has the SCHISM implementation and parameterization of wind farm monopiles been validated? Given the potential uncertainty in the subgrid-scale parameterization for monopile foundations, this aspect could substantially affect predictions of current and SST changes.
4. Have changes in sea surface salinity (SSS) been evaluated? Salinity variations can strongly influence coastal circulation, particularly through baroclinic effects.
5. Please provide a table summarizing the number of wind turbines, as well as the key parameterizations (e.g., hub height, rotor diameter, power coefficient) used for each wind farm scenario.
6. It is not clear what wind product is used to represent wind field for the 2050 OWF scenario. The authors should address the uncertainty of future climate (wind) projection that may limit the credibility of the findings of the study.

Reviewer #2 (Remarks to the Author):

Reviewing of the manuscript 'Cumulative hydrodynamic impacts of offshore wind and tidal wakes' by N. Christiansen et al. submitted to Communications Earth & Environmental (Manuscript ID: COMMSENV-25-3197-T).

This work investigates the effects of wind farm constructions on hydrodynamics in the North Sea, e.g., due to the wind speed reduction and tidal wakes. The method is numerical simulations, and the finding is that the basin-scale physical footprint of offshore wind farm has unignorable effects on the surface temperature, current velocity, turbulent kinematical energy (TKE), and mixing. I have a couple of questions, comments, and suggestions to this work, which is listed as follows.

1. Title. The current one is not accurately consistent with the contents of this manuscript. It is suggested to use 'Cumulative impacts of offshore wind farms on the hydrodynamics on the central and southern North Sea', or other proper one.
2. This is the model applications to resolve or give guidance for the practical engineering construction. The work is regionally specific or and lacks a little bit of scientific knowledge and novelty. For example, how this work contributes to the general understanding of other works in similar regions. This work maybe more proper to be submitted to the journal like Coastal Engineering or Ocean Engineering.
3. The conclusion is understandable and basic in physical oceanography area. The reviewer considers that this work needs a more in-depth analysis and discussion to justify and better separate the wind-induced effects (e.g., air-sea momentum flux, surface wind stress, wind-induced mixing, wind-induced Ekman transport etc.) and tidal effects (e.g., tidal strain, tidal mixing, tidal transport etc.) introduced by the wind farms.
4. Given that this work is mainly based on the simulated results. The reviewer suggests that model calibration and validation should be carried out. For example, the modelled results should be compared with observations for the scenarios with and without the wind farms for the hydrodynamic variables, e.g., current velocity, tidal currents and components, water temperature etc.
5. Line 58: 'Both offshore wind and tidal wakes have been shown to generate large-scale impacts on ocean currents, vertical mixing, and density stratification'. This statement should be clarified, since the wind generated scale is large (e.g., 100 km) while the tide-induced scale maybe small (e.g., several hundred meters or 1 km). Please double check it.
6. Line 71: 'Our primary objective is to understand how wind and tidal wakes interact to influence regional hydrodynamics and to assess the cumulative long-term changes resulting from large-scale offshore wind energy expansion'. The grammar of this sentence seems not correct, and please rewrite this sentence to improve the English.
7. Model experiment design needs to be described or added. How are the scenarios of only wind speed reduction effect, only tidal wake effects, and their combined effects calculated or designed?
8. Line 164-166: 'Notably …… wind wakes insignificant', maybe changed to 'Notably, …… tide wakes insignificant'. Please double check it.
9. The geographic names (e.g., Dutch and Belgian coast, German Bight) that are mentioned in the texts better be marked in the figure correspondingly.
10. Line 346: '…… the strong induced mixing', it seems that the subject is lacking between 'the strong' and 'induced mixing'.
11. The authors may need to add the descriptions that how the model resolve the wind farms and monopile in the model domain (e.g., grid resolution and wind farm boundary lines).
12. Year 2023 scenario is already passed, is it appropriate that the model design for the 2023 simulation with wind farms as a future scenario? Maybe treated as realistic scenario better.

Reviewer #3 (Remarks to the Author):

This is a very well-written manuscript that documents cutting-edge research on modeling the cumulative environmental impact of offshore wind farm development using a one-way coupled atmospheric-ocean circulation modeling approach. I find the results and conclusions to be generally very convincing. The modeling approach has been clearly presented and validated in earlier publications, and I do not have any major concerns about them.

Minor comments:
1. As the authors state in Lines 257-260, the coarse resolution of the model grid and the method used to simulate the wind turbine foundations do not allow for a proper simulation of between-turbine effects. These near-field effects, such as sediment scouring due to increased shear stress between piles, could be important for turbine foundation siting.
2. The 700-meter grid resolution appears to be quite coarse. I wonder if this resolution can be further refined to tens of meters, given the flexibility of the unstructured grid and the computational efficiency of SCHISM. This would allow finer-scale changes within the wind turbine farm to be better captured using the same modeling approach.
3. SCHISM model open boundary: It appears to me that the model's open boundary is too close to the wind farms (e.g., Figures 3, 4, and 5 and the Supplementary Figure 2). As a result, the model results may not fully reflect (mostly under-predict) the actual effects of the wind farms for the 2050 Scenario.

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Version 1:

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 Christiansen,

Your manuscript titled "Cumulative hydrodynamic impacts of offshore wind farm wakes on North Sea currents and surface temperature" 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, which pertain to deepening the discussion of wind/tide processes and their interactions. 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,

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

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I appreciate the authors' time and effort in revising the manuscript to address my comments and those of the other reviewers. I am satisfied with the revision, particularly the additional model validations. In its current form, the manuscript is suitable for publication in Communications Earth & Environment. I have one minor clarification question for the authors to consider.

1) While the manuscript primarily refers to tidal currents, it also mentions ocean currents. Typically, "ocean current" implies non-tidal flow. Because salinity and temperature are included in the model, density-driven circulation is also represented. How are non-tidal and tidal currents distinguished in the analysis? If "ocean current" is intended to refer to the combined tidal and non-tidal components, please clarify this in the manuscript. Greater clarity and consistency in terminology would improve readability.

Reviewer #2 (Remarks to the Author):

Reviewing of the revised manuscript 'Cumulative hydrodynamic impacts of offshore wind and tidal wakes' by N. Christiansen et al. submitted to Communications Earth & Environmental (Manuscript ID: COMMSENV-25-3197A). The authors have incorporated some of my comments and the manuscript has been improved. However, there are still a couple of issues not clear. What is the novelty of this work? This is a manuscript for scientific publication instead of environment assessment or coastal engineering applications. Therefore, the scientific novelty and driving mechanisms should be significantly improved, e.g., the wind-induced individual processes, tide-induced individual processes, as mentioned in the last round, and their interactions. The model validation should add more observations and stations, while the current work still needs more work. The Copernicus reanalysis data is not observation, the SSH data range is short, and tidal (current) comparison between simulations and observations are lacking. BTW, could you double check again whether the geographic names suggested by the reviewer are included in the updated version of the figures? Instead of the let the reviewer to look for the response to specific comment in sections 3.2 and 3.3, the authors better specify it in the response letter.

Reviewer #3 (Remarks to the Author):

I want to thank the authors for including my comments and recommendations in the revision. I don't have any further comments.

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Reviewer #1

Reviewers comments in **black**
Point-by-point response in **red**

This manuscript presents a modeling study on the cumulative hydrodynamic impacts of offshore wind (OSW) and tidal wakes. The topic is highly relevant to the ocean energy and coastal science community and aligns well with the scope of Communications Earth & Environment. The study's objectives, research approach, and discussion of results are generally clear. However, there are several concerns on the methodology and the numerical experiments that must be addressed before the manuscript can be considered for publication.

Thank you very much for your helpful comments and review! We tried to incorporate your feedback into our manuscript. We improved the description and presentation of the methodology and the numerical model. Also, as requested by the other reviewers, we added more in-depth analysis to the process understanding. Please find our point-by-point response below.

1. The current title does not clearly convey that the study investigates cumulative impacts on ocean physics from offshore wind farm development, such as changes in tidal currents and sea surface temperature (SST). Please revise the title to reflect this focus.

Your totally right. We revised the title to be more specific and reflect the focus of the study as well as the study area.

2. SCHISM was used to simulate both natural ocean conditions (control scenario) and wind farm scenarios. However, there is no validation of tidal elevations and currents, which is essential. Please include tidal current validation. The SST and SSS validation was performed at only one station (FINO1); are additional datasets available? Furthermore, please consider validating temperature and salinity profiles, as stratification and mixing strongly influence turbulence and tidal wake dynamics.

We have expanded the model validation. A new paragraph on the model performance was added to the methods section, and more validation was provided in Supplementary Figure 3. In the new version, we show time series for tidal elevations, SST, and SSS at two long-term monitoring stations. To show model performance in terms of stratification and vertical temperature and salinity profiles, we added vertical transects across the stratified North Sea areas, comparing our model with the validated Copernicus Reanalysis product that is used as boundary forcing. Given, that the model setup was also validated in a previous publication (Christiansen et al., 2022), we think that the model is now sufficiently validated to be used for the impact analysis.

3. Has the SCHISM implementation and parameterization of wind farm monopiles been validated? Given the potential uncertainty in the subgrid-scale parameterization for monopile foundations, this aspect could substantially affect predictions of current and SST changes.
Yes, all parameterizations used here are validated. Performance of the monopile parameterization is discussed and validated in detail in Christiansen et al. (2023). Of course, the parameterizations have limitations, which are discussed in the publications. Additionally, we added a new subsection to the Results & Discussion, where we address the uncertainties of our model approach and potential implications. In general, the subgrid-scale parameterization does not allow for representation of processes in-between turbines (which is mainly due to the coarse resolution) and assumes fixed drag coefficients. However, it performs well and is in agreement with observations when it comes to

the impact on mixing/stratification or blocking of currents at the wind farm scale (see Christiansen et al., 2023).

4. Have changes in sea surface salinity (SSS) been evaluated? Salinity variations can strongly influence coastal circulation, particularly through baroclinic effects.
Yes, we checked SSS and found a similar pattern to SST. We added the long-term impact on SSS to the Supplementary Figures. In the end, however, we decided to go with SST for the main text. Showing that wind farms as a mitigation measure to climate change create similar impacts on SST as climate change itself was the more interesting storyline in our opinion. Furthermore, we found that the SST changes are more significant compared to natural variabilities. Magnitudes of SSS changes are below 0.1, which is minor compared to the spatial variability and gradients in the North Sea, which are caused by freshwater input. Moreover, the model shows better performance in reproducing the thermal stratification than the haline stratification, which makes our results on SST a bit more reliable.

5. Please provide a table summarizing the number of wind turbines, as well as the key parameterizations (e.g., hub height, rotor diameter, power coefficient) used for each wind farm scenario.
Done. Information on number of turbines and wind farms, as well as drag coefficients and diameters for monopiles are summarized in a table. Parameters such as hub height, rotor diameter, or power coefficient are not considered in the parameterizations and therefore not listed.

6. It is not clear what wind product is used to represent wind field for the 2050 OWF scenario. The authors should address the uncertainty of future climate (wind) projection that may limit the credibility of the findings of the study.
There might be a misunderstanding here. We used the same data product for the (undisturbed) wind field in all simulations. Wind wakes have been accounted by an online wind speed reductions implemented in the SCHISM model. The 2023 and 2050 scenarios refer to technical/development scenarios for wind energy, meaning we considered the respective wind farm polygons of each scenario, while the simulations remained hindcast simulations for 2008-2017. We only show the potential impact of the amount of wind farms projected for 2050. We do not provide future predictions for 2050, but process understanding under hindcast conditions.

Regarding your comment on future climate projections, multiple climate model ensembles consistently indicate that annual mean wind speeds in the North Sea are not expected to change significantly under climate change (see for example Susini et al. 2022; Hahmann et al., 2022). For that reason, and since we are not using detailed atmospheric modeling of wind wakes, where climate change could become relevant for other processes than wind, we neglected the climate change discussion here. Also, considering the wind speeds, we do not expect significant differences, given the results of the ensemble studies.

Reviewer #2

Reviewers comments in **black**
Point-by-point response in **red**

This work investigates the effects of wind farm constructions on hydrodynamics in the North Sea, e.g., due to the wind speed reduction and tidal wakes. The method is numerical simulations, and the finding is that the basin-scale physical footprint of offshore wind farm has unignorable effects on the surface temperature, current velocity, turbulent kinematical energy (TKE), and mixing. I have a couple of questions, comments, and suggestions to this work, which is listed as follows.

Thank you very much for your helpful comments and review! We tried to incorporate your feedback into our manuscript. As addressed by you and Reviewer 1, we improved the model validations and description of the methodology. Furthermore, we added more in-depth analysis, by trying to disentangle the processes leading to the identified surface warming. Please find our point-by-point response below.

1. Title. The current one is not accurately consistent with the contents of this manuscript. It is suggested to use 'Cumulative impacts of offshore wind farms on the hydrodynamics on the central and southern North Sea', or other proper one.
We agree with you. This point was also addressed by Reviewer 1. We revised the title to be more specific and reflect the focus of the study as well as the study area.

2. This is the model applications to resolve or give guidance for the practical engineering construction. The work is regionally specific or and lacks a little bit of scientific knowledge and novelty. For example, how this work contributes to the general understanding of other works in similar regions. This work maybe more proper to be submitted to the journal like Coastal Engineering or Ocean Engineering.
We disagree with that. Turbine density is an aspect that could become relevant for the construction of offshore wind farms, but this is not the main message of this study. We demonstrate here the cumulative effects of offshore wind farms, and their long-term and large-scale environmental impacts, highly relevant for marine ecosystem dynamics. While the methodologies used are not new, the results are novel and create new knowledge on the interaction between wind and tidal wakes, as well as on how North Sea dynamics might change on the long term under offshore wind production. These results can also be transferred to other regions. We added a new subsection on the contextualization of the model results to highlight key mechanisms and make them applicable to other coastal environments that are faced with offshore wind production.

3. The conclusion is understandable and basic in physical oceanography area. The reviewer considers that this work needs a more in-depth analysis and discussion to justify and better separate the wind-induced effects (e.g., air-sea momentum flux, surface wind stress, wind-induced mixing, wind-induced Ekman transport etc.) and tidal effects (e.g., tidal strain, tidal mixing, tidal transport etc.) introduced by the wind farms.
Thank you very much for this suggestion. Taking a deeper look into the processes helped us to better understand the mechanism causing the surface warming. We added more in-depth analysis and a new figure showing the role of surface heat fluxes and improving the general processes understanding, also relevant for other coastal regions. The main goal of this study, however, is to demonstrate the cumulative impacts of wind-induced and tidal-induced effects, since this had not been shown in detail for the North Sea before. Therefore, we do not address individual or separated

wind-induced and tidal-induced effects here. These have been addressed in recent literature (like effects on Ekman dynamics, influence of tides, etc.) and would go beyond the scope of this study.

4. Given that this work is mainly based on the simulated results. The reviewer suggests that model calibration and validation should be carried out. For example, the modelled results should be compared with observations for the scenarios with and without the wind farms for the hydrodynamic variables, e.g., current velocity, tidal currents and components, water temperature etc.
Model validation was also addressed by Reviewer 1. We expanded the model validation. A new paragraph on the model performance was added to the methods section, and more validation was provided in Supplementary Figure 3. This includes validation of tidal elevations, time series of SST and SSS, and validation of temperature and salinity stratification. However, we did this only for the control simulation. Comparing the wind farm simulations with the observations would not be useful. The simulation period of our study is 2008-2017. This time period is different from the construction periods of the wind farms. Most of the wind farms did not exist during these periods and thus their effects would not show up in the observations.

5. Line 58: 'Both offshore wind and tidal wakes have been shown to generate large-scale impacts on ocean currents, vertical mixing, and density stratification'. This statement should be clarified, since the wind generated scale is large (e.g., 100 km) while the tide-induced scale maybe small (e.g., several hundred meters or 1 km). Please double check it.
Checked and rephrased.

6. Line 71: 'Our primary objective is to understand how wind and tidal wakes interact to influence regional hydrodynamics and to assess the cumulative long-term changes resulting from large-scale offshore wind energy expansion'. The grammar of this sentence seems not correct, and please rewrite this sentence to improve the English.
Checked and rephrased.

7. Model experiment design needs to be described or added. How are the scenarios of only wind speed reduction effect, only tidal wake effects, and their combined effects calculated or designed?
We rephrased the model section in 3.2 & 3.3 to improve the description of model experiments.

8. Line 164-166: 'Notably ..... wind wakes insignificant', maybe changed to 'Notably, ... tide wakes insignificant'. Please double check it.
Typo corrected.

9. The geographic names (e.g., Dutch and Belgian coast, German Bight) that are mentioned in the texts better be marked in the figure correspondingly.
Names are added to all maps. More details can be found in Supplementary Figure 2.

10. Line 346: '..... the strong induced mixing', it seems that the subject is lacking between 'the strong' and 'induced mixing'.
Checked.

11. The authors may need to add the descriptions that how the model resolve the wind farms and monopile in the model domain (e.g., grid resolution and wind farm boundary lines).
We rephrased the model description in 3.2 & 3.3 to include all important information and improved the description of the model parameterizations.

12. Year 2023 scenario is already passed, is it appropriate that the model design for the 2023 simulation with wind farms as a future scenario? Maybe treated as realistic scenario better.
We separated the 2023 and 2050 scenarios into “present-day” and “future” scenario in the text.

Reviewer #3

Reviewers comments in **black**
Point-by-point response in **red**

This is a very well-written manuscript that documents cutting-edge research on modeling the cumulative environmental impact of offshore wind farm development using a one-way coupled atmospheric-ocean circulation modeling approach. I find the results and conclusions to be generally very convincing. The modeling approach has been clearly presented and validated in earlier publications, and I do not have any major concerns about them.

Thank you very much for your kind feedback! We find your comments very important and valid. Please find our point-by-point response below.

Minor comments:

1. As the authors state in Lines 257-260, the coarse resolution of the model grid and the method used to simulate the wind turbine foundations do not allow for a proper simulation of between-turbine effects. These near-field effects, such as sediment scouring due to increased shear stress between piles, could be important for turbine foundation siting.
You're totally right about that. We have added a sentence on this to the manuscript. In our study, we focus on large-scale effects from offshore wind expansion. However, we agree that there is also great need to understand local fine-scale effects, which should be addressed by future studies.

2. The 700-meter grid resolution appears to be quite coarse. I wonder if this resolution can be further refined to tens of meters, given the flexibility of the unstructured grid and the computational efficiency of SCHISM. This would allow finer-scale changes within the wind turbine farm to be better captured using the same modeling approach.
Yes, in theory it would be possible to increase the resolution and resolve fine-scale processes using the SCHISM model. However, there are a couple of arguments against it, which is why we did not do it. Most importantly, SCHISM is a hydrostatic model, meaning that equations assume that horizontal scales are always much larger than vertical scales. Increasing the resolution to tens of meters would violate this assumption, making the model equations inadequate. Therefore, the model results at these scales become unreasonable and lack non-hydrostatic processes, which are particularly important for monopile-induced mixing. Also, the refinement can cause instabilities in the high-resolution cells. Secondly, the SCHISM model does not account for advection of TKE. Hence, by refining the resolution below the expected length of tidal wakes we would underestimate the areas affected by TKE production in the wind farms. Given the numerical constraints of the SCHISM model, the finer we get in resolution, the more the model is lacking an adequate representation of the monopile-induced effects. In an earlier study, we went down to 250m resolution to test the influence of the grid size but found that the overall effects from the wind farms remained similar to a resolution of 1000 m.

3. SCHISM model open boundary: It appears to me that the model's open boundary is too close to the wind farms (e.g., Figures 3, 4, and 5 and the Supplementary Figure 2). As a result, the model results may not fully reflect (mostly under-predict) the actual effects of the wind farms for the 2050 Scenario.
This is a very important point that we overlooked. When we initiated our study, we started from the existing model setup from Christiansen et al. (2022) and decided to go for the 2023 scenario.

However, during the analysis, we decided to include the 2050 scenario as well, but didn’t adjust the model boundaries for that. You’re completely right that in that case there could be problems due to the open boundaries that should be considered when interpreting the results. “Luckily”, our analysis focuses strongly on the central parts of the model domain, which are less influenced by the boundaries. However, we will consider this in future work!

Reviewer #1

Reviewers comments in **black**
Point-by-point response in **red**

I appreciate the authors' time and effort in revising the manuscript to address my comments and those of the other reviewers. I am satisfied with the revision, particularly the additional model validations. In its current form, the manuscript is suitable for publication in Communications Earth & Environment. I have one minor clarification question for the authors to consider.

1) While the manuscript primarily refers to tidal currents, it also mentions ocean currents. Typically, "ocean current" implies non-tidal flow. Because salinity and temperature are included in the model, density-driven circulation is also represented. How are non-tidal and tidal currents distinguished in the analysis? If "ocean current" is intended to refer to the combined tidal and non-tidal components, please clarify this in the manuscript. Greater clarity and consistency in terminology would improve readability.

Yes, we used "ocean current" as a reference for combined tidal and non-tidal components. We agree that we might have used it too loosely and tried to be more specific in the updated version. Thank you very much for your suggestion.

Reviewer #2

Reviewers comments in **black**
Point-by-point response in **red**

The authors have incorporated some of my comments and the manuscript has been improved. However, there are still a couple of issues not clear. What is the novelty of this work? This is a manuscript for scientific publication instead of environment assessment or coastal engineering applications. Therefore, the scientific novelty and driving mechanisms should be significantly improved, e.g., the wind-induced individual processes, tide-induced individual processes, as mentioned in the last round, and their interactions. The model validation should add more observations and stations, while the current work still needs more work. The Copernicus reanalysis data is not observation, the SSH data range is short, and tidal (current) comparison between simulations and observations are lacking. BTW, could you double check again whether the geographic names suggested by the reviewer are included in the updated version of the figures?

Thank you very much for your comments and the important points raised. Below, we address the comments grouped into topics.

- Novelty of Work: Offshore wind farm impacts (on the North Sea) remain associated with considerable uncertainties, as this is a relatively young research field. There is limited process understanding, in particular regarding the cumulative and long-term effects. To our knowledge, this study is the first peer-reviewed publication to investigate the combined effects and interactions of wind-induced and tide-induced wakes in the North Sea. It is also the first to publish decade-long simulations to assess the long-term footprint of offshore wind farms in the North Sea. Therefore, our process-oriented analysis provides valuable new insights to the understanding of offshore wind farm effects.
Individual wind-induced and tidal-induced processes are analyzed in the first part of this study and addressed throughout the manuscript. We agree that more analysis of individual wind- and tide-related processes could offer even more insights but would go beyond the scope of a single study. Ultimately the focus of this study is on cumulative effects, not individual. Nonetheless, as also requested by the editor, we put more emphasis on the discussion of wind and tidal processes in the revised version to highlight their roles.

- Model Validation: We consider our validation strategy as appropriate and sufficient for the objectives of this study. This view is shared by the other two reviewers. The intention of this work is not to provide future predictions, but to generate process understanding. This requires a realistic representation of the dominant North Sea characteristics (e.g. seasonal stratification, tides), which are well captured by the model. Observations with the necessary spatial and temporal resolution for our model setup are not available. In this context, the Copernicus reanalysis data provides a good alternative, which is widely validated and a commonly used reference dataset. In addition, the model agrees well with measurements from two permanent observation platforms in terms of surface temperature, salinity and tidal elevations. We agree that the time window for tidal elevation comparisons is short, but we selected it to clearly resolve the tidal cycles; longer period would make it complicated to see short term variability. Importantly, the comparison is performed five years into the simulations, showing that the model can still reproduce the tidal elevations long after initialization.

- Geographical Names: We checked and geographical names are added to the figures.

Reviewer #3

Reviewers comments in **black**
Point-by-point response in **red**

I want to thank the authors for including my comments and recommendations in the revision. I don't have any further comments.