Reviewer 1.

The basic concept underpinning this analysis of the ecosystem impact of floating photovoltaic (PV) platforms is sound. However, I raise three concerns: (1) Some aspects of the presentation make the results inconclusive. (2) The analysis is not very detailed and does not prove the mechanisms proposed for the apparent effects. (3) The implementation is not unambiguously described.

To expand on these points:
(1) The vertical profile of light in the ocean is driven by the scattering and absorption of optically active constituents (algal particles and sediment) in the water, and the water itself. Strong scattering in all directions leads to a diffuse light field. Light from open water areas between the PV platforms will be scattered into the waters beneath the PV platforms. Any SCUBA diver knows that beneath a ship it is not totally dark. There is a fundamental length scale – the horizontal dimension of the PV platforms – that is omitted from any consideration here. If the PV array is comprised of relatively small units (order several tens of metres horizontal extent) then there will still be considerable light available for photosynthesis beneath them. If they are massive, of the dimension deployed in some lakes, the effect will be more substantial. To engineer a network of PV platforms in the marine environment with the probability of high sea state conditions it seems unlikely that these will be massive rigid units with little mechanical flexibility to endure large waves. I am speculating here that the platforms are likely modest in size, but that is certainly the case for the prototype units that have been described in engineering publications and press releases. The authors have wholly neglected the lateral scattering of light in this analysis and consequently the results are an extreme worst case for the decrease of the available light.

ANSWER: The 1D model takes an area-averaged approach, and cannot resolve horizontal variations such as the size of platforms and related light diffusion. With the current model, we can only account for the 'area-averaged light deficit' introduced by the platforms, i.e. the amount of light that does not enter the water column due to the presence of the platforms. Then, for real field implementations, the well mixed conditions of the water column, and the horizontal propagation of phytoplankton due to tidal currents, suggests that the total amount of light available for each phytoplankton cell is fairly resolved by the present light model (as long as the horizontal size of the power plant is of the order of several tidal excursion lengths, page 16 line 10, otherwise indeed the present approach overestimates the impact). Light attenuation is calculated in the vertical, accounting for 1) absorption by clear water, 2) coloured disolved organic matter (CDOM) 3) suspended mineral sediment, 4) chlorophyll, and 5) suspended organic matter (detritus). Hence the results should be taken as a first estimate of the potential effects. Modulation of these results by processes acting at the platform scale should be considered for further work. We acknowledge that 'shadow' is a misleading term in the current context, and have replaced this by 'area-averaged light deficit' or an equivalent term. We will also include more detail about the light extinction calculations, and add a remark on platform-scale light propagation effects to the suggestions for further work.

1.1) Changes to manuscript:
We have added 'large scale' and 'from a water-column model' to the title.
We have removed the term 'shadow' in relation to the 1D model throughout the manuscript and figures
We have included in the abstract that, for spatial homogeneity to hold, phytoplankton need to remain underneath a farm throughout several tidal cycles.
We have added a paragraph to Section 2.2, including equations, describing the light-extinction method used by the model.
We have added to the abstract that for small farms the effects are likely to be smaller.

(2) The order of sections 3.2.2 and 3.2.1 should be reversed.
ANSWER: We chose this order deliberately to present the over-all result first and subsequently delve into the components. The other reviewers do not seem to have a problem with this, so we will keep it as it is.

Changes to manuscript:
None.

In section 3.2.1 on page
10 it is claimed that sediment concentration drives decreased irradiance due to lowered eddy viscosity due to decreased surface turbulence due to the presence of the platforms (page 10, line 12). The reader is asked to accept this without being shown the eddy viscosity profiles to prove that changes originate at the surface. Or somehow it is left to the readers to deduce this themselves from inspection of Figure 5a,b which shows the effect but not the cause. In Section 3.2.2 some attempt is made to explain the dynamics, so this should come first so that the regional differences (presently in 3.2.1) can be understood. This said, I don't think the present section 3.2.2 adequately explains the dynamics. The possibility that reduced bottom stress decreases the sediment resuspension rate, and water column turbulence, is not considered. We should be shown the different vertical profiles of velocity (and hence shear that is important in the turbulence closure), the different profiles of vertical eddy viscosity (or vertical turbulent sediment flux), and the modified light profiles, not just summary results in terms of the percent change for the different scenarios. A more nuanced look at the model results is essential to justify the suggested mechanisms by which the presence of PV platforms drive the effects observed. As stated in the text these are not proven conclusively.
ANSWER: We will add these figures with accompanying text.

1.2) Changes to manuscript:
We have added the requested figures to section 3.2.1, and modified the text to accommodate this.

(3) Unclear details of the configuration:
Page 5 line 1 says the model is forced with a "time series of depth averaged velocities". But doesn't the profile of vertical shear evolve with the model physics in response to the imposed surface stress and the evolved stratification and velocity shear? Please explain more fully what is being done here. The bottom stress that suspends sediment is driven by the combined depth-average plus sheared velocity – they can't be considered separately.

ANSWER: This is the standard way to force GOTM. The vertically resolved solution of the model is the dynamic response to all these forcings, and the bottom shear stress is indeed the combined result. We will add some text to Section 2.2 to clarify this.

1.3) Changes to manuscript:
We have added the following sentences to the first paragraph of Section 2.2:
"The model uses these depth-averaged velocities to set up spatial gradients of external pressure that it uses as forcing. GOTM uses all these forcings, including bed-shear stress, to calculate the time-evolution of vertical distributions of turbulence and currents (Burchard et al., 2006). It is also possible to explicitly force GOTM with spatial gradients, e.g. to simulate salinity stratification (Simpson et al., 2002), but this was not used here."

Returning to the issue of the vertical light profile: How is this computed in ERSEM? Is it strictly 1-d vertical that ignores lateral scattering, upward scattering, or perhaps any scattering at all? Maybe that has been addressed long ago by the designers of ERSEM and my concerns in point (1) can be dismissed, but the way ERSEM handles light is not documented here and it is central to the analysis.

ANSWER: We have added a more detailed description of the calculation of the vertical light profile in ERSEM to Section 2.2- essentially it's an extinction-coefficient based exponential profile, where the extinction coefficient is *composed of a number of contributing factors (absorption by clear water, CDOM, suspended sediment, chlorophyll and detritus).*

1.4) Changes to manuscript:
Added a paragraph to Section 2.2.

In the Appendix, equation (2) implicitly assumes there is no change in the atmospheric marine boundary layer over the PV platforms – that there is just a gap in the momentum transfer from air to sea. If the platforms are small this might be reasonable, but what if they are massive? Again, the dimension of the platforms is relevant.

ANSWER: This is a valid comment and was suggested for further work (page 17 line 4, previous version). This cannot be addressed with the current model, and that requires substantial additional work involving the physics of atmospheric flow around obstacles, including details of the obstacle geometry. We would expect such processes to modulate the current results, and now mention that this is ignored, and explain better this point to the recommendations for further work.

1.5) Changes to manuscript:
We have added the assumption to the text with eq. 2, and explained better this point to the list of further work in the discussion.

Similarly, equation (3) is an equilibrium assumption. In reality a modified boundary layer under the platforms will evolve from the leading edge. If the platforms are large the boundary layer might be fully developed for the majority of the distance, but what if they are small? In that case fully developed boundary layers are unlikely and this simple modified drag parameterization may be poor.

ANSWER: Similarly here, this is a valid comment, but we would regard this as a subject for further work, and have added it to the recommendations.

1.6) Changes to manuscript:
Added the assumption to the text with Eq 3, and added the point to the list of further work in the discussion.

Summary comment:
The agreement between model and observations (Figure 2) is spectacular, so I am confident the fundamental model is sound. The major flaw is in the simplicity of the optical model.

ANSWER: Thank you for the positive comments.

Reviewer 2

The authors present a study of potential impacts of solar panels on primary production (PP) in the North Sea. They analyse the different factors and their individual and combined effects on PP in three different North Sea regions using a new parameterisation of floating panels in the 1D coupled physical-biogeochemical model GOTM-ERSEM-BFM. They find that up to a surface coverage fraction of 20% impacts on PP are relatively small, while PP drops significantly for higher coverage. According to their study, reduced light availability (due to surface coverage) is the main factor for PP reduction, while changes in mixing (due to wind shielding and platform friction) are comparably small. They conclude that the 1D model results likely overestimate the actual impacts due to various limitations of this type of model, and they recommend an implementation of the new solar panel implementation to a 3D model to achieve a better/more realistic assessment of likely impacts.

The general purpose and objective of the study is of high relevance, considering the importance of moving toward renewable energies and away from fossil fuel consumption. The manuscript is concise, generally well written and easy to (see comments below). The 1D model analysis is thorough and includes a sensitivity analysis of the platform's roughness height. However, I have one main criticism; that is—as also stated in the discussion/conclusion—the 1D model has significant limitations compared to a 3D model and, therefore, the study can only be considered a testbed for the implementation and sensitivity analysis of the new parameterisation, while conclusions on the actual likely impact of floating solar panels (or any other type of surface-covering platform) do not seem adequate to me. This should be made clear from the very beginning (including the title and abstract).

ANSWER: We think that this is an exaggeration, and that there is merit in the results. 1D models have been used before to estimate first order responses of marine ecosystems. We will, however, include in the title that we have used a water-column model. This is already stated clearly in the abstract, the last quarter of which is already devoted to caveats - we regard this as sufficient. See also the changes made in response to related comments by Reviewer 1.

2.1) Changes to manuscript:
added: 'from a water-column model' to the title.

For the same reason, I wonder whether submitting the manuscript to Geoscientific Model Development (GMD; https://www.geoscientific-model-development.net/) would be more appropriate? However, that would require the paper to be turned into a bit more technical description of the model.

ANSWER: Part of the purpose of the manuscript is to raise awareness of a potential environmental issue that requires attention, consideration and further work to advance understanding. A publication in Ocean Science would serve that purpose and reach the required audience, while a publication in GMD would most likely not. Hence we oppose this suggestion.

Changes to manuscript:
None

I recommend reconsideration for publication (possibly in GMD) after moderate revisions.
ANSWER: Thank you!

General points

It needs to be stated clearly in title, abstract and at the end of the introduction that the present study is only a test case and does not allow for sound conclusions on the actual impacts of solar panels on the North Sea (or at best provides an estimate of the upper limit of their impact).

ANSWER: The manuscript already contains numerous caveats and warnings to this extent. However, we have reviewed the text and made further warnings where appropriate.

2.2) Changes to manuscript:
See response to comments by Reviewer 1.

There is no information on the dimensions of solar panels to be deployed in marine environments (and distances in between them) in the manuscript. That makes it hard to get an idea about the transferability of the 1D model results to a real-world application. Factors like "patchy" light availability/light scattering (depending on the size of the panels) inside the solar parks in combination with advection/and mixing would likely result in a weaker reduction in PP than simulated for the 1D case (and presumably than in the 3D case as well as the response of phytoplankton to light is non-linear as currently implied by reducing surface light by the coverage fraction). These information should be provided in the introduction or in the methods; and their implications for the interpretation of results need to be discussed. Depending on the size, solar panels may also have quite different impacts on waves, which are not considered in this study (e.g. wave damping)

ANSWER: We recognise these issues, and have mentioned most of them in the manuscript. However, spatially resolved processes can not be simulated with an area-averaged 1D model, and most of these points must be the subject of further work. We have reviewed the current text to make these points even more clearly.

2.3) Changes to manuscript:
Three separate additions to the text of Section 2.3 to stress this.

Specific points
Page 1, lines 15-21: Given the limitations of the 1D model parameterisation (see general points), I am not convinced that the results are applicable to "very large-scale implementations of [evenly distributed] offshore floating platforms".

ANSWER: This statement relates to the assumption of negligible horizontal gradients underlying the application of a 1D model. In that sense, the scale of a hypothetical farm must be large enough to ensure that phytoplankton do not move outside the farm by e.g. tidal currents for a considerable time. We have reviewed the text and now make this point more clearly. See also similar comment by Reviewer 1.

2.4) Changes to manuscript:
of at least several hundreds of square kilometers <u>such that phytoplankton remain underneath a farm throughout several tidal cycles.</u>

Page 2, lines 10-19: Information on the design of aquatic solar panels/farms should be provided here.
ANSWER: This is not the subject of this paper, and not relevant in the 1D context used here. However, we will assess the earlier publications to see if dimensions are provided. Technical details of the planned small-scale test farm are confidential. At this stage no reliable information on the design of future installations is available.

2.5) Changes to manuscript:
The manuscript now provides dimensions of a fresh-water implementation.

Page 3, lines 11-17: In this paragraph it should be stated clearly that this study is only a testbed for the parameterisation.

ANSWER: We disagree with the reviewer (see above). We will, however, include a statement that substantial further work is needed.

2.6) Changes to manuscript: we have added:
For more detailed, spatially resolved results, and to include additional processes, substantial further work is needed.

Page 4, line 19: How reasonably is it to assume constant S for the Noordwijk station (I assume it's Noordwijk-10 although not specified)? E.g. de Kok et al. (2001; https://doi.org/10.1006/ecss.2000.0627) show that there is quite some salinity stratification.
Page 6, lines 14-16: I am quite surprised that there are no other data sources for two of the three stations? Are these Oyster Grounds and West Gabbard (please specify in-text)? What about rosetta casts/bottle samples during earlier years?

ANSWER: The locations of the stations are specified clearly on p. 3, l. 31-32, and in Figure 1. We will add that we used Noordwijk 10 (throughout the manuscript). These are indeed well-studied sites. However, we have chosen to only describe the (time-series) data that we have used; providing a full catalogue of data observed at these sites is beyond the scope of this paper. Thank you for the reference on salinity stratification at Noordwijk-10. We have considered this carefully and made changes to the text when discussing this site. Our objective was to simulate shallow, well-mixed conditions. Although it is possible to represent salinity stratification with GOTM (Simpson et al., 2002), doing so requires detailed observations of spatial gradients in salinity.

2.7) Changes to manuscript:
We have changed Noordwijk to Noordwijk 10 everywhere.
We have changed the last sentence of the first paragraph of Section 2.1 into:
Both locations are characterized by relatively strong tidal currents, high suspended sediment concentration and high primary production (van der Molen et al., 2016; https://data.gov.uk). The West Gabbard location remains well mixed during the entire year. The Noordwijk-10 location can stratify by combined temperature and salinity effects when river outflow is high (de Kok et al., 2001). For the purpose of this study, we ignore salinity effects at Noordwijk-10, which may lead to an under-estimation of the occasional stratification.

Page 9, line 9: Can you explain that increase?

ANSWER: Yes, this is because of a reduction in suspended sediment concentration. We will add this to the text, including an additional figure illustrating the underlying causes related to a decrease in eddy diffusivity (see comment by Reviewer 1).

2.8) Changes to manuscript:
We have added that this is caused by lower suspended sediment concentrations, and refer to the additional text and figure requested by Reviewer 1.

Page 10, lines 13-15: I don't understand this vertical difference in turbulence. Why is it increased near the surface (wind shielding effect < friction effect?) but opposite in mid-water?
ANSWER: Yes, wind shielding effect < friction effect for the well mixed areas. The introduction of platform friction results in a change in the shape of the velocity profile. A small (or zero) vertical gradient at mid depths and a large vertical gradient at the surface. This leads to high shear production (and thus turbulent kinetic energy) near the surface and low at mid depths. See also response above, and to comments by Reviewer 1.

2.9) Changes to manuscript:

We have added an additional figure and text to explain this.

Page 11, lines 1/2: I agree that PP shifts to the surface because of the shallower mixed layer. However, light is also reduced due to the panel shadow; so subsurface PP does not necessarily need to increase. In this particular case it does because the increase in light due to shallower mixed layer (ML) outweighs the decrease in light due to shadowing. I suggest to clarify this.

ANSWER: We will clarify this.

2.10) Changes to manuscript:
We have added that the effect of the upwards shift outweighed the light deficit induced by the platforms

You could provide numbers of light at ML depth averaged over the year for the different scenarios.

ANSWER: That would not be representative as it would need to be calculated over the part of the growing season with stratification. Although it is possible to do this, we do not see how this would add to what can be read/understood from Figure 6.

Changes to manuscript:
We have made no changes.

The decrease in ML depth with higher surface coverage also reduces the nutrient inventory available for PP (assuming that nutrients below the ML cannot be accessed by phytoplankton). Can you comment on whether this has a measurable effect?

ANSWER: This is the reduction in net primary production between 0 and 15 m in Figure 6b. We will add a comment on the reduced nutrient inventory.

2.11) Changes to manuscript:
We have added that a thinner layer holds less nutrients.

Page 16, lines 2-20: this discussion of the limitations of the 1D model and the applied parameterisation should be expanded a little bit (see comments above)

ANSWER: We will do this, also considering suggestions by the other reviewers.

2.12) Changes to manuscript:
We have added text suggesting further work on:
-the influence of horizontal light diffusion
-the effect of platforms on the wind
-the effect of platforms on air-sea gas exchange
-the size of structures: effect on development boundary layer for friction

Minor/Technical corrections

Title: in addition to changing it (see earlier comments), “PV” should be replaced by “photovoltaic”
OK, done.

Page 1, line 4: “photovoltaic (PV)”
ok, done.

Page 1, line 6: “seasonally stratified” instead of “summer-stratified”?
ok, done

Page 1, line 20: “three-dimensional” instead of “3D”
ok, done

Page 2, lines 20/21: “(Trapani and Millan, 2012; Grech et al., 2016; …)”
ok, done

Page 2, lines 32/33: “570,000”; riverine freshwater runoff (which produces barotropic pressure gradients) also controls hydrodynamics
ok, “buoyancy gradients” includes this as well.

Page 2, line 34: “Sündermann” (with umlaut)
ok, done

Page 3, line 12: “seasonally stratified” instead of “summer-stratified”?
ok, done

Page 3, lines 31/32: add degree sign (°) to geographical locations
ok, done

Page 4, line 2: please add a reference for the sentence ending on this line
ok, done

Page 4, line 4: please add reference
ok, done

Page 4, line 16: no comma after “model”
ok, done

Page 4, line 17: “one-dimensional vertical (1DV)”
ok, done

Page 5, lines 6/7: “(Baretta et al., 1995; Ruardij et al., 1997; Vichi et al., 2007; van der Molen et al., 2018; …)”
ok, done

Page 5, line 15: see van der Molen et al. (2014)
ok, done

Page 7, Table 2: the initial detritus concentrations seem very large to me (10^5?); please specify their unit (mmol N/m^3?); include multiplication sign before “10^5”;
ok, done. We also corrected the units for benthic detritus.

I further think Tables 2 and 3 could be merged into one.
No, we want to make a clear distinction between parameters that were set, and the initial conditions that were tuned. Using one table for both would be confusing.
No change.

Page 7, line 6: please specify the averaging time period: annually? Growing season?
OK, done.

Page 7, section 2.5: what is the output time step of the simulations?
Daily, now stated.

Page 8, Fig 4: the x axis labels of panels a,b,c differ from the others
Ok, done

Page 8, line 6: You should add a brief concluding statement on the general(ly good) performance of the model
ok, done

Page 10, line 5: Should it be only Fig. 5B?
Both are needed, We have improved the sentence: ' surface suspended sediment (Figure 5 b) on irradiance (Figure 5 a)*'.*

Page 10, line 12: comma after “mixed locations”
ok, done

Page 10, lines 15/16: Fig 5c always shows a decrease; it’s only weaker for high surface coverage
ok, we have rephrased

Page 10, line 20: It only collapses for 100% coverage.
We have removed the phrase 'collapse'.

Page 11, lines 1/2: Please add how MLD was determined (e.g. maximum T gradient)
It is calculated as the shallowest layer with tke smaller than a certain value (10^-5)., now added

Page 11, lines 7/8: remove the sentence on ecosystem collapse
Ok, changed into 'strong reduction in primary production'.

Page 12, line 4: “factor” instead of “effect”
Ok, changed.

Page 12, lines 7/8: I don’t understand the statement on wind shielding and “blocked” postponement of stratification; please rephrase
we replaced “blocked” with “prevented”

Page 13, lines 9/11: I don’t understand this sentence. Whose impact on PP is compensated by roughness height? Please rephrase
We have added: 'the impact of the installations'

Page 15, Fig 8: the x axis labels are cut off
ok, fixed

Page 15, line 1: give a number for the “small” reduction
10%, done.

Page 16, line 8: It’s not the only tidal currents but also wind-driven and/or geostrophic currents
Tidal currents should be equivalent to geostrophic currents and they are the dominant currents within the North Sea. We have added a statement that tides generate the dominant currents in the North Sea.

Page 16, line 14: “three-dimensional” instead of “3D”
ok, done

Page 17, line 13: “high-resolution”
ok, done

Line 18, Eq (5) related description: I think the first term does not give a length scale as unit. Viscosity has Pa s as unit, i.e. kg m-1 s-1. So, the first term is in kg m-2. What’s the source of the scalar factors in both terms?
In Fluid Dynamics kinematic viscosity is often used and called as viscosity. This is viscosity over density, thus m^2/s. The source of the scalar factors: Burchard et al. (1999). We have now included units and the reference.

Reviewer 3.
1 Summary
The question addressed in the paper is practical and applied, rather than of a fundamental scientific nature, but appears to lie well within the journal scope. The paper itself is exceptionally well written, structured and easy to follow. Methodology is well explained and, importantly, the limitations of 1D water column approach modelling (compared to a 3D modelling) are clearly noted and explained. Despite the constraints of a 1D approach, useful guidelines, albeit of a preliminary nature, are obtained concerning the proportion of surface area covered before significant effects on primary productivity might be expected. The application to the three sites is also very useful in giving an idea about how generic these results might be. I have a technical concern about the formulation surface friction effect that is discussed below. Apart from this, there are only a few minor suggestions for manuscript improvement. Overall, the paper is a very clearly written description of a well-motivated and executed study and deserves publication with minor modifications.
ANSWER: Thank you for these very positive comments.

2 Shear stress formulation
If I've understood correctly, the definition of the structure surface shear stress appears to explicitly depend on layer thickness of the 1st grid cell (h in equation 4). Clearly the structure drag is a real physical quantity that cannot depend on how a particular model is set up. For example, if the user decided to refine the mesh near the sea surface then as h -> 0 the stress coefficient given by eqn. 4 is unbounded. It seems a real physical length scale needs to be included in the formulation - the depth of the structure below the surface would be an obvious candidate (but note, a straight substitutes of h with structure depth wouldn't work). It probably doesn't make a difference to the results obtained here as the authors show these are rather insensitive to the details of the formulation (fig. 8), but a grid independent estimate of the structure drag seems to be desirable.

ANSWER: This is a good point that needs to be clarified. h/2 below the platform is the vertical location of the velocity u in eqn 3. U is proportional to ln((h/2+zo)/zo), thus h=0 leads to no slip conditions. Then tau is independent of h (For more information see Burchard (1999): GOTM, a general ocean turbulence model, theory implementations and test cases, chapter 3.3) We will add the equation for u.

3.1) Changes to manuscript:
We have added the equation for u.

3 Suggested text amendments
Authors could mention the study is also relevant to other proposed offshore developments e.g. large-scale aquaculture/seaweed farming.
ANSWER: We intended to make this point in the very last sentence (p. 17, l. 26). We will improve this sentence to make this point more clearly.

3.2) Changes to manuscript:
We have added the example of seaweed farming to the last sentence.

p line 5 16. Phaeocystis is omitted from model then suggested as explanation for peaks in chlorophyll not captured by model (p 8 line 6). Although I understand that if phaeocystis is linked to nutrient peaks from rivers it is quite legitimate to exclude it in a 1d model, nevertheless, on 1st reading of p8 line 6, it seems slightly odd to blame the mismatch on something deliberately excluded from the model. A rewording here, or on p 5 line 6 , might Just help the reader understand this more quickly.
ANSWER: We will add this.

3.3) Changes to manuscript:
We have added that inclusion led to spurious interannual variability within the 1D context on p.8.

p 6. line 8-9. How was the light extinction coefficient calibrated from observations?
If I understand correctly, then the SPM at the OG causes greater light attenuation for a given concentration that at the other sites. A brief mention in the discussion might interesting; is the difference just an artifice of calibration and not real , or is there some reason for the SPM at OG being different to the other sites.
ANSWER: This is an artifice of calibration; we will mention this in the manuscript.

3.4) Changes to manuscript:
We have changed the text into:
Site-specific values for the porosity of the sea bed and salinity were defined based on observations (table 1). The light-extinction factor for suspended sediment (the contribution to the light-extinction coefficient by suspended sediment is this factor multiplied by the suspended sediment concentration) was kept at the standard value for West Gabbard and Noordwijk 10, but half the standard value for Oyster Grounds as that gave better results.

p 6. detritus. Is this seabed or water column detritus? Brief explanation on what detritus is and why it is necessary to adjust its value.
ANSWER: Sea-bed detritus. This is by far the largest pool of material in the model. We will add a few words stating this.

3.5) Changes to manuscript:
We have added 'benthic' to detritus in this sentence. We have also included:
"Benthic detritus is by far the largest pool of carbon and nutrients in the model, so using it to set the nutrient content of the 1D model in combination with a long spin-up of more than twice the response time of the benthic system to re-distribute this content appropriately within the ecosystem is a simple and effective tuning approach."

4 Minor format issues
fig 2 Suggest put quantity name (chlorophyll, nitrate, silicate) at top of each of the 3 column of plots so reader immediately knows what is being shown rather than having to read caption.
ok, done

fig 5,6 Very minor, but I think is easier to read having the letter label before the text instead of after, e.g. “(a) irradiance at 3 meters depth” , instead of “irradiance at 3 meters depth (a)”
ok, done

p 15 line 2. The regime 2 text misses out on a general conclusion that the other regimes get. Suggest text be amended to something like ”: : :.. a substantial spread occurred between sites. Thus, no general, site-independent, conclusions can be drawn. In regime 3: : :: : :: : :”
ok, done

Reviewer 4.

Overall Statements
The manuscript "Effects of floating (solar PV) platforms on hydrodynamics and primary production in a coastal sea" by Karpouzoglou et al. describes the effect of photovoltaic platforms (disposed at the sea surface) on physical and ecosystem features in the water column. In times of global warming when mitigating strategies and renewable energy production become important, such basic assessments are necessary and welcome. The overall result is that the shading effect is more important than shielding from wind and friction on currents. To my knowledge the model-system does not include 3-D scattering of light. This effect would increase underwater-light availability and thus might corrupt the central finding of the manuscript. The authors must tackle this challenge seriously, otherwise I cannot recommend the manuscript for publication.

ANSWER: See also the responses to comments by Reviewer 1. Indeed, the 1D model cannot simulate shadow, shading and horizontal light diffusion, but rather considers the overall reduction in the amount of light entering the water column and available for growth (which is a real physical effect that the 1D model can represent). The current text is confusing, and we will reformulate using a term such as 'area-averaged light deficit induced by the platforms'.

4.1) Changes to manuscript:
See responses to comments by Reviewer 1.

The second major difficulty of the manuscript is the method of individual spin-ups over 26 years using different starting values for nutrients. Does the model system include sink terms, like burial and N2 release during denitrification?
ANSWER: No. There is no burial below the part of the sea bed that the benthic system represents, and nitrogen released by denitrification is re-introduced immediately as nitrate by atmospheric deposition.

4.2) Changes to manuscript:
We have added the following sentence to Section 2.2:
Within the 1D model context, nitrogen, phosphorus and silicate are fully conserved. N2 gas produced by denitrification processes is fed back immediately as nitrate in the form of atmospheric deposition. Carbon and oxygen are exchanged with unlimited atmospheric pools at constant concentration.

In this case the model will show a drift which should be clearly seen over these years.
ANSWER: This does not apply, see above.

Changes to manuscript:
We have made no changes.

I understand that the initial conditions must be different for different places, but this very long spin-up must be justified. The initial very high detritus concentrations appear very artificial.
ANSWER: This is the first time we've ever been accused of having a spin-up period that is too long :-). The benthic system in the model has a typical response time of a decade or so. So roughly two decades is reasonable. Part of the detritus redistributes into the rest of the ecosystem during this time until it settles into a quasi-steady initial state. Using one ecosystem component in combination with a long spinup is a much more straight-forward method than tuning the initial settings of all components at the same time. We have added a few words to the text to this effect. See also comment by Reviewer 3.

4.3) Changes to manuscript:
See response to comment by Reviewer 3.

The manuscript is structured and written very well. Thus, I hope the puzzles can be clarified.

Answer:
Thank you, please see above, and responses to the comments of the other reviewers.

Detailed remarks
P1 L4: Define here the “PV” abbreviation.
OK, done.

P1 L27: Also discuss possible conflicts with shipping and offshore windfarms.
ANSWER: This is a technical section on how the platforms were implemented in the model. Moreover, spatial planning is beyond the scope of this paper as a whole.
We have made no changes.

P5 L24: Why do you exclude gas exchange?
ANSWER: This is a good point. We already included air-sea exchange in the recommendations for further work. We will change it to air-sea gas exchange.

P5 L30 ff: The air circulating around the platforms will be accelerated and behind the platform I expect a turbulent wind field. Can you estimate these effects?
ANSWER: We're sorry, but no. The current model is limited to the hydrosphere. However, this is a good suggestion (also raised by another reviewer), and we have added it to the list of things that may need to be looked at in further work.

P6 Table 1: Did you use SPM concentrations? Please give the corresponding values.
ANSWER: No, that is, we did not prescribe them. They are calculated dynamically by the model, as is stated clearly in Section 2.2. We have not made changes to the manuscript.

P6 L10 ff: It is not the mass of nutrients, which is conserved. It is the amount of nitrogen, phosphorus and silicon, which is conserved, if there is no sink and source within the water column (see overall statements).
ANSWER: Thanks, we have re-formulated this.

P7 Table 2: You mention detritus. Which element describes detritus? Is it pelagic detritus? This are very high values. In this case the shading of detritus would be much larger than the shading of the platform.
ANSWER: This is benthic detritus. See the response to the equivalent comment by Reviewer 3.

P7 L6: Fraction = 1 appears very artificial. Please mention this already here.
ANSWER: we now mention that the high end of this range was included for completeness, but may never be realised.

P8 Figure 2 abc: The arrangement of x-axis labels does not allow to identify the exact positions.
ANSWER: we have corrected this.

P12 L7 ff: This sentence is over-complex. Please rephrase.
ANSWER: we have split this sentence:
"Reduced mixing resulting from wind shielding prevented a later onset of stratification and spring bloom that would otherwise be caused by the effect of platform shadow (decreased buoyancy input). It thus prevented the partly compensating effect of a later spring bloom on net primary production that occurred at the well-mixed sites."

Effects of large scale floating (solar ~~PV~~photovoltaic) platforms on hydrodynamics and primary production in a coastal sea from a water column model.

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Abstract.

An improved understanding of the effects of floating solar platforms on the ecosystem is necessary to define acceptable and responsible real-world field implementations of this new marine technology. This study examines a number of potential effects of offshore floating solar ~~PV~~ photovoltaic (PV) platforms on the hydrodynamics and net primary production in a coastal sea for the first time. Three contrasting locations within the North Sea (a shallow and deeper location with well-mixed conditions and a ~~summer-stratifying~~ seasonally stratifying location) have been analysed using a water column physical-biogeochemical model (GOTM-ERSEM-BFM). The results show strong dependence on the characteristics of the location (e.g. mixing and stratification) and on the density of coverage with floating platforms. The overall response of the system was separated into contributions by ~~platform shadow~~platform-induced light deficit, shielding by the platforms of the sea surface from wind, and friction induced by the platforms on the currents. For all three locations, ~~platform shadow~~ light deficit was the dominant effect on the net primary production. For the two well-mixed locations, the other effects of the platforms resulted in partial compensation for the impact of ~~platform shadow~~light deficit, while for the stratified location, they enhanced the effects of ~~platform shadow~~light deficit. For up to 20% coverage of the model surface with platforms, the spread in the results between locations was relatively small, and the changes in net primary production were less than 10%. For higher percentages of coverage, primary production decreased substantially, with an increased spread in response between the sites. The water-column model assumes horizontal homogeneity in all forcings and simulated variables, also for coverage with floating platforms, and hence the results are applicable to very large-scale implementations of offshore floating platforms that are evenly distributed over areas of at least several hundreds of square ~~kilometres~~kilometers, such that phytoplankton remain underneath a farm throughout several tidal cycles. To confirm these results, and to investigate more realistic cases of floating platforms distributed unevenly over much smaller areas with horizontally varying hydrodynamic conditions, in which phytoplankton can be expected to spend only part of the time underneath a farm and effects are likely to be smaller, spatial detail and additional processes need to be included. To do so, further work is required to advance the water-column model towards a ~~3D~~ three-dimensional modelling approach.

1 Introduction

With a growing world population and growing global energy demand, new options need to be explored to generate energy. While traditional fossil fuels emit carbon dioxide and other harmful gases which cause global temperature to rise, renewable forms of energy offer a sustainable alternative that can remediate climate change. Two of the most promising sources of renewable energy are the sun and the wind. Wind farms are built both onshore and offshore, but utility scale photovoltaic (PV) solar farms are until now installed only on land. Growing space constraints, higher land costs, increased public resistance and competition with other functions will ultimately set a limit to the potential of onshore solar development, especially in densely populated areas. Such constraints may be less relevant at sea, and offshore solar energy generation has huge potential.

Large scale floating solar farms, reaching up to 1.4 km^2 (70 Mw) already exist inshore (https://www.pv-tech.org/news/worlds-largest-floating-solar-plant-connected-in-china)and are rapidly being developed all around the world (da Silva and Branco, 2018). The effects of these structures on the ecosystem have been discussed mainly for standing water environments (Santafe et al., 2014; Sahu et al., 2016; da Silva and Branco, 2018). These studies argue that (inshore) floating platforms decrease the evaporation rate and increase water quality by reducing primary production due to the ~~shadowing effect of~~ light deficit introduced by the platforms. However, these studies did not investigate these effects in detail. The potential of offshore solar energy has recently been highlighted in several policy roadmaps in The Netherlands, and the world's first demonstration of an offshore solar farm of 50 Kw is expected to be operational by the beginning of 2020 (https://www.reuters.com/article/netherlands-solar-offshore/dutch-plan-to-build-giant-offshore-solar-power-farm-idUSL8N1Q46M0), stressing the need to investigate potential environmental effects.

At sea only a few small scale tests have been carried out with floating PV concepts (~~Trapani and Millar (2012); Grech et al. (2016)~~ Trapani and Millar, 2012; Grech et al., 2016; swimsol.com/#lagoon, oceansun.no). There are substantial differences between offshore and inshore environments caused by stronger winds, higher waves, and the presence of tides which causes the water column underneath the floating platforms to be constantly replaced. Moreover, the water motion induced by wave and tidal processes suspend sediments, which affect the under-water light climate and consequently net primary production (Wetsteyn and Kromkamp, 1994). Offshore floating platforms have the potential to influence these processes. Hence, the effects of such platforms on marine ecosystems are expected to be different from those in standing (fresh) water, and require separate investigation. As of yet, there are no studies that consider the possible environmental effects of offshore floating platforms on the marine ecosystem.

This study investigates the potential effects of large-scale arrays of offshore floating platforms on the ecosystem of coastal seas such as the North Sea, adjacent to The Netherlands. The North Sea is a relatively shallow marginal sea (average depth 74 m) of the Atlantic Ocean. It is located between the continent of western Europe and the United Kingdom, and covers an area of about ~~570.000~~ 570,000 km^2 (Otto et al., 1990). The hydrodynamics of the North Sea are controlled by tides, winds and buoyancy gradients. In the shallower regions of the southern bight of the North Sea, tidal currents are strong and wind waves can cause substantial near-bed wave-orbital velocities, resulting in well mixed conditions during the whole year (Sündermann and Pohlmann, 2011; Pickering et al., 2012). In deeper areas further to the north, tidal currents are weaker and wave effects rarely reach the sea bed, allowing temperature stratification during summer (van Leeuwen et al., 2015). Such stratification limits vertical exchange of nutrients and determines the timing of the spring bloom (Sverdrup, 1953; Ruardij et al., 1997). We hypothesise that offshore floating platforms will modify currents, waves and stratification, and primary production. The platforms will ~~cast shadows~~ induce light deficit under water, reducing heat input and likely affecting temperature stratification. We also expect reductions in under-water light intensity to affect phytoplankton growth. The friction of the rigid platforms with the tidal currents and shielding of the water surface from the wind are expected to result in weaker currents. The platforms can also be expected to have an impact on waves. Changes due to these forcings will affect turbulence and the resulting vertical mixing, suspended sediment and nutrient concentrations, and phytoplankton growth.

Here, we assess three contrasting locations in the North Sea for which time-series observations of hydrographic and biological quantities are available: a shallow and a deeper well-mixed site, and a ~~summer-stratified~~ seasonally stratified site. We focus on changes in net primary production induced by the effects of floating platforms on the physical environment. In absence of field observations with floating platforms present, we used a water-column model to obtain first estimates of the potential effects of covering part of the sea-surface area on hydrodynamics and net primary production. We have made the necessary assumptions such that these estimates are near the upper limits of the effects. This model allowed for easy development and testing of the implementation of the effects of the floating structures on light (~~shading~~light deficit), wind forcing (shielding) and currents (platform friction). For more detailed, spatially resolved results, and to include additional processes, substantial further work is needed.

The following research questions are addressed in this paper:

1) What is the overall potential effect of floating platforms on the net primary production at different locations in the North Sea as a function of coverage density?

2) What is the relative importance of the individual effects of ~~platform shadow~~platform-induced light deficit, wind shielding and platform friction?

3) For which percentages of coverage does the model suggest ~~noticable~~ noticeable changes in the response of primary production?

2 Material and Methods

2.1 Study sites and observations

Three study sites were selected for which time-series observations of hydrographical and biogeochemical variables were available, with contrasting hydrographic conditions: Oyster Grounds (~~54.41 N, 4.02~~ 54.41° N, 4.02° E), ~~Noordwijk (52.301 N, 4.303~~ Noordwijk-10 (52.301° N, 4.303° E) and West Gabbard (~~51.9895 N, 2.08983~~ 51.9895° N, 2.08983° E) (figure 1). Oyster Grounds is located at 45 m depth, and stratifies every summer between April and October (Tijssen and Wetsteyn, 1984). It is characterized by relatively low tidal current velocities, low suspended sediment concentrations and low primary production. The sites West Gabbard and ~~Noordwijk~~ Noordwijk-10 are located at 32 m and 18 m depth respectively. ~~These locations remain well mixed during the entire year and they~~ Both locations are characterized by relatively strong tidal currents, high suspended sediment concentration and high primary production (van der Molen et al., 2016; https://data.gov.uk). The West Gabbard location remains well mixed during the entire year. The Noordwijk-10 location can stratify by combined temperature and salinity effects when river outflow is high (de Kok et al. , 2001). For the purpose of this study, we ignore salinity effects at Noordwijk-10, which may lead to an under-estimation of the occasional stratification.

At the three study sites, time-series observations were collected using SmartBuoys deployed by the Center for Environmental Fisheries and Aquaculture Science (Cefas) (www.cefas.co.uk/publications-data/smartbuoys). SmartBuoys are moored, automated, multi-parameter recording platforms which are used to collect marine environmental data. They measure, at 1 m below the sea surface, salinity, temperature, turbidity, oxygen saturation, chlorophyll fluorescence and nitrate and silicate concentration. Data were collected in 10-minute bursts; here we have used daily averages. The buoys also collected and preserved water samples which were used to calibrate the sensor data. For this study, we used observations from the following years: from 2006 to 2008 for Oyster Grounds and West Gabbard, and from 2001 to 2002 for ~~Noordwijk~~Noordwijk-10.

2.2 Model description

For the purpose of this work the coupled physical-biogeochemical model GOTM-ERSEM-BFM was used. The General Ocean Turbulence Model (GOTM; Burchard et al. (2006); www.gotm.net) is a public domain, one-dimensional Finite Differences water column model ~~,~~ that includes the most important hydrodynamic and thermodynamic processes related to vertical mixing in natural waters. The model solves the one-dimensional vertical (1DV) Reynolds-averaged Navier Stokes equations and the Reynolds-averaged transport equations of temperature and salinity, under the Boussinesq and hydrostatic approximations. In this offshore application of GOTM, salinity was considered constant. The model was forced with meteorological hindcast data obtained from the European Centre for Medium-Range Weather Forecast (ECMWF) ERA-40 (datasets/data/era40-daily/levtype=sfc/). Moreover, it was forced with time series of depth-averaged tidal velocities reconstructed from the harmonic analysis of a 3D model (van der Molen et al., 2017). The model uses these depth-averaged velocities to set up spatial gradients of external pressure that it uses as forcing. GOTM uses all these forcings, including bed-shear stress, to calculate the

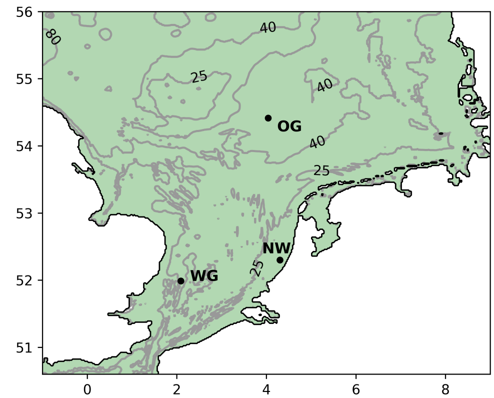

Figure 1. Map with the Smartbuoy stations of Oyster Grounds (OG), West Gabbard (WG) and ~~Noordwijk~~ Noordwijk-10 (NW)

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time-evolution of vertical distributions of turbulence and currents (Burchard et al., 2006). It is also possible to explicitly force GOTM with spatial gradients, e.g. to simulate salinity stratification (Simpson et al., 2002), but this was not used here.

Coupled with GOTM, the European Regional Seas Ecosystem Model-Biogeochemical Flux Model (ERSEM-BFM) was used. ERSEM-BFM is a development of the model ERSEM III (~~Baretta et al. (1995); Ruardij et al. (1997); Vichi et al. (2007); van der Mol~~ Baretta et al., 1995; Ruardij et al., 1997; Vichi et al., 2007; van der Molen et al., 2018; www.nioz.nl/en/about/cos/ecosystem modelling). It is a pelagic-benthic ecosystem model describing the biogeochemical fluxes in the lower trophic levels of the marine food web. The model simulates the cycles of carbon, nitrogen, phosphorus, silicate and oxygen, allowing for variable internal nutrient ratios within the different groups. Within the 1D model context, nitrogen, phosphorus and silicate are fully conserved. N_2 gas produced by denitrification processes is fed back immediately as nitrate in the form of atmospheric deposition. Carbon and oxygen are exchanged with unlimited atmospheric pools at constant concentration. The model applies a functional group approach and contains six pelagic phytoplankton groups (diatoms, flagellates, picophytoplankton, resuspended benthic diatoms, dinoflagellates and phaeocystis), four zooplankton groups and five benthic faunal groups (four macrofauna and one meio-fauna groups). Pelagic and benthic aerobic and anaerobic bacteria are also included. The model also simulates suspended particulate matter (SPM) concentrations in response to waves and currents, which influence the under-water light conditions and net primary production (van der Molen et al., 2017). A simple wave model (based on the Sverdrup-Munk-Bretschneider method, U.S. Army Corps of Engineers (1984), see ~~(van der Molen et al., 2014)~~van der Molen et al., 2014) is used to calculate significant wave height, period and direction. Resuspension of detritus is coupled to the resuspension of sediment. As inclusion of phaeocystis without a riverine nutrient source led to spurious interannual variations, it was excluded from the calculations.

The model calculates light attenuation in the vertical, accounting for absorption by 1) clear water, 2) colored dissolved organic matter (CDOM) 3) suspended mineral sediment, 4) chlorophyll, and 5) suspended organic matter (detritus). For a mathematical description of light attenuation in the model, see Appendix B.

2.3 Implementation of platforms

GOTM-ERSEM-BFM was modified to allow representation of the spatially-averaged effects of the floating platforms on the hydrodynamics and ecosystem dynamics of the water column. The model accounted for the platforms through the introduction of three individual effects that can be activated separately or together: the ~~shadow of~~ light deficit due to the platforms, shielding of the water surface from the wind and the friction of the platforms acting on the currents. The implementation allowed for variable platform coverage as a fraction of the model surface. As the model represents averaged conditions over a unit surface area at each depth interval, it can not distinguish between different ways of distributing this coverage over the unit surface area, nor include details of platform dimensions or design, and for the purpose of this study we assume the coverage to be distributed uniformly in space~~. The shadow of the platforms~~ , in an area-averaged sense. The platform-induced light deficit and the wind shielding effects were expressed by a linear reduction of surface irradiance and surface wind stress with coverage. The frictional effects of the platforms on the currents was represented, in similarity to the bottom friction, by an additional surface shear stress that was calculated with the logarithmic law of the wall, applied as a linear function of coverage. For mathematical expressions of the implementation of the floating structures, see Appendix A. In absence of design details of operational systems, the roughness of the platforms is as yet not known, and may also vary during deployment due to biofouling. As a first approximation, the roughness height of the floating structures was assumed equal to that of the sea bed (h_{0s} = 0.05 m). A series of experiments with varying values of h_{0s} between 0.0125 and 0.4 m was carried out to provide insight into sensitivity of the model results to this parameter. Apart from coverage, this was the only parameter associated with the addition of floating platforms to the model. A sensitivity analysis of other parameters is beyond the scope of this paper, and the reader is referred to section 3.1 for a comparison with observations.

2.4 Model setup and initial conditions

For each site, a water-column model was set up with 40 vertical levels with increased resolution near the surface and bottom. Time steps were 300 s for the hydrodynamics, and 3600 s for the biology. Site-specific values for the porosity of the sea bed ~~, the~~ and salinity were defined based on observations (table 1). The light-extinction factor for suspended sediment (the contribution to the light-extinction coefficient by suspended sediment is this factor multiplied by the suspended sediment concentration) ~~, and salinity were defined based on observations (table 1)~~was kept at the standard value for West Gabbard and Noordwijk-10, but twice the standard value for Oyster Grounds as that gave better results. As the water-column model is a closed system that conserves ~~nutrient mass~~nitrogen, phosphorus and silicon, it can only reproduce observations if the total amount for each nutrient integrated across all ecosystem components reflects the average amount present in the vicinity of the site. In absence

Table 1. Site-specific constants.

Site-specific constants	Oyster Grounds	~~Noordwijk~~ Noordwijk-10	West Gabbard
Porosity of sea bed	0.423	0.45	0.45
Light-extinction factor SPM ($\mathrm{m^2 kg^{-1}}$)	1.1 ~~10^{-4}~~$\times 10^{-4}$	0.55 ~~10^{-4}~~$\times 10^{-4}$	0.55 ~~10^{-4}~~$\times 10^{-4}$
Salinity (psu)	35	30	35

of direct observations of the amounts of nutrients in all ecosystem compartments, we tuned the initial concentrations of nitrate, silicate, phosphate and benthic detritus in such a way that the model results, after a spin-up period of 26 years, matched the observed biogeochemical data as well as possible for each site. Benthic detritus is by far the largest pool of carbon and nutrients in the model, so using it to set the nutrient content of the 1D model in combination with a long spin-up of more than twice the response time of the benthic system to re-distribute this content appropriately within the ecosystem is a simple and effective tuning approach. Because for two of the three sites only a few years of observations were available, and differences between years had to be accounted for in the tuning process, we did not have enough data for an independent validation of the model. The tuning of the initial conditions of the model was done by minimising the value of the root mean square (RMS) error and maximising the value of the correlation coefficient between the modeled and observed time series for chlorophyll-a, nitrate and silicate. The model setup with initial values that gave the minimum RMS error and maximum correlation was chosen for the simulations.

2.5 Model experiments

The resulting model was run for the period 1972-2008 for each site, providing daily outputs. The first 26 years were considered as spin-up and only the years 1998-2008 were taken into account for the results. A reference run without platforms was carried out first. Subsequently, four scenarios were defined to investigate the separate effects of 1) ~~platform shadow~~platform-induced light deficit, 2) wind shielding, 3) platform friction, and 4) to simulate the combined overall effect. For each effect, model runs were conducted for different values of coverage fraction (0.1-1.0 in steps of 0.1). The high end of this range may never be reached in practical applications, but was included here for completeness. The sensitivity of the time-averaged (over the whole run period), depth-integrated values of modeled net primary production to platform coverage was evaluated for the different effects and the different locations, and the relative change was calculated compared to the reference run without platforms. To investigate the model response in more detail, climatological depth-integrated yearly time series and vertical profiles averaged over the 1998-2008 period were also calculated and compared. Finally, for each site, and for the combined overall effect of the

Table 2. Final values of model's tuning parameters.

Tuning parameters	Oyster Grounds	~~Noordwijk~~ Noordwijk-10	West Gabbard
Initial nitrate concentration $(\mathrm{mmol/m^3})$	6	21	21
Initial silicate concentration $(\mathrm{mmol/m^3})$	5	40	7.5
Initial phosphate concentration $(\mathrm{mmol/m^3})$	0.15	1.2	0.15
Initial benthicdetritus concentration ~~$(\mathrm{mmol/m^3})$~~ $(\mathrm{mmol/m^2})$	1.5 ~~10^5~~ $\times 10^5$	6 ~~10^5~~ $\times 10^5$	1.8 ~~10^5~~ $\times 10^5$

platforms, the sensitivity of the modeled net primary production to the roughness of the platforms was investigated by setting the values of the roughness height of the platforms to h_{0s}= 0.0125, 0.025, 0.05, 0.1, 0.2 and 0.4 m.

3 Results

3.1 Tuning initial conditions

The resulting values of the tuning parameters, the initial concentrations of nitrate, silicate, phosphate and benthic detritus, are given in table 2. The values of the minimum RMS error and maximum correlation coefficient between modeled and observed time series are given in table 3. The results of the model with tuned initial conditions were compared with the observations for chlorophyll-a (figure 2, panels a,d,g), nitrate (panels b,e,h) and silicate (panels c,f,i).

Over all, the model reproduced the seasonality of the three locations well. For silicate and nitrate the agreement between model and observations was better for the locations of Oyster Ground and West Gabbard than for ~~Noordwijk~~ Noordwijk-10 (see also Table 3). For chlorophyll-a, the model reproduced the seasonal cycle at the three sites, but underestimated the high concentrations during the spring bloom at West Gabbard and ~~Noordwijk~~ Noordwijk-10 (figure 2). These locations are characterised by frequent blooms of phaeocystis (Blauw et al., 2010) (excluded from the model because inclusion led to spurious interannual variability within the 1D model context, see Section 2.2).

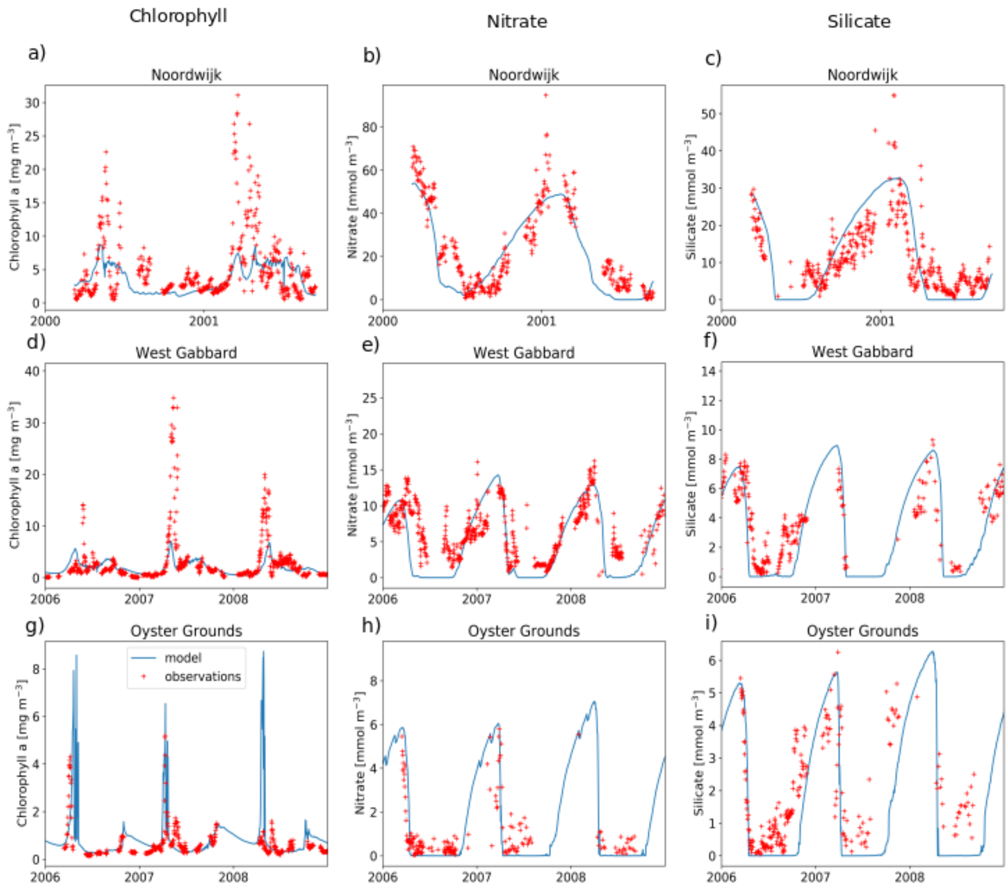

Figure 2. Assessment of the model's performance (blue line) for the three locations through comparison with observations from the Smartbuoys (red crosses). The variables of chlorophyll a (panels a,d,g), nitrate (panels b,e,h) and silicate (panels c,f,i) are presented.

3.2 Sensitivity of net primary production to coverage

3.2.1 Comparison between locations

To compare the effect of floating platforms between the three locations (research question 1), the relative change in net primary production was plotted as a function of coverage (Figure 3). The response was different at each of the three locations, but all sites showed, with increasing coverage, a limited reduction in net primary production followed by an accelerated reduction leading to a ~~complete collapse~~ strong decline of net primary productivity. Taking all sites together, three ranges of coverage can be distinguished. From 0% to approximately 20% coverage the difference in response between the three locations was relatively small. Also, the impact of the floating platforms on net primary production was relatively small (less than 10% reduction), while for West Gabbard even a small increase was simulated because of a reduction in suspended sediment concentrations (see

Table 3. The RMS error and correlation coefficient, after tuning, between the modeled and observed time series for chlorophyll-a, nitrate and silicate.

	Oyster Grounds	~~Noordwijk~~ Noordwijk-10	West Gabbard
RMS error chlorophyll-a ($\mathrm{mg/m^3}$)	1.22	4.26	4.44
RMS error nitrate ($\mathrm{mmol/m^3}$)	1.30	7.57	3.55
RMS error silicate ($\mathrm{mmol/m^3}$)	1.51	6.55	1.97
correlation coeff. chlorophyll-a	0.36	0.39	0.51
correlation coeff. nitrate	0.79	0.59	0.72
correlation coeff. silicate	0.70	0.59	0.81

below for more detail). Within this range of coverage, the two well-mixed locations appeared more resilient to the effects of the platforms than the stratified location of Oyster Grounds. From roughly 20% to approximately 40% coverage an increased spread in the results occurred between the three sites. Beyond approximately 40% of coverage, the net primary production at the two well-mixed locations sloped down rapidly~~, indicating collapse of the ecosystem~~. A similar ~~collapse~~ decline at the Oyster Grounds occurred later, at 60-80% coverage. These results suggest a different response for the stratified than for the two well-mixed locations. The two well-mixed locations appeared more resilient to small percentages of coverage, while they experienced an earlier ~~ecosystem collapse~~decline of primary production.

The resilience of the well-mixed locations for small percentages of coverage with floating platforms can be explained by the migration of their spring bloom towards the sunnier summer months (Figure 4) and by the compensating effect of decreased surface suspended sediment (Figure 5 b) on irradiance (Figure 5 a~~,b~~). In contrast, the timing of the spring bloom at the stratified location of Oyster Grounds, which is known to coincide with the onset of stratification (Ruardij et al., 1997), did not change substantially for coverage up to at least 60% (Figure 4c).

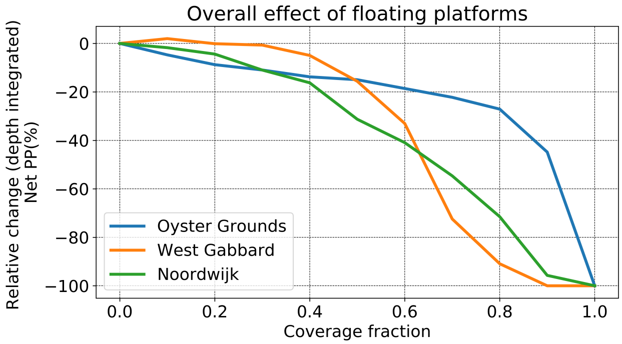

Figure 3. Relative change against the reference of net primary production with increasing coverage under the overall effect of floating platforms for the three locations of the experiment.

Considering irradiance near the surface (Figure 5a), for small percentages of coverage, a weaker reduction of subsurface irradiance occurred at the two well-mixed locations in response to a stronger reduction of suspended sediment at the surface (figure 5b), which allowed more light to penetrate the water column. The change in surface suspended sediment concentration with coverage followed the behavior of subsurface eddy diffusivity (figure 5c) in accordance with theory, as lower values of eddy diffusivity result in less upward mixing of suspended sediment (Burchard et al., 1999). For the two well mixed locations, the change in eddy diffusivity, and subsequently in suspended sediment near the surface, was caused mainly by the effect of friction of the platforms on the currents ~~. The friction of the platforms resulted in decreased vertical velocity gradients in mid layers and thus reduced shear stress and turbulence, while the pattern was opposite~~ (figure 6 a,b). Figure 6 and 7 illustrate the above for West Gabbard, while the response of Noordwijk was similar. For 10% of coverage eddy diffusivity decreased strongly due to platform friction (figure 6 a). This led to a decrease of suspended sediment in the upper water column (figure 6 b). Platform friction reduced velocity near the surface (figure 7 a). However, the effect near the bottom was minor, leading to no significant effect on suspension of sediment. On the other hand, the change in the shape of the velocity profile resulted in small (or zero) vertical gradients of velocity at mid depths and large vertical gradients of velocity near the surface (figure 7 a). This led to an increase of shear production (and thus turbulent kinetic energy) near the surface ~~where turbulence increased. The~~ and a decrease at mid depths (figure 7 b), affecting eddy diffusivity and suspended sediment concentration (eddy diffusivity is proportional to the the second power of turbulent kinetic energy). According to figure 7 b, the depth of the layer of increasing turbulence increased with coverage. Thus, the subsurface layers experienced a strong decrease in eddy diffusivity for low percentages of coverage ~~and an increase for higher levels of coverage~~ while further increase of coverage led to increasing values of eddy diffusivity (figure 5c). For the Oyster Grounds location, where tidal currents are weaker, the effect of wind shielding was more important. There, the reduction of wind forcing resulted in a gradual decrease of turbulence and eddy diffusivity over the whole water column.

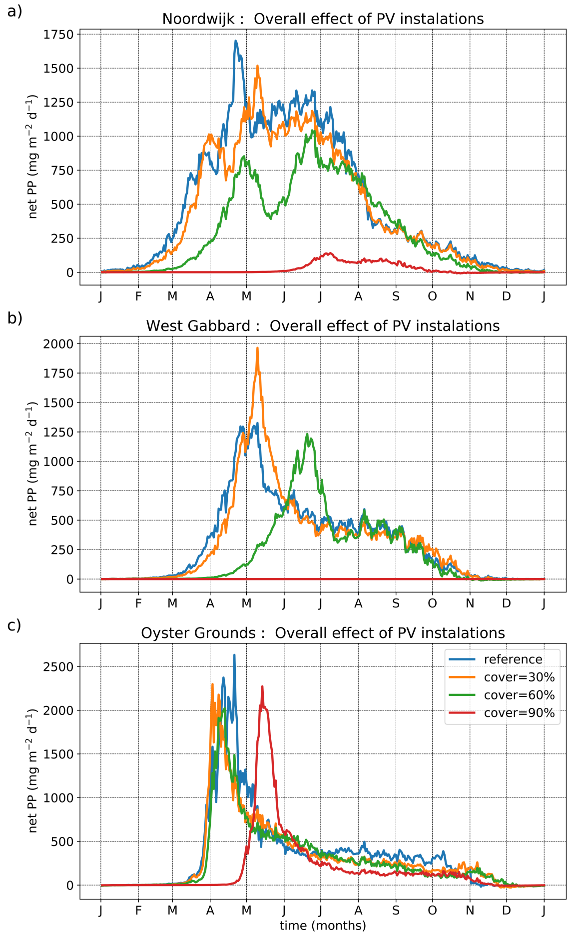

Figure 4. Depth-integrated yearly time series (averaged over 1998-2008) of net primary production for the three locations of the experiment. The results are presented for different scenarios of coverage under the overall effect of floating platforms.

The later ~~ecosystem collapse~~ strong decline of primary production for high percentages of coverage at the Oyster Grounds location can be explained by the effect of the platforms on stratification. Figure 8 shows the time-averaged vertical profile of net primary production (a) and the yearly time series of surface mixed layer depth (the depth where turbulent kinetic energy is becoming lower than 10^{-5} m^2/s^2) (b), for different percentages of coverage. The reduction of the depth of the surface mixed layer with coverage (figure 8b) that followed the reduced mixing due to wind shielding, resulted in upward displacement of the net primary production maximum that is located below the surface mixed layer (figure 8a). Due to its shift towards the surface

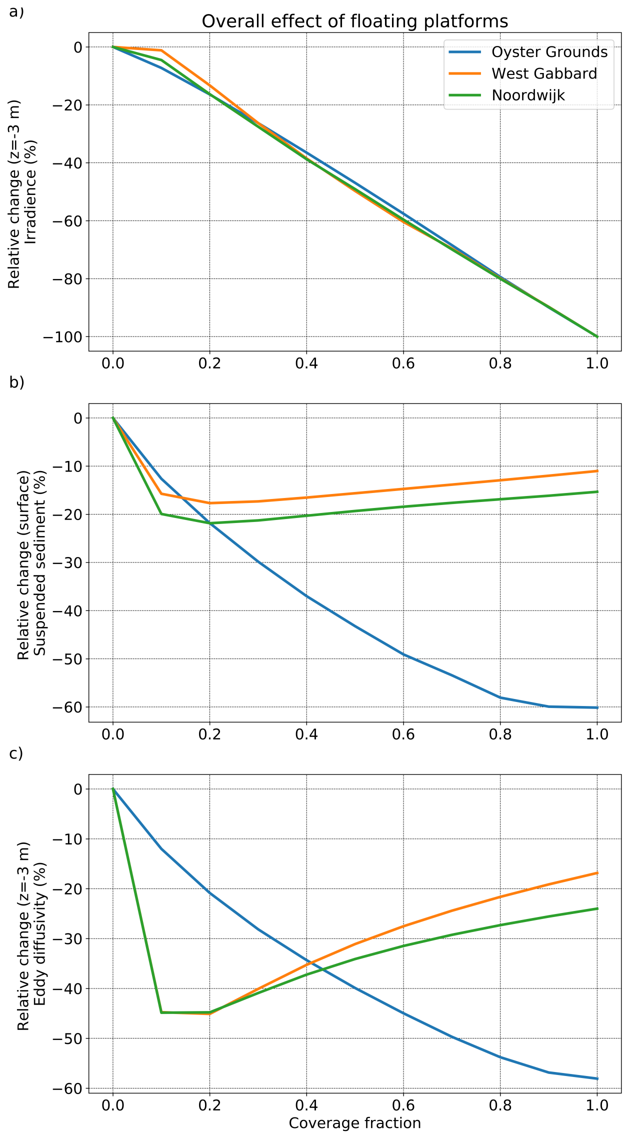

Figure 5. Relative change against the reference of (a) irradiance at 3 meters depth, (~~a~~b) ~~,~~ suspended sediment at the surface and (~~b~~c) ~~and~~ eddy diffusivity at 3 meters depth~~(c)~~. The results are presented for increasing values of coverage under the overall effect of floating platforms for the three locations of the experiment.

and hence towards the light, the subsurface maximum of time-averaged net primary production ~~(which happened mainly in summer) increased, while a~~ increased, as the effect of the upwards shift outweighed the light deficit induced by the platforms. A reduction of time-averaged net primary production occurred within the surface mixed layer (~~which happened during the spring bloom)~~figure 8a), as a thinner layer holds less nutrients. Above 60% of coverage, insufficient light reached the thermocline in summer, and the net primary production maximum observed at the stratified location of Oyster Grounds disappeared. The

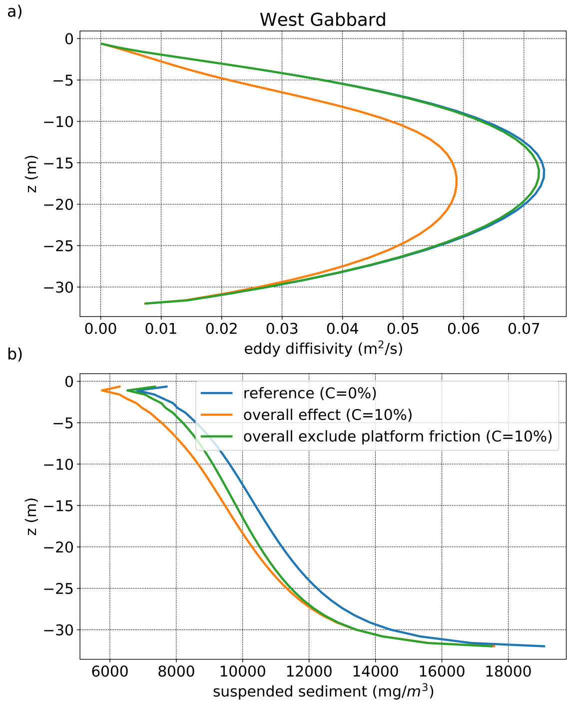

Figure 6. Vertical profiles of (a) eddy diffusivity and (b) suspended sediment concentration (averaged over 1998-2008) for the location of West Gabbard. The results are presented for the reference scenario (coverage=0%), and for 10% coverage under the overall effect and the overall effect excluding platform friction.

collapse of the net primary production maximum was accompanied by an increase of net primary production within the surface mixed layer, observed even for 90% of coverage with floating platforms. This explains the later ~~ecosystem collapse~~ strong decline in primary production for this location.

3.2.2 Contributions to changes in net primary production by separate processes

To compare the importance of the individual effects of the floating platforms (~~platform shadow~~platform-induced light deficit, wind shielding, platform friction) (research question 2) the response of net primary production to the different effects is presented in figure 9. ~~Platform shadow~~ The light deficit was the dominant ~~effect~~ factor for all three locations. For the two well-mixed locations (figure 9 a and b) platform friction increased primary productivity, resulting in an overall effect that was smaller than the individual effect of ~~platform shadow~~the light deficit. In contrast, for Oyster Grounds, the impact of the ~~platform shadow~~ light deficit effect was enhanced in particular by wind shielding (figure 9c). Reduced mixing resulting from wind shielding ~~blocked~~ prevented a later onset of stratification and spring bloom that would otherwise be caused by the effect

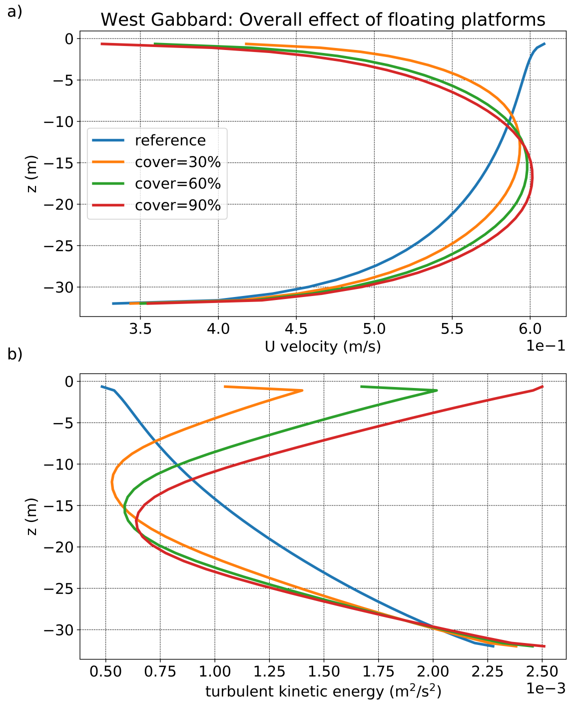

Figure 7. (a) Vertical profiles of velocity and (b) turbulent kinetic energy (averaged over 1998-2008) for the location of West Gabbard. The results are presented for different scenarios of coverage under the overall effect of floating platforms.

of ~~platform shadow~~ the light deficit (decreased buoyancy input)~~, and~~. It thus prevented the partly compensating effect of a later spring bloom on net primary production that occurred at the well-mixed sites.

3.2.3 Roughness of the platforms

To assess the uncertainty introduced by the assumed value of the roughness height of the platforms (h_{0s}=0.05 m), and to evaluate the potential importance of the platform design and maintainance, model runs were conducted for different values of h_{0s}. For coverage up to 20%, the difference was small for all sites (Figure 10). At the well-mixed sites (panels a,b), for higher levels of coverage (>40%), the range of values of platform roughness showed a spread in the impact of the floating platforms on the net primary production equivalent to a difference of approximately 10% in coverage, by modifying the eddy diffusivity, and thus the suspended sediment concentration near the surface. For the Oyster Grounds location (panel c) and coverage levels higher than 60%, the increase in roughness height compensated the impact of the installations on net primary

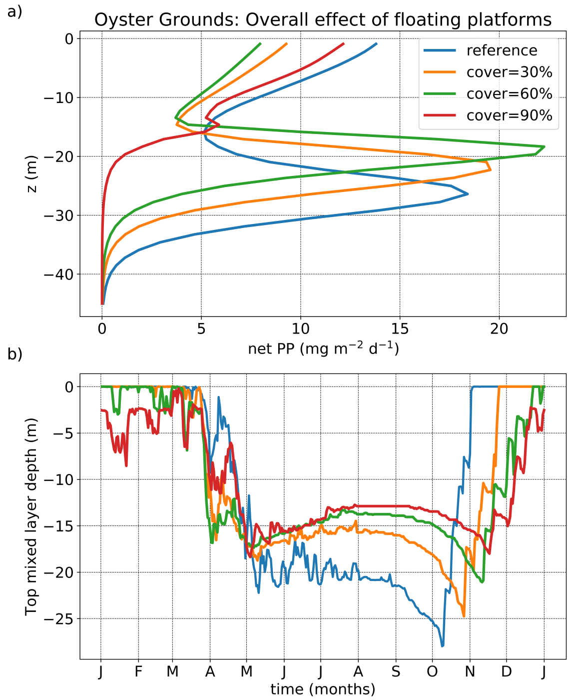

Figure 8. Vertical profiles of (a) net primary production and (~~a~~b) ~~and~~ yearly time series of top mixed layer depth (~~b) (~~averaged over 1998-2008) for the location of Oyster Grounds. The results are presented for different scenarios of coverage under the overall effect of floating platforms.

production to some extent. This compensating effect for high values of the roughness height on net primary production is not fully understood, but may be related with the deeper surface-mixed layer under higher values of roughness height.

4 Discussion and conclusions

The direct and indirect effects of floating platforms on net primary production have been analysed for three contrasting locations in the North Sea using a water-column model, showing overall reductions for increasing levels of coverage. Three response regimes were identified. In regime 1 (less than approximately 20% coverage), the three locations were relatively resilient to the presence of the platforms, and the reduction of net primary production was relatively small (less then 10%). This seems to be a relatively robust response, that can possibly be extrapolated to other sites in the North Sea. In regime 2 (approximately 20-40% coverage), a substantial spread in the results occurred between the sites. Thus, no general site-independent

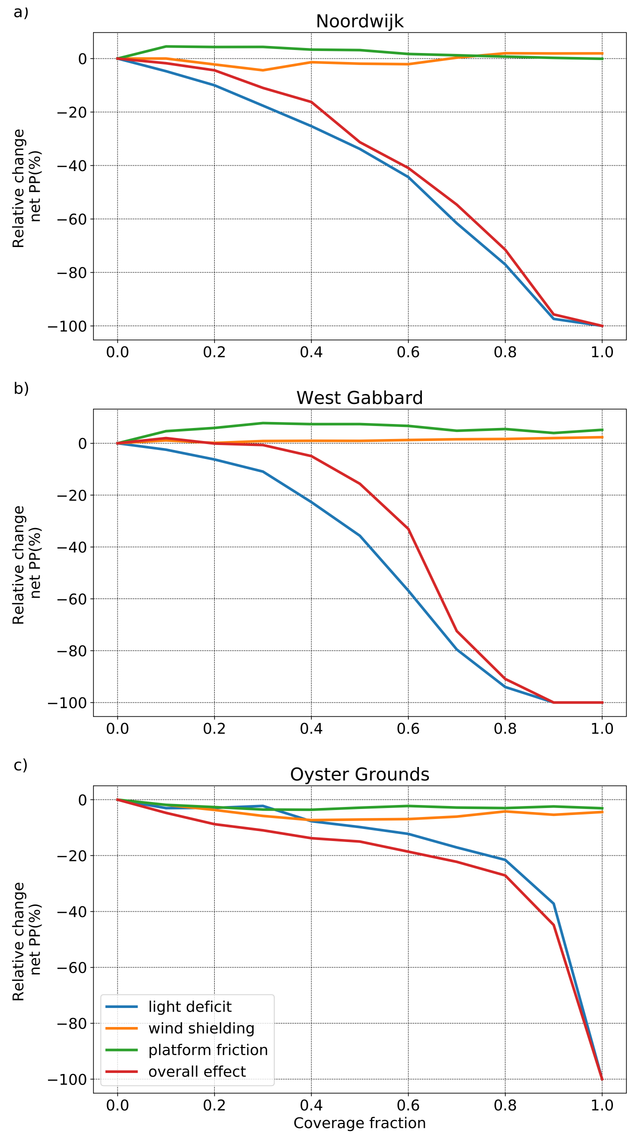

Figure 9. Relative change against the reference of net primary production with coverage, for the three locations of the experiment under the different effects as a function of coverage with floating platforms.

conclusions can be drawn. In regime 3 (more than approximately 40% coverage), all three curves sloped down rapidly, albeit at different levels of coverage. This again is a similar and robust response indicating serious disruption of the ecosystem, ultimately leading to a full collapse.

The water-column model assumes a 'unit' horizontal extent and spatial homogeneity, not only in terms of the oceanographic and biogeochemical properties but also in terms of coverage with floating platforms. As the spatial homogeneity assumption

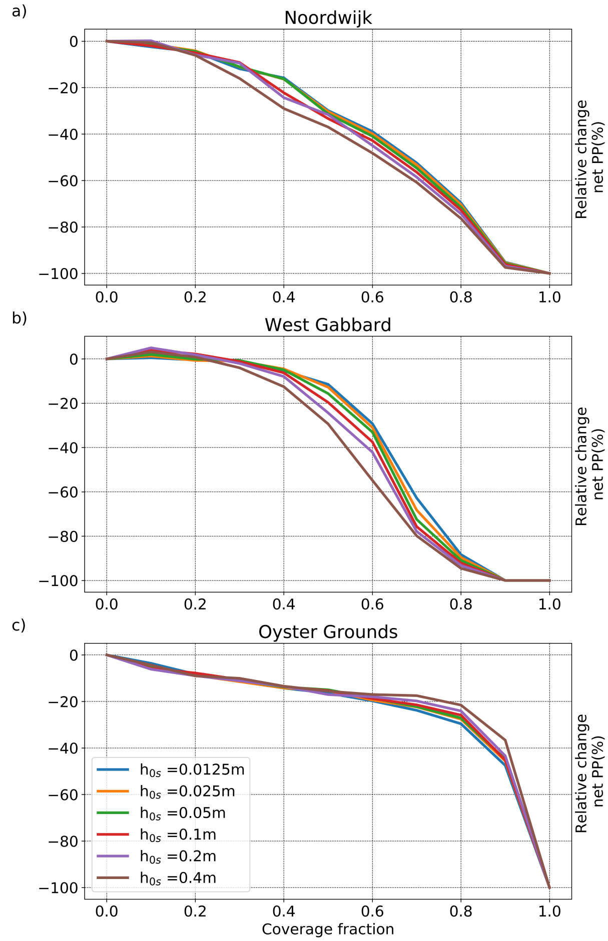

Figure 10. Relative change against the reference of net primary production with coverage, for the three locations of the experiment and different values of roughness height of the platforms (h_{0s})

implies having the same conditions into infinity, it is not immediately clear how the water-column model results can be related to solar PV farms of a finite extent. We can, however, provide a rough estimate of a minimum spatial scale needed to start to approximate spatial homogeneity. To obtain equivalent (changes in) primary production conditions as simulated by the water-column model, phytoplankton, which are transported by the tides, would need to spend a significant amount of time underneath a farm of a certain size (longer than they can chemically buffer solar energy photosynthesized before they were advected into or out of the farm area). Hence, as tides generate the dominant currents in the North Sea, we could take the tidal excursion length as a measure of minimum horizontal size corresponding to the conditions simulated by the water-column model: if a farm is smaller, it does not conform to the spatial homogeneity assumption of the model because individual phytoplankton cells would be advected into and out of the farm on a time scale of hours. Considering the M2 harmonic constituent as the dominant tidal component, taking the tidal current amplitudes at the three locations from a ~~3D~~ three-dimensional model, and integrating over half a tidal cycle (6.25 hrs), the estimated tidal excursion lengths are 3.3 km for Oyster Grounds, 7.3 km for ~~Noordwijk~~ Noordwijk-10 and 12.5 km for West Gabbard (Table 4). For solar PV farms smaller than this length scale, the modelled reductions in net primary production presented here may be over-estimates, and simulations with spatially resolved models are needed to obtain more accurate results. A similar argument holds if substantial residual currents are present in addition to tides. We also note that the results presented here are based on the assumption that platforms are distributed homogeneously in space. Estimates of potential modulations of the current results that may be induced by inhomogeneous distributions of platforms in space can only be made with spatially resolved models.

Table 4. M2 tidal velocity amplitudes, Estimated tidal excursion length as the Minimum length scale of farms with floating platforms for which the water-column model results are valid.

Location	M2 tidal velocity amplitude	Estimated tidal excursion length
Oyster Grounds	0.23 m/s	3.3 km
West Gabbard	0.87 m/s	12.5 km
~~Noordwijk~~ Noordwijk-10	0.51 m/s	7.3 km

These first model simulations have ignored a number of physical and biological processes that should be considered in further work. The implementation of PV-coverage with a 1DV model does not allow for a realistic representation of the spatial configuration of a solar power plant, the characteristics of which (e.g., the distance between platforms, service lanes) could result in a different response of the ecosystem, as they would influence the horizontal light diffusion below the platforms and the development of the surface boundary layer from friction with the platforms. Moreover, wave-platform interactions and their effects on the mixing of the water column and the resuspension of sediment have been ignored in this study and may well depend on platform dimensions. To account for these processes in further work, simulations with three-dimensional (3D) models are needed. Also, additional ecosystem components could be considered in a three-dimensional model, such as phaeocystis in areas with high nutrient loads, and growth of hard-substrate flora and fauna on the platforms. It may also be possible that there are effects on atmospheric properties (effect of platforms on the wind) and air-sea gas exchange.

We used three contrasting and relatively data-rich locations in the North Sea for this first study to illustrate the effects of floating platforms on net primary production. The differences in the response between the sites indicate that studying new locations will add valuable information. The study focused on the response of the marine (eco)system to floating platforms in terms of water-column structure and net primary production, but other quantities with indicator qualities should also be considered in further work, such as changes in sediment transport, disturbance of the balance of organisms, and the integrity of the sea bed in terms of biomass, species composition and biogeochemical functioning. A good next step would be an examination of the effects of floating platforms with a local ~~fine-resolution~~ high-resolution 3D model. The water-column model as presented here can, despite its limitations, be used as a test bed to support further work.

This first study was carried out as an exploratory investigation of potential effects and mechanisms, and has elucidated the principle response of the ecosystem. Extreme care should however be taken to use the results for specific planning purposes, and in principle further investigations should be carried out for specific cases. However, as a rough rule of thumb, in absence of better data/models/knowledge, adopting the precautionary principle, and disregarding other effects and criteria that were not considered here (e.g., ecosystem variables other than net primary production, impact on waves, impact of biofouling on the biogeochemistry, specific spatial distribution of floating structures within a farm, acceptable levels of impact, political and planning considerations, etc.), we recommend that real-world field implementations of floating infrastructure in the marine environment should not enter regimes 2 (too uncertain) and 3 (significant disturbance). This implies that, according to our results, coverage density should not exceed approximately 20% for farms of a size in the order of magnitude of the local tidal excursion length or larger. We also advise that for general and individual cases 'acceptable' levels of impact are defined and motivated, and further work is carried out to improve understanding of environmental effects of floating (solar PV) platforms, or any other large floating infrastructure in the marine environment such as large-scale seaweed farming, in general and for specific cases.

Appendix A: Mathematical implementation of the floating structures

The incident radiation with floating ~~strucures~~ structures is given by

$$I_0' = (1-C)I_0 \tag{A1}$$

with I_0 the incident radiation without platforms, and C the coverage fraction a number between 0 and 1. The surface wind stress with floating structures , assuming that the platforms do not affect the wind speed, is given by

$$\boldsymbol{\tau}'_w = (1-C)\boldsymbol{\tau}_w \tag{A2}$$

with $\boldsymbol{\tau_w}$ the surface wind stress vector without platforms. The surface shear stress by floating structures, according to the logarithmic law of wall, and assuming that the platforms are large compared with the development distance of the platform boundary layer, is given by

$$\boldsymbol{\tau}'_s = -r_s\boldsymbol{u}||\boldsymbol{u}||C \tag{A3}$$

Here, $\boldsymbol{u}$ is the velocity vector in the surface cell given by

$$\boldsymbol{u} = \frac{\boldsymbol{u_{*s}}}{\kappa} \ln\left(\frac{z_{0s} + h/2}{z_{0s}}\right), \tag{A4}$$

with $\boldsymbol{u_{*s}}$ the frictional velocity at the underside of the floating structures, and r_s the surface drag coefficient of the floating structures given by

$$r_s = \left(\frac{\kappa}{\ln(\frac{z_{0s}+h/2}{z_{0s}})}\right)^2, \tag{A5}$$

~~with~~ where κ is the Von Kármán constant, h the height of the surface cell, and z_{0s} the surface roughness length of the floating structures, defined by

$$z_{0s} = 0.1\frac{\nu}{u_{*s}} + 0.03h_{0s}. \tag{A6}$$

Here, $\nu = 1.3\text{E-}6$ (m^2/s) is the molecular (kinematic) viscosity, h_{0s} the mean height of the roughness elements at the bottom of the platform, ~~and~~ u_{*s} the magnitude of the friction velocity ~~at the underside of the floating structures.~~ and the scalar factors are from (Burchard et al., 1999).

Appendix B: Mathematical description of light attenuation

The radiation at different depths of the water column is given by

$$I'_{(z)} = I'_0\, e^{-k_d(h-z)} \tag{B1}$$

where I'_0 is the incident radiation, h the water depth, z the height above bed and k_d is the total extinction coeficient, due to scattering and absorption processes, and is given by

$$k_d = k_{d,w} + k_{d,cdom} + k_{d,spm} + k_{d,chl} + k_{d,det} \tag{B2}$$

with $k_{d,w}$, $k_{d,cdom}$, $k_{d,spm}$, $k_{d,chl}$ and $k_{d,det}$ the extinction coefficients due to clear water, colored dissolved organic matter, (mineral) suspended sediment, chlorophyll and detritus, respectively.

Code availability. The code versions used for the coupled model are available from the authors on request. Stand-alone code for GOTM can be downloaded following instructions on gotm.net.

Data availability. SmartBuoydataareavailablefromCefas,seewww.cefas.co.uk/cefas-data-hub/smartbuoys for details.

Author contributions. Thodoris Karpouzoglou did this work as MSc student at Utrecht University. Brigitte Vlaswinkel initiated the study. Johan van der Molen formulated and planned the project.

Competing interests. Brigitte Vlaswinkel is Research Director of Oceans of Energy, a commercial company that develops offshore solar power arrays. The interests of Oceans of Energy include aims to not exceed acceptable impacts on the environment, and commercial interest have not played a role in the study. The other authors declare that they have no conflict of interest.

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