Responses to: Review of the manuscript “Increasing turbidity in the North Sea during the 20th century due to changing wave climate”, by Wilson and Heath.

General comments

The authors use historic and current proxies for suspended particulate matter concentration (SPM) and bed shear stress (BSS). It is their goal to show that changes in both have been related since 1900. I like the general idea of the manuscript. It has potential and can advance the knowledge on the changes in the North Sea, but it needs significant improvement at this stage, especially to facilitate the understanding of what data are used and what assumptions are made. A large amount of data from many sources is downloaded. The description in the manuscript is very difficult to follow. I strongly advice a table where the following fields are shown: URL or FTP address, short description, date range, spatial and temporal resolution.

In particular, there is an inaccuracy in the satellite SPM data description. What authors are downloading is the CMEMS global optics L4 reprocessed product, which in turn is generated from Globcolour data. Therefore, a proper reference to the CMEMS web page is expected, as well as to the product QUID and PUG. For instance, here is the QUID document of the product they are using: http://resources.marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-030-032-033-037-081-082-083-085-086-098.pdf

A data table has now been added, and Globcolour references have been corrected. We have clarified the use of CMEMS data by providing the approprotitate links to the relevant product user manuals.

In fact, and as a side comment, I am surprised to see a paper led by a scientist from PML download a Globcolour dataset when the CCI dataset could be used instead: http://resources.marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-064-065-093.pdf. This product provides global marine reflectances and has been developed by PML scientists, having a much better characterization of quality and uncertainties. This product contains Rrs(670) which can safely be used as a surrogate for turbidity. Other products like particle backscattering and also newer releases can be checked outside CMEMS, in the CCI website.

The practical reason for this is that the lead author was working at the University of Strathclyde while this paper was written. The original submission erroneously did not provide a double affiliation, but this has now been fixed in the resubmission.

The use of Rrs_670 reflectance was something we considered during the analysis. However, we expect that the paper is targeted at a very broad audience, in particular marine ecologists, and we believe that using marine reflectance, and not SPM will reduce the accessibility of the paper. Furthermore, while there are some benefits to using the OCCCI data products, it is unclear to us if they are superior for our purposes. The critical issue is that we use a product that best captures temporal changes in turbidity. As far as we know there has yet to be an empirical comparison of various products in this regard.

See also a typo in the ftp address provided in the manuscript, “cems”. Here, the authors downloaded the global product and resampled for the North Sea instead of directly downloading the product for the European North-West Shelf Seas, for the obvious reason that a REP product is not available for the for that region. Even though this is a complaint and authors did well, it must be stated in the manuscript as a need for service improvement.

We have now removed references to the ftp sites. CMEMS often change where data is stored, so adding an ftp that is likely to become redundant is probably a bad idea.

We are unsure that the paper is an appropriate venue for calls for service improvements for CEMS. If we do this for CEMS, we should do this for the other data providers, who sometimes have a greater need than CEMS to improve services.

The water temperature is another CMEMS product. The URL indicated needs to be specific to that product, as well as the reference to the product QUID and PUG documents.

We have now added relevant QUID and PUB documents.

Though not being a specialist in the physics of the ocean, I understand that a key point in the authors' is that BSS is caused by waves, which is caused by wind. Apparently all the physics is in another paper, but it would be good if authors did a summary of how one physical quantity determines another.

Section 2.4: Methods should be described in a comprehensive for any scientist independently of the software used. So I would prefer a description in terms of equation rather than mentioning R packages.

All of the equations used in the analysis are supplied in Wilson et al. 2018. We have now made this clearer. We believe that is more appropriate to point readers there instead of repeating the equations in new supplementary material.

The Secchi disk analysis is a weak point of the paper that undermines the analysis of the historic trends. A rigorous trend analysis must be made and the significance of such trends must be made. Also it is likely that authors missed many samples by forcing samples before and after 1905 to be close in space. Here I advise the authors to divide the North Sea in areas to cluster the Secchi disk measurements. Then the corresponding time series would be decomposed in seasonal, long-term and irregular trends using an approach like the X11. In open areas where data is expected to be more scarce but also less horizontal variability is expected, regions would be of greater size than coastal areas.

We have now moved the Secchi disk analysis to a separate figure, which shows changes by season. The aim of this analysis was to give a prelimenary, and admittedly indicative, view of the spatial changes in Secchi Disk depth. The approach taken runs into the problem that in many regions there is sparse data, and the langugage used in the original paper was perhaps not cautious enough. However, we are skeptical that alternative approaches are available. The aggregation methods of Dupont and Aksnes (2013) and Capuzzo et al. (2015) do not effectively deal with spatial sampling bias. For example, Dupont and Aksnes (2015) control for bottom depth and distance to the coast. However, bed shear stress and sediment properties are likely to be more important covariates. Given that there are huge differences in the spatial coverage in Secchi disk samples pre- and post-1950 we are concerned that the aggregation methods used in other studies do not result in partly spurious trends.

The paper as it is now seems to effectively prove a link between SPM and BSS for the satellite era (Figs. 1-3) but I cannot say the same based on the historic period (Fig. 4). Assuming the Secchi disk analysis correct, which I am not sure about, I am unable to appreciate any relationship between the left and right panels of Fig. 4, and the related discussion in Fig. 4 seems misleading. I particularly disagree with the sentence "Over the longer term, spatial patterns in changes in bed shear stress between 1910-1929 and 1990-2009 correspond with spatial patterns in differences between Secchi disc depth pre- and post-1950."
We agree the original paper overstates the ability of the reanalysis to recreate the historical trends in the original figure 4. In reality, because of the sparseness of the historical Secchi Disk depth data we cannot say with huge confidence what the spatial patterns were. However, while the big picture – North Sea water clarity declined – remains in in place, there are some indications this was not universal across the North Sea. The paper's text has now been reworded to be more cautious.

Regressions in Fig. 3 lack their statistical parameters. How were they calculated? What weight is given to outliers? What do a similar slope but different intercept mean in terms of physics?

In the original manuscipt the statistical parameters were given in the supplementary materials. These have now been moved to the main text.

The analysis left as a supplement may be of interest for the main manuscript if is accordingly treated. Here, authors seem to find a reversal of the long-term water darkening, accompanied with a corresponding decrease in BSS. As commented above for the historic period, trends have to be rigorously calculated and tested for significance.

"Our analysis shows that changes in wave energy have been a key, and probably the dominant driver of changes in water clarity in the North Sea." That is a very strong statement and I would like authors to spend some time explaining the physics behind.

This statement in the original text was probably too strong. We have now reworded it to make it clear that we have shown that changes in the wave regime caused large increases in bed shear stress. Because of the spatial sparsity of the Secchi Disk depth data, there is a lot of uncertaintity in the actual changes in Secchi Disk depth, so we should have been more cautious in interpreting the results.

The key result of the paper is that the wave changes shown by the wave reanalysis would have resulted in large reductions in water clarity. The original placement of this result side by side with the Secchi disk depth data result probably provided a misleading impression. The new figures arrangement is more reflective of the key results in the paper.

Minor comments

The page numbering restarts at every page, which I am not sure is due to journal format, but a unique numbering for the whole manuscript would help.

Page numbering restarts in each page as part of the Copernicus default template.

The words "disc" and "disk" are found in the manuscript. Authors might unify the grammar choice.

This has now been changed to "disk" throughout.

Correct "Capuzz"

This has now been corrected.

The reference Jafar-Sidik et al. (2017) is not found in the reference list.

This has now been added.

Page 6, line 5: "drive" should be "driven"

This has been corrected.

Page 2, line 6: “SMP”

This has been corrected to “SPM”.

Page 9, line 5: replace “are” with “is”

This has been corrected.

Replies to: Interactive comment on “Increasing turbidity in the North Sea during the 20th century due to changing wave climate” by Robert J. Wilson and Michael R. Heath

Jochen Wollschlaeger (Referee) jochen.wollschlaeger@hzg.de Received and published: 1 July 2019

General comments The authors relate historical observations regarding water transparency (Secchi-disk depth) with calculations of shear bed stress based on model hindcast simulations. By this, they demonstrate that increased mobilization of sus- pended particulate matter is a major driver for the negative trend in tranparency that was observed in the last century in the area of the North Sea. I really like the concept and the idea of the paper. Although the trend of decreasing overall transparency in the North Sea over the last century is already known (as the authors show well with their comprehensive literature review), the reasons and drivers remain largely speculative to date. In this respect the current work contributes to understand some of the underlying processes. However, in some cases, the conclusions drawn are not always supported clear enough by the data shown. In this respect, I would recommend improvement of the manuscript. Hopefully, the remarks and questions below are helpful in this context.

Introduction: As I understand the linear regression given in Håkanson (2006), it shows a linear relationship between the log values of SPM concentration and Secchi disk depth. Thus, changes in one parameter are transferred logarithmically to the other. Therefore, I would be careful with the “20 % increase in SPM” statement (also in the discussion), inasmuch as it is based on the average decrease in Secchi disk depth Capuzzo et al. found.

We have removed the 20% reference in the introduction, as it wasn’t really necessary. The 20% increase in the discussion was referring to the approximate increase in SPM we would expect in the south eastern North Sea. This was based on the regressions for that region. The original text did not make that clear, so we have reworded it.

Methods: Page 3, Line 4: Does diffusivity play really a role in this context? If so, please elaborate a little bit more on that and/or give a citation.

The influence of diffusivity on the vertical profile of SPM is discussed in Heath et al. 2017. We have therefore moved the reference to Heath et al. 2017 to the end of this sentence, where it is more appropriate.

Page 3, Line 7: What is the rationale behind the 0.5 ◦C difference as threshold for a stratified water column? If this is a common value, please refer to the appropriate literature.

The use of 0.5 C was motivated by the North Sea Region Climate Change Assessment, which used this as the metric for the onset of seasonal stratification. The text has been modified to make this clear, and to reference the North Sea Region Climate Change Assessment.

Page 3, Line 27+: Could you explain why you are using two different datasets for calculating bed shear stress hindcasts? Wouldn’t it be better to use the larger one in terms of being consistent in the data over the whole period (although missing the years 2011 to 2017)?

Ideally, we would use one data set, not two. However, the comparison with satellite SPM was carried out to provide the best available quantitification of the large-scale influence of waves on SPM. The ERA-20c reanalysis is much less appropriate than the ERA-interim for two key reasons. First, it’s temporal coverage is limited to before 2011. Second, ERA-interim is a higher quality data product.

The methods section has now been adjusted to make clearer why two separate wave reanalysis were used.

Page 4, Line 26: What means "Core data analysis" in this context?

This has been reworded to state that we were referring to the R package used for the bulk of the data manipulation.

Results: Page 5, Line 8-9: From my point of view, the seasonal pattern is not readily visible in Figure 1 (right).

After looking at this figure again, we agree the seasonal pattern is not particularly clear. We have experimented with a number of different colour scalings and have concluded that this cannot be made readily visible. Instead we have switched to just showing annual mean bed shear stress.

Page 6, Line 3-4: That the relation is positive is not visible from the R2 values given in Figure 2. Maybe refer also to Figure 3 at this point. Further- more, I would soften the statement "across almost the entire study domain", because even when the water column is mixed, there are some exceptions (as also stated by the authors). However, beside the two plume regions mentioned, also the English Channel, the Irish Sea, as well as the whole British east coast appear poorly impacted by the shear stress in terms of SPM.

The original paragraph was poorly worded. It has now been amended to make it clear that in tide-dominated regions the R^2 values is low.

Page 7, Line 1-5: If the relation between shear bed stress and SPM is decoupled in the stratified season, what are then the drivers for the Secchi-disk decline in these months? Or is in this season also the decline in Secchi-disk depth lower? If so, the authors could refer to the appropriate literature or show the respective data.

"Decoupled" is perhaps not a totally accurate term. What we mean to say is that when the water column is stratified variations in vertical current shear and diffusivity appear to have a much greater influence on temporal variations in surface SPM. However, this does not mean that bed shear stress does not explain the decline in water clarity during spring and summer during the 20th century. If stratification levels remained the same then bed shear stress likely drove a large part of the decline. However, whether this is true is an open question.

The results section now has a sentence stating that during stratified conditions the influence of the thermocline etc. dominates the vertical profile of SPM.

Page 7, Line 10+: Maybe incorporate the change in the trend into the main manuscript, as it is interesting and contributes to the whole story.

This an interesting part of the story, but we have reluctantly chosen to keep it in the supporting materials. The key focus of the paper is on what happened during the 20th century. Moving the two supporting figures to the main text risks undermining that, as we would have 6 figures on present day conditions, but only one on historical changes.

Page 9: The authors emphasize the strong decline in Secchi-disk depth south of 53∘N (Figure 4, right side), and explain it with an pronounced increase in shear stress across the region. However, according to the left side of the figure, I cannot see that the decrease in Secchi-disk depth at this point correlates to an increase in bed shear stress, which appears to be relatively small in this area (approx. 0-20%). However, as in this area the East Anglian plume as well as the plume of the Rhine is present, I would rather think that the decline in Secchi-disk depth here might be controlled by changes in e.g. river outflow (as stated by the authors before). Nevertheless, for the Northeastern part of the area (53-56◦N, 4-8◦E) the relationship appears to be valid, although the number of data points is comprehensively small.

We have now moved the historical Secchi disk depth data to a separate figure. This was originally placed beside the bed shear stress figure to reduce the figure count more than anything. However, with hindsight this was likely not a good choice. Because the data is very sparse, we can only get an indicative idea of what the spatial patterns of Secchi disk depth changes were. The key issue is whether the big picture stories agree, and they largely do.

Discussion: Page 10, Line 13-14: I think this statement is too strong. Instead I would claim that according to the data available shear bed stress is probably an important parameter in order to explain the transparency decrease in the last century.

The text has been changed to be something more cautious. We have now changed the text to say large reductions in water clarity would have resulted from the bed shear stress changes shown.

Page 11, Line 12-18: Maybe some of the discrepancies could also be explained by a seasonally variable contribution of the organic (e.g. phytoplankton) part of SPM. Turbidity is also influenced by the presence of pelagic phytoplankton.

This should have been stated on page 11 lines 8-13, which referenced Jafar-Sidik who found that satellite SPM potentially mixes up SPM and phyotoplankton during summer months. The text has been amended accordingly.

Minor comments

Page 3, Line 14-15: Check the brackets for the reference.

This has been corrected.

Page 6, Line 1: “and SPM” after bed shear stress appears to be doubled.

This has been corrected.

Page 7, Line 7: Maybe replace “bed shear stress and SPM” with “the two parameters” to avoid doubling of the terms with the begin of the sentence.

Agreed. This has been changed.

Page 11, Line 9 + 13: “in situ” instead of “in-situ”

This has been corrected.

Caption Figure 1: In the text is stated that the bed shear stress calculations are calculated after Soulsby & Clarke (2005), but in the caption stated Soulsby (2006). Please explain or correct.

It should have been Soulsby and Clarke in the caption. Now corrected.

Caption Figure 4: “Century” or “century”; please keep consistent

This has now been made consistent throughout the text

Reply to: Interactive comment on “Increasing turbidity in the North Sea during the 20th century due to changing wave climate” by Robert J. Wilson and Michael R. Heath

Anonymous Referee #3

Received and published: 17 July 2019

General Comments: The authors investigate the relationship between suspended par- ticulate matter (SPM) and bed shear stress (BSS) by means of historic, satellite and model data. They motivate well in their literature review that decreasing water clarity in the North Sea may be linked to increased SPM content. The premise of this work is enticing. It can help to motivate further research and provide an explanation for the long term increase of water turbidity. I find the paper to be well written, language wise, and the motivation and analysis part to be comprehensive, but the analysis needs to be more quantitative. Particularly, I like the message that changing wave regimes should not be neglected in long term simulations with reference to climate change. There are some details and nit-picks that need reworking.

Introduction: The statement of SPM increase possibly exceeding 20% needs to be made cautiously. While the method of Hakanson 2006 is perhaps not ideal to show this, I am more concerned about the vague phrasing. I find no basis for it.

While we believe the original phrasing was cautious in that 20% is within the bounds shown by some empirical studies, we have now removed the 20% reference, as it was not really necessary.

The authors mention several times that tides can be assumed to be free of long-term changes, which is not exactly true, pedantically speaking. There are long period tides (see e.g. Wunsch 1967), which may be negligible directly due to their low amplitude (<1cm) but they play a role in low frequency climate oscillations. Furthermore, sea level rise has an effect on the tidal regime. It is certainly more feasible to neglect them, but then perhaps this should be mentioned.

We have now added a reference to Wunsch, and a second reference showing the potential impacts of climate change.

Methods: There is a vast amount of data used and it would be helpful to expand on the particular choices of data sources and organise it for the reader’s eyes (perhaps in a table or figure). Some data was taken from CMEMS/MetO-NWS-REAN-PHYS to determine if a water column was stratified (section 2.1), but depth-averaged veloc- ities were taken from an FVCOM model, while those same velocities are available at CMEMS as well. It would be helpful to motivate the individual data choices. There may have been easier choices for a unified data set with fewer independent sources.

A table has now been added to make it easier to understand the data used. With hindsight some easier choices could be made, however data choices were in some cases the result of what was available through certain projects., and we decided against simplifying them, given data processing methods were already in place.

Page 3, line 4 (diffusivity): as a physicist, I do understand the role of diffusivity, given that turbulent diffusivity is of course in orders similar to sinking velocities. So perhaps just add the word “turbulent” there.

The word “turbulent” has now been added to clarify the text.

The threshold of 0.5◦C appears arbitrary and needs further explaining. One could e.g. refer and compare to the definition of the mixed layer depth (MLD) used in CMEMS/MetO-NWS-REAN-PHYS or Kara et al. 2000. Alterna- tively, one could just use said CMEMS data of the MLD instead of coming up with a new one (i.e. if the MLD is smaller than the water depth, the column is stratified).

The choice of 0.5 C came from the North Sea Region Climate Change Assessment 2016, who defined stratified waters as those with prolonged periods with temperature differences between surface and seabed above 0.5 C. We believe this is a reasonable proxy for stratification for the purposes of this paper. The aim is to illustrate which months have mixed water columns, not to provide precise quantifications.

Because the ERA-interim and ERA20c are different data sets, they cover a combined period of 1990-2017. It should be made clear that there is no combined data set or otherwise how a potential integration is carried out and bias is made impossible.

The text in the methods section has now made this clearer, and we have stated that two reanalysis were used because the ERA20c reanalysis does not overlap fully with the satellite SPM.

I am unfamiliar with R, but as far as I can see, no tremendously complex statistical operations have been carried out that would require elaboration beyond textbook knowledge and I would know how to achieve the same results in MATLAB. However, it is perhaps helpful to provide some algorithms as flow diagrams in a supplement.

All of the equations used to calculate shear stress are provided in the supplementary materials of Wilson et al., 2018. We have now made this clear in the text. The actual bed shear stress code is written in C++, not R. This has also now been made clearer in the text.

Results: The results section starts off with an explanation of a seasonal climatology of near surface SPM, as well as BSS. This would be more suitable in the methods chapter.

We have now moved the SPM climatology to the methodology, with the BSS climatology still in the results. We have kept the BSS climatology in the results because we have now added a panel showing the relative contribution of waves to bed shear stress.

Figure 1 is the first of several cases where the authors say in the text that there was something to see in the figure which is actually hard to see (in this case the seasonal cycle of BSS, which is noted in the text but not well visible in the image).

We agree that this does not read very well. Because of the very large spatial variation in BSS, we have concluded that it is not possible to map seasonal BSS with the seasonal variations being particularly clear. And so we have just gone with an annual mean. The map of bed shear stress is big picture context for the main results, and is one that has appeared in various other papers. So it makes sense to stick with an annual climatology.

For figure 2, the same criticism applies as for figure 1: the text says that there is a clear positive relationship, but the figure shows dark blue colours on the left panels in several areas where the right panels show bright yellow. It needs to be made clearer what constitutes as a “clear positive relationship”, i.e. a by threshold value or something of the sort and the colour maps need to be modified accordingly. For example, in the text (page 7, line 4ff) it says that the transition to mixed water increases the link between SPM and BSS, which can be seen south west of Ireland in November, but in the figure, it is dark blue there, which indicates a weak correlation. The message that figure 2 carries could be made clearer also by an area correlation, which is more quantitative than a visual comparison.

The original text was poorly explained. We forgot to state that in tidally dominated regions waves will have little influence, so we do not expect the model to explain much. This is illustrated by the new figure 3, which approximates the relative influence of waves. The region South West of Ireland has a relatively low influence of waves. We therefore expect relatively low R^2 values in the regressions. It is notable that the R^2 values are a lot higher in this region in December and January than in November, which is attributable to higher waves.

The monthly stratification was not previously described as climatological, as it is pre- sented here in figure 2. Instead it was written in section 2.1 that the percentage of stratified water columns was taken for each month over a period of 20y. Since the analysis covers 20y and the BSS is assumed to change due to changes in wind stress, the stratification would potentially show trends as well due to changed turbulent mix- ing. Climatological stratification thus makes less sense than monthly means over 20y, unless it can be shown or motivated that the change in stratification is negligible. In the first paragraph of page 7, it says that SPM and BSS become uncoupled in strati- fied regions in summer months. However, with reference to figure 1, the authors claim a seasonality in both parameters. What is the reason for the uncoupling? Can it be explained?

The text in section 2.1 has now been clarified to make it clear we calculated a climatology.

It is true that stratification potentially changed during this time period and also during the 20th century. Analysing this was out of the scope of this paper. However, it is important to quantify this relationship. It is true that there will be complex relationships between bed shear stress and stratification due to the influence of winds. So this ought to be resolved by future work.

In general, the goal of our study was to quantify the influence of bed shear stress on sediment in the water column, not necessarily its vertical profile. This was why the linear regressions in figure 3 were carried out when waters were mixed. Moving towards accounting for stratification is something we will consider in future.

The reason for the decoupling is that variations in the depth and strength of the thermocline etc. appear to be the dominant influence on sediment reaching the surface. This is also potentially complicated by the influence of winds on both waves and stratification.

The description of the methodology for figure 3 belongs in the methods chapter (per- haps 2.4), not the figure caption, and it needs elaboration. It says “For each mapped box and month, grid points with a 20y record of SPM are selected.” Are all grid points within a box selected for which there are 20y of continuous data, or are these random choices? Were the grid points that do not have continuous data coverage neglected?

We only chose grid points with a 20 year record to improve the quality of the data being used in the regressions. The points neglected are essentially those at the northern fringe of satellite coverage. These points have low reliability and we were retiscent to use then. This was an attempt to reduce the amount of variation in the data caused by poor satellite coverage. This potentially could have been developed further. It is noticeable that the R2 of the regression models are notably lower in January than in March.

A sentence has now been added to section 2.4 to clarify this.

Why was a complete area average unfeasible?

Area averaging is problematic because for some regions it can result in temporal comparisons not being apples to apples. Roughly speaking, we are trying to estimate what would happen if, say, bed shear stress doubled in a region. However, to do this the points of comparison must be consistent. The relationship between bed shear stress and SPM varies significantly in space due to variations in sediments and bathymetry. As a result, a strict area averaging will increase the amount of noise due to poor satellite coverage and could lead to sampling bias.

Furthermore, the authors again say that there is a “clear positive relationship”, which is easy to see e.g. for box 12, but not so much for e.g. box 1. Regression parameters are in the supplemented tables, but it would be much handier if they were besides the respective plots as well (at least R2).

We believe that the regression results should be interpreted carefully. A major challenge is understanding how much of the variation in SPM is caused by noise within the satellite SPM. This is particularly true for box 1, i.e. the north eastern North Sea. Our regressions show that there is a high p-value for the regressions in January, February and November, but not in March. This is potentially simply down to low light and cloud coverage creating a very noise satellite SPM record that cannot be explained in any detail by bed shear stress. Arguably some of the regressions should be removed because of this, but we believe it is better to caveat that there can be large uncertainties in the satellite SPM.

The parameters have now been moved to the main text.

Also, all boxes are of the same size, but some are only partially covered with water, some cross widely different domains, physically speaking (e.g. box 11 covering parts of the Rhine and East Anglia plume, but reaching close to the Dogger Bank, box 5 covering the Norwegian trench and thus depths from 50-300m). This may be as a minor nit-pick, but it could be argued that a more appropriate choice of boxes could have been made (e.g. as in Capuzzo et al. 2015 or O’Driscall 2014/ICES boxes).

The boxes were chosen as they could provide an estimate of the spatial variation. As with all choices they have limitations. We agree that alternatives are possible, but was unclear to us that they do not run into similar problems. For example, many of the zones used by Capuzzo et al. often cover a very broad range of shear stress, sediment and bathymetric regimes. Furthermore, our choice of boxes was motivated partly by the desire to choose regions that would have highly correlated wave climates, which makes aggregating bed shear stress over a region reasonable.

In figure 4, the changes in Secchi depth are marked as blue and red, yet ranging from +50 to +50 to positive. Red is presumably negative, i.e. a decline, so it should be -50% there.

Something went wrong when the figure was being tweaked prior to submission. We have now fixed this figure so that the legend is correct.

I really struggle with the sentence p.9, l.5. The evidence indicates an increase, more than it indicates a decline or no change (in that the plotted points are blue, and strongly so). Unless the data coverage is sufficient to make a claim, a claim should not be made. Perhaps a measure of certainty should be given (e.g. through marker size).

We believe that the original paragraph was suitably caveated, and we were clear that these results were indicative. Our key message here was that while the data show that there seems to have been a decline in water clarity across the North Sea, we cannot be sure it was universal. This was the implication of the work of Capuzzo et al. (2015), but there really isn’t sufficient data to be confident of the exact spatial details of the changes.

Again for figure 4, the relationship between decline in Secchi depth and bed stress change is hard to see at first. This may be due to sparsity of data, and as the authors stated earlier, the SPM content in the areas south of 53◦N are heavily influenced by river intrusions. Hence, modifying the map by highlighting areas of high river intrusions could help clarify the link between the left panels and the right. Furthermore, a less selective method of data comparison than choosing points with 50km of each other might help here as well.

At p.9, l.8, it says that there was a significant increase in BSS across the entire shelf between 1910-1929 and 1990-2019. This is immensely confusing, because previously (figure S2), a trend of decreasing BSS was shown for the latter period, so it invokes the understanding that the two periods are investigated individually, and not against each other. Perhaps this could be clarified by rephrasing. In the same paragraph it says that the changes are driven by increased significant wave height (SWH), which could be shown in a figure, e.g. by an area correlation. Is there literature as to why the increases in SWH were so variant over space?

The clarifying phrase “between the periods” has been added to the text.

We have amended the text to make it clear that long-term spatial variation in changes in bed shear stress are not simply down to changes in significant wave height, but that the relative importance of waves in determining bed shear stress is also critical. Figure 2 now shows the ratio of wave-only bed shear stress to combined wave and tide bed shear stress. This gives an indication of the regions of tide and wave dominance. Say we have a region where 10% of stress comes from waves, and one where 50% comes from waves. If we simplify the physics and ignore interactions a doubling of wave stress in one region will result in a 10% increase in overall stress, but it would result in a 50% increase in the other. So a lot of the spatial pattern in the 20th century changes really comes down to how relatively influential waves are.

Discussion: In the first paragraph of the discussion, it is argued that there is a decline in primary production (PP), which is attributed to reduced clarity. However, figure S1 shows decreasing trends in SPM. There is a need for elaboration as to why there can be declining SPM as a main contributor to turbidity and reduced PP. The authors later provide this elaboration on page 11, but for easier understanding, the two paragraphs should be interwoven. As a side note: a large number of Secchi depth measurements are taken from near shore stations, e.g. the NIOZ facility on Texel, NL. This will heavily skew measurements in a surrounding area.

We agree. The discussion has now been modified to combine these paragraphs. We further agree with the reviewer that there is great potential for Secchi depth measurements to be skewed in the way mentioned. While some existing studies fail to account for this, we also recognize that it is often very difficult to do so.

The statement in line 13-14 is too strong and needs to either be more strongly moti- vated (quantitatively), or weakened. In line 19 on page 10, it is again said that there would be an expected increase of 20% in SPM. There needs to be a source for this claim and a direct reference as to how this claim can be made.

We have reworded the sentence to say that wave regime was a driver of the decline in water clarity.

In lines 12ff on page 11, biological activity is mentioned as a potential impact on SPM and BSS. Note that before 1950, larger areas of the North Sea had benthic flora (see e.g. Capuzzo et al. 2015), which impacts BSS heavily (and thus also tides, as to my earlier point).

Relevant text has now been added.

Minor comments: A search for typos and grammar mistakes is appropriate. My main points of criticism are with the figures, as stated above.

Page 6, line 1: “Fig. 2 shows the R2 value for the linear regressions of 8-day SPM and bed shear stress and SPM for each month between 1997 and 2017, and stratification throughout the year.” This sentence is hard to follow. Perhaps it should be “. . . the linear regressions of 8-day SPM and bed shear stress [. . .] for each month. . .”?

This sentence has been tidied up

Line 2: “The relationship between bed shear stress shows a seasonal switch.”, seems to be missing that extra “SPM” from line 2. Line 5: “. . . driven. . . ”.

A correction has been added to the text.

Increasing turbidity in the North Sea during the 20th century due to changing wave climate

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Abstract. Data on Secchi disk-depth (the depth at which a standard white disk lowered into the water just becomes invisible to a surface observer) show that water clarity in the North Sea declined during the 20th century, with likely consequences for marine primary production. However, the causes of this trend remain unknown. Here we analyze the hypothesis that changes in the North Sea's wave climate were largely responsible, by increasing the concentrations of suspended particulate matter (SPM) in the water column through re-suspension of seabed sediments. First, we analyzed the broad-scale statistical relationships between SPM and bed shear stress due to waves and tides. We used hindcasts of wave and current data to construct a space-time dataset of bed shear stress between 1997 and 2017 across the northwest European Continental Shelf, and compared the results with satellite-derived SPM concentrations. Bed shear stress was found to drive most of the inter-annual variation in SPM in the hydrographically mixed waters of the central and southern North Sea. We then used a long-term wave reanalysis to construct a time series of bed shear stress from 1900 to 2010. This shows that bed shear stress increased significantly across much of the shelf over this period, with increases of over 20% in the south eastern North Sea. An increase in bed shear stress of this magnitude would have resulted in a large reduction in water clarity. Wave-driven processes are rarely included in projections of climate change impacts on marine ecosystems, but our analysis indicates that this should be reconsidered for shelf sea regions.

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1 Introduction

The vertical attenuation of light with depth in the oceans is a complex process of scattering and absorption by particulate and dissolved materials in the seawater. Particulate material may be biogenic or mineral. In the open ocean the majority of particles are biogenic, but this is often not the case in shallow shelf seas. Here, mineral suspended particulate matter (SPM) from land-runoff, dust deposition and re-suspension of seabed sediments can form the majority of light-scattering and absorbing material. The sub-surface light environment is a major determinant of primary production and the feeding behaviour and vertical distribution of visual predators (Dupont and Aksnes, 2012), so natural and anthropogenic factors which affect SPM concentrations in shelf seas have the potential to cause cascading trophic effects throughout food webs (Heath et al. 2016). Modern electronic instrumentation for measuring underwater light has only a recent history, but in many areas of the world there is a long archive of Secchi disk-depth measurements. These refer to the depth at which a standardized white disk lowered into the sea just becomes invisible to a surface observer. Secchi disk measurements have been collected in the North Sea since the early 1900s and show long-term declines in water clarity in the central and southern North Sea (Capuzzo et al., 2015; Dupont & Aksnes, 2013). It is speculated that these changes have impacted the ecology, including a decline in North Sea primary productivity over the last 25 years (Capuzzo et al., 2017).

A shallowing of Secchi disk depth by approximately 50% over the 20th century (Capuzzo et al., 2015) needs to be explained. Secchi disk depth might be expected to depend on both SPM and phytoplankton (chlorophyll) concentrations. However, empirical data show that by far the strongest correlation is with SPM, with a roughly 1:1 relationship between percentage change in SPM, and percentage reduction in Secchi disk depth (Håkanson, 2006). Hence we might expect the reported changes in the North Sea to be associated with substantial increases in SPM.

There are insufficient empirical data extending back to the early 20th century to directly estimate changes in SPM in the North Sea. An alternative is to analyze physical environmental drivers that might have led to changes in SPM. These might include widespread sediment disturbance due to waves and tides and more local disturbances due to human activities (trawling, dredging and mining), coastal erosion and inputs from river discharges (Capuzzo et al, 2015). Here we examine the scope for changes in SPM to have been caused by trends in natural bed-shear stress arising from the combination of tidal and wave climate. We can assume that the tidal regime in the North Sea has remained constant over the 20th century, despite there being some minor long-term changes due to long-period tides (Wunsch, 1967) and the influence of climate (De Dominicis et al., 2018). In contrast, hindcast simulations based on historical weather data consistently show that there has been a large increase in significant wave height in the North Sea (Vikebø et al., 2003; Weisse et al., 2012) and the entire northeast Atlantic (Gulev & Grigorieva, 2006).

This study has three aims. The first is to assess if there is evidence that the reductions in Secchi Disk depth occurred across the entire southern and central North Sea during the 20th century. The second is to establish the broad scale statistical relationship between inter-annual changes in bed shear stress and SPM. This relationship will show the potential sensitivity of SPM to long-term changes in bed shear stress. The third aim is to construct a time series of bed shear stress on the European Continental Shelf covering the years from 1900 to 2010. We then use the changes in bed shear stress to estimate the changes in SPM caused by changes in wind regime.

2 Methods

2.1 Summary and overview

The region of study was the northwest European Continental Shelf, which we define to be regions shallower than 150 meters between 48°N and 62°N and 13°W and 9°E. This region has large variation in seabed sediments (Wilson et al., 2018), wave and tidal conditions (Neill et al., 2014; Semedo et al., 2015), suspended sediment (van der Molen et al., 2016), and natural and anthropogenic disturbance of the seafloor (Aldridge et al., 2015; Diesing et al., 2013).

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Our two key goals were to 1) quantify the large-scale temporal relationship between bed shear stress and SPM across this region between 1997 and 2017 and 2) quantify how bed shear stress changed during the period 1900-2010. This choice of time periods was largely a result of the availability of data (table 1). High-resolution spatiotemporal maps of SPM are available through the conversion of satellite reflectance data to SPM (e.g. Gohin et al., 2011), and these are available for 1997 onwards. The calculation of bed shear stress requires data on bathymetry, sediment properties, and wave and tidal parameters. We assumed that long-term changes in bed shear stress were caused largely by changes in wave regime on the grounds that changes in tidal parameters are likely to be minimal. Bed shear stress was therefore calculated using climatological tidal conditions, bathymetry and sediment properties. Wave parameters are available from high resolution reanalysis products that cover both the present day and the 20th century. However, no single product exists that covers both the historical period we are interested in and the entirety of the satellite era. We therefore chose to calculate bed shear stress during the satellite SPM era using the ERA-interim reanalysis, which will provide the best available relationship between bed shear stress and SPM. For the 20th century, we used the ERA20c reanalysis which provides high resolution wave parameters for the period 1900-2010. All analysis was carried out at a spatial resolution of 0.125° by 0.125°.

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Table 1: Data used for calculation of bed shear stress and stratification indices over the time periods 1997-2017 and 1900-2010. Calculations were calculated at a spatial resolution of 0.125° by 0.125°, and all data was available at that or finer resolution.

	Data	**Source**	**Time period**	**Reference**
1	Tidal velocities	Scottish Shelf Model	Climatology	De Dominicis et al. 2017
2	Present day wave parameters	ERA-interim reanalysis	1997-2017	Dee et al., 2011
3	Historical wave parameters	ERA20c	1900-2010	Poli et al., 2016
4	Surface non-algal suspended -algal particulate matter	Copernicus-Globcolour	1997-2017	Gohin 2011
5	Surface and seabed temperature	Atlantic-European North West Shelf – Ocean Physics Reanalysis	1997-2014	O' Dea et al., 2012
6	Bathymetry	General Bathymetric Chart of the Oceans	-	GEBCO
7	Sediment parameters	Gridded median grain size map	-	Wilson et al., 2018

2.2 Suspended particulate matter and stratification

Monthly and 8-day estimates of non-algal surface SPM (g m^{-3}) from September 1997 to August 2017 were calculated using Copernicus-Globcolour data, which is derived from satellite observations using the algorithm of Gohin (2011). We used the Copernicus Marine Environment Monitoring Service (CMEMS, http://marine.copernicus.eu) global ocean SPM reprocessed product (QUID: http://resources.marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-030-032-033-037-081-082-083-085-086-098.pdf ; PUM: http://resources.marine.copernicus.eu/documents/PUM/CMEMS-OC-PUM-009-ALL.pdf). SPM data from Copernicus-Globcolour were available at 4 km resolution, and we therefore interpolated monthly SPM onto the 0.125° by 0.125° grid using bilinear interpolation.

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A seasonal climatology of near-surface SPM for the years 1997 to 2017 is shown in Fig. 1. SPM shows large spatial variation. Deeper regions typically have lower SPM due to lower rates of sediment re-suspension, greater sea-surface altitude above the seabed, and remoteness from river inputs. Coastal SPM is notably elevated near river plumes such as in the East Anglian Plume and near the Severn Estuary. Furthermore, there is a notable seasonal cycle, with SPM lowest in summer.

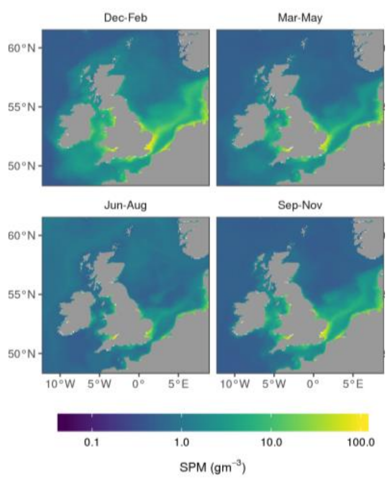

Figure 1: Seasonal climatologies of non-algal suspended particulate matter at the water surface for the period 1997-2017. SPM was calculated from Copernicus-Globcolour estimates which are derived from remote sensing data using the Gohin (2011) algorithm.

SPM concentrations throughout the water column are strongly determined by the combination of net re-suspension flux from the sediments and vertical mixing and turbulent diffusivity (Heath et al., 2017). Seasonal thermal stratification may therefore play a role in determining patterns of SPM in the near-surface waters. We therefore created a stratification index to analyze this influence.

Differences between surface and seabed temperature is a commonly used proxy for stratification level (Coma et al., 2009), and a difference of 0.5 °C has previously been used to reference the onset of seasonal stratificationin the North Sea (Quante et al., 2016). The water column was therefore classified as being stratified when the difference between the surface and seafloor temperature was greater than 0.5 °C. Daily temperatures were taken from the MetO-NWS-REAN-PHYS-004-009 reanalysis product, available from CMEMS. This reanalysis (PUM: http://resources.marine.copernicus.eu/documents/PUM/CMEMS-NWS-PUM-004-009.pdf; QUID: http://resources.marine.copernicus.eu/documents/QUID/CMEMS-NWS-QUID-004-009.pdf) uses the FOAM-AMM7 operational forecast system (O'Dea et al., 2012). Daily seabed temperatures from 1997-2014

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Deleted: These data were downloaded from the Copernicus Ma Environmental Monitoring Service website (http://marine.copernicus.eu/services-portfolio/access-to-product were interpolated onto each 0.125° by 0.125° grid point and we then calculated the average percentage of days the water column was stratified during each month. We then calculated a monthly climatological average for the period 1997-2014.

2.3 Bed shear stress calculations and inputs

Bed shear stress was calculated using an existing algorithm based on the vector combination of orbital velocities due to wave action and directed flows due to tidal and other barotropic and baroclinic currents over smooth and rough beds. The shear velocity due to tidal flow was calculated using the water column averaged velocity using the "law of the wall" method (Soulsby & Clarke 2005). This assumes that there is a logarithmic decrease in velocity with proximity to the sediment-water interface. Wave orbital velocities at the seabed were calculated using the equations of Soulsby (2006). Bed shear stress was then calculated using the equations of Soulsby & Clarke (2006), and this accounts for both the magnitude and the relative direction of tides and waves.

In most shallow shelf sea situations, the flows are dominated by tides. The physical inputs necessary for these equations are depth-averaged current speed and direction, wave orbital velocity amplitude and orientation at the seabed, bed roughness, and bathymetry. The wave orbital velocity calculations require data on significant wave height, wave direction, wave period and bathymetry as inputs. The equations used to calculate bed shear stress were summarized in Wilson et al. (2018).

Bathymetry data were acquired from the General Bathymetric Chart of the Oceans (GEBCO). Data were downloaded at 30 arc second resolution from https://www.gebco.net/data and products/gridded bathymetry data/. We then used bilinear interpolation to re-grid this to 0.125° by 0.125° resolution.

Depth-averaged tidal velocities were derived from an unstructured grid, finite-volume 3D hydrodynamic model FVCOM ("The Scottish Shelf Model"; De Dominicis et al., 2017). A one-year climatology (1990-2014) of atmospheric forcings was used to run the model. We assumed that annual changes in currents (mostly due to tides) have a negligible influence on inter-annual changes in bed shear stress.

Wave fields (significant wave height, period and direction) were acquired from reanalysis products from The European Centre for Medium-Range Weather Forecasts (ECMWF). The reanalysis product ERA-interim (Dee et al., 2011) provides a state of the art reconstruction of global climate from 1979 to the present day. This provided the wave fields necessary for bed shear stress calculations over the period 1997 to 2017.

Bed shear stress was hindcast further back in time using ERA20c (Poli et al., 2016), which provides a reanalysis of global climate from 1900 to 2010. Six hourly wave direction, period and significant wave height are available for this period. All ECMWF data was downloaded from the ECMWF website https://www.ecmwf.int at 6-hourly and 0.125° by 0.125° resolution.

Bed roughness was calculated from the median grain size maps of Wilson et al. (2018), which were developed using a combination of legacy sediment composition data and environmental conditions to create synthetic maps of median grain size across the northwest European shelf. Using the inputs outlined above, bed shear stress was calculated at 15 minute intervals over the 1900-2010 and 1997-2017 periods, across the entire 0.125° latitude x 0.125° longitude grid. Bed shear stress in wave-dominated regions will be more sensitive to changes in wave regime than in areas dominated by tides. We

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therefore mapped the ratio of wave-only bed shear stress to combined wave and tide bed shear stress. This gives an approximate indication of the contribution of waves to total bed shear stress.

2.4 Secchi disk depth data in the 20th century

Secchi Disk depth data were acquired from ICES (https://ocean.ices.dk/Project/SECCHI/), NOAA's World Ocean Database (https://www.nodc.noaa.gov/OC5/WOD/secchi-data-format.html) and Cefas (https://www.cefas.co.uk/cefas-data-hub/dois/cefas-historic-secchi-depth-measurements/). The data include all those analyzed by Capuzzo et al. (2015), and were subject to the same screening and checking.

Changes in Secchi disk depth were mapped by identifying comparable samples from before and after 1950 (following Capuzzo et al., 2015). First, we split the samples into spring, summer, autumn and winter periods. Then for each Secchi disk record before 1950 we compared it with the mean Secchi disk depth of all post-1950 samples within 50km.

2.5 Statistical modelling

The sensitivity of SPM to bed shear stress is not straightforward because biological activity causes seasonality in the consolidation of seabed sediments which affects the resistance of particulate material to resuspension (Heath et al., 2017). Hence, we analyzed the statistical relationship between SPM and bed shear stress on a month-by-month basis across years. Linear regressions were created for each 0.125° by 0.125° grid point and for larger compartmentalised regions in the North Sea. The response variable for the regressions was each available data point for 8-day SPM and the mean bed shear stress for that time period was treated as the predictor.

Illustrative large-scale relationships were also evaluated by dividing the North Sea into 10 2° by 2° compartments (Fig. 3). For each month between September 1997 and August 2017, mean SPM and bed shear stress was calculated for each compartment. In some boxes there were months when the northern cells occasionally lacked satellite SPM coverage due to cloud cover. We therefore only used cells which had 20 years of estimates. This prevents the possibility of spurious inferences due to sampling bias. For each month and compartment, we then created linear regressions of mean SPM and bed shear stress.

All statistical analysis was carried out in the statistical environment R, and data was manipulated principally using the R package dplyr (Wickham & Francois, 2016). The bed shear stress calculations were written in C++ and implemented as an R library using the package Rcpp (Eddelbuettel et al., 2011). Figures were produced using the package ggplot2. Spatial interpolation and processing of netcdf files were carried out using the Climate Data Operators tool (Schulzweida, 2017).

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3. Results

The mapped changes in Secchi disk depth (Fig. 2) show that Secchi disk depth declined (implying increasing SPM) across broad areas of the southern and central North Sea. However, this was potentially not uniform. Comparisons of pre- and post-1950 samples show a clear decline in Secchi disk depth in regions south of 53° N. Here, 89% of the comparisons (n-99) showed declines of Secchi disk depth, with Secchi disk depth declines of over 50% predominating, and this trend is consistent across seasons. In contrast, most of the comparisons in the region north of 53° N and west of 2° E show increases, implying declining SPM and increasing water clarity. However, the number of samples in this region is small, and this should only be viewed as indicative evidence that this region did not see declines in Secchi disk depth.

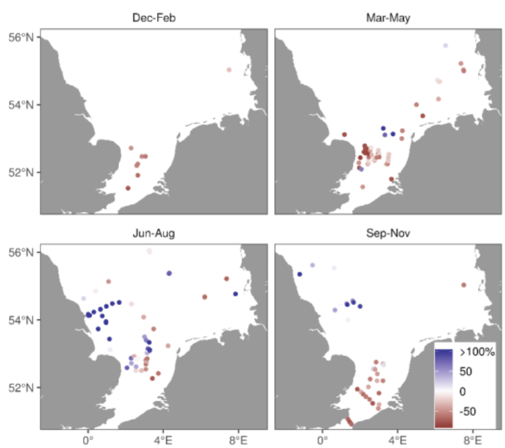

Figure 2: **: Seasonal changes in Secchi disk depth in the 20th century. Changes were estimated by detecting observations pre- and post-1950 that were in the same season and within 50 km of each other.**

Climatologies of bed shear stress and an approximation of the relative contribution of waves to bed shear stress are shown in Fig. 3. Bed shear stress is typically highest in low bathymetry coastal environments where surface energy can be more easily propagated to the seabed. However, some deep regions such as the English Channel also have high bed shear stress due to strong tidal currents. The contribution of waves to bed shear stress shows large spatial variation. Regions such as the English Channel, Norwegian Trench and Irish Sea are almost completely dominated by tidal forces. In contrast, much of the eastern

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North Sea and western Irish coasts are wave-dominated Bed shear stress follows a seasonal pattern because of the general decline of wave energy between winter and summer, and this is reflected by the large reduction in the role of waves in shear stress during summer months. For example, there is a pronounced decline in the role of waves in the Northern North Sea during summer months.

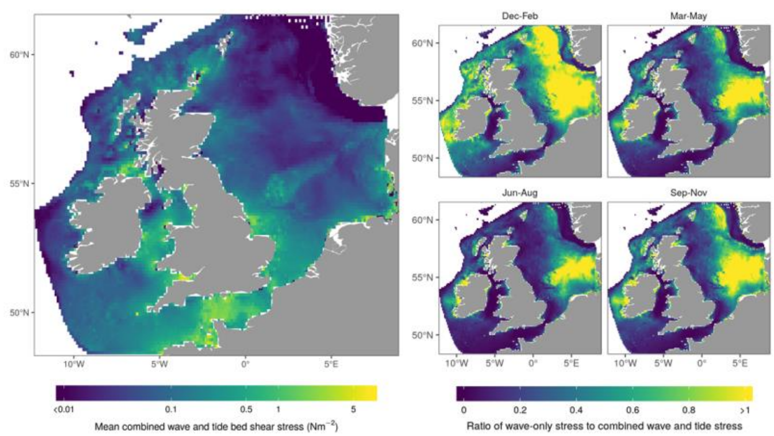

Figure 3. Left: Annual mean of combined wave and tide bed shear stress for 1997-2017. Right: ratio of mean wave-only stress to combined wave and tide stress. Regions with high ratios are wave-dominated, whereas regions with low ratios are tide-dominated. Bed shear stress was calculated using the equations of Soulsby and Clarke (2005) and tidal inputs from the Scottish Shelf Model and wave inputs from the ERA-interim reanalysis.

Fig. 4 shows the R^2 value for the linear regressions of 8-day SPM and bed shear stress using data from 1997 to 2017, and stratification throughout the year. The relationship between bed shear stress and SPM shows a seasonal switch. When the water column is vertically mixed, there is a clear positive relationship between SPM and bed shear stress across most of the study domain. The only exceptions are for river plumes such as the East Anglian Plume and the Severn Estuary, where SPM trends are likely driven by river flow and not the influence of waves on bed shear stress, and for tide dominated regions such as the English Channel where wave variation has little effect on bed shear stress. The inability of bed shear stress to explain SPM

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trends during stratified conditions implies that the depth and strength of the thermocline is the dominant influence on surface SPM through its influence on the vertical profile of SPM.

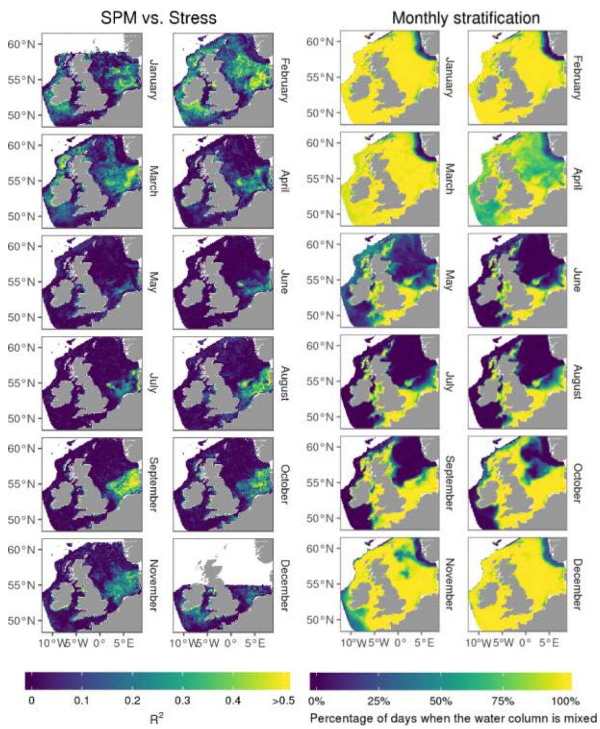

Figure 4. Monthly relationship between bed shear stress and SPM, and stratification. The left panel shows the monthly correlation coefficient between mean monthly SPM and bed shear stress in each 0.125° by 0.125° grid point between 1997 and 2017. The right panel shows the percentage of days when the water column is mixed, with the water column classified as mixed when the difference between the sea surface and seafloor temperature is less than 0.5° C. White areas in the region are those with insufficient satellite coverage for regressions.

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In contrast, the development of a stratified water column in spring sees the decoupling of trends in SPM from bed shear stress. The transition from mixed to stratified systems in spring is reflected in a significantly reduced relationship between SPM and bed shear stress. In Autumn the spread of mixed waters is reflected by an increased positive relationship between SPM and bed shear stress, shown clearly by comparing SPM and bed shear stress south west of Ireland and in the central northern North Sea in November.

Regional monthly regressions of SPM versus bed shear stress in the North Sea (Fig. 5) show a clear positive relationship between the two parameters. Comparison of the monthly regressions shows that the slope of the regression line is approximately the same across months. In contrast, the absolute values show a significant seasonal pattern. SPM declines after January once bed shear stress is controlled for. Linear regressions (Table 2) are significant ($p<0.05$) across almost all months and regions, and for the majority $p<0.01$. Time series of annual SPM in these regions show that there has been an apparent decline in SPM between 1997 and 2017 (Fig. S1). This trend is consistent with the decline in mean bed shear stress over the same period (Fig. S2).

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Table 2: Results of linear regressions of monthly SPM and bed shear stress. – indicates there is insufficient data for a regression. P-values below 0.01 are indicated using *.

	Parameter	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Jan	Intercept	-0.20	-	-	-0.84	-3.03	-0.99	1.25	2.40	-0.22	-1.81	5.89	-2.1
	Stress	21.52	-	-	68.79	64.87	28.75	5.69	6.53	80.16	56.78	25.39	53.86
	R^2	0.12	-	-	0.28	0.43	0.28	0.12	0.15	0.69	0.63	0.09	0.71
	p-value	0.13	-	-	0.02	<0.01	0.02	0.14	0.10	*	*	0.19	*
Feb	Intercept	0.15	-0.64	-0.06	-0.32	-3.29	-0.39	-0.18	0.94	-1.43	-0.89	-0.10	-0.46
	Stress	11.81	36.90	19.86	37.30	86.74	19.00	12.51	13.14	95.30	51.45	50.78	49.96
	R^2	0.046	0.38	0.48	0.57	0.53	0.23	0.26	0.28	0.75	0.71	0.37	0.54
	p-value	0.37	*	*	*	*	0.03	0.02	0.02	*	*	*	*
Mar	Intercept	-2.14	-0.53	0.04	-0.19	-1.52	-1.49	-0.35	0.31	-0.51	-0.84	2.61	-0.57
	Stress	31.86	31.24	15.50	32.69	58.68	27.57	13.16	14.27	77.27	46.18	29.95	43.60
	R^2	0.55	0.48	0.47	0.44	0.52	0.48	0.51	0.44	0.57	0.53	0.24	0.42
	p-value	*	*	*	*	*	*	*	*	*	*	0.02	*
Nov	Intercept	-0.52	0.08	0.08	-0.61	0.35	-0.71	-1.135	-0.60	-0.16	1.70	-0.29	1.34
	Stress	16.96	11.84	12.56	33.23	25.41	18.23	15.88	19.70	55.28	19.77	33.76	25.33
	R^2	0.14	0.31	0.41	0.56	0.30	0.26	0.51	0.57	0.53	0.27	0.28	0.26
	p-value	0.10	0.01	*	*	0.01	0.02	*	*	*	0.02	0.02	0.02

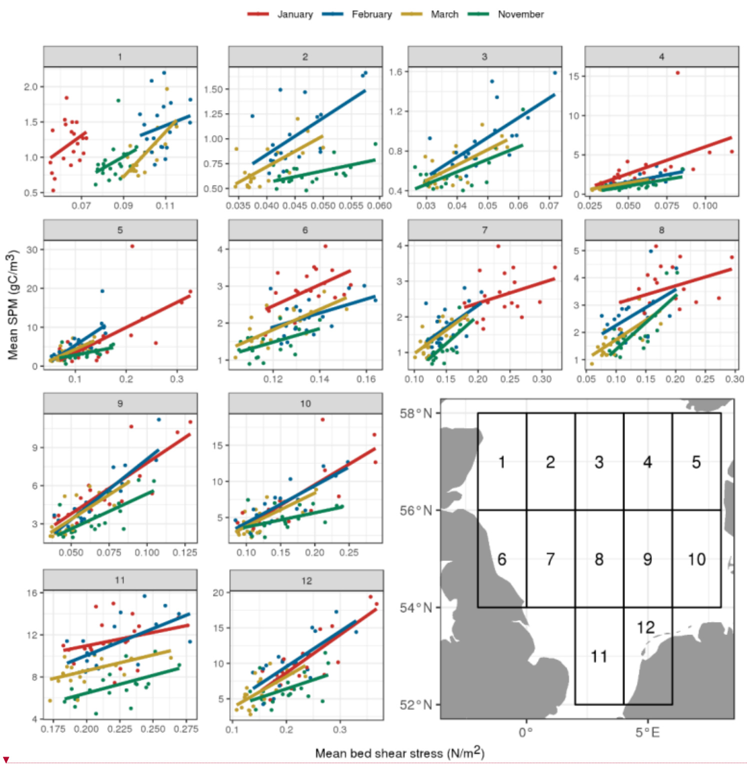

Figure 5. Monthly regressions of mean SPM and bed shear stress for binned regions in the North Sea. The coloured lines represent regressions for the months January, February, March and November. For each mapped box and month, grid points with a 20-year record of SPM are selected. The regression of monthly SPM and bed shear stress is then derived by averaging the selected values in each. Months shown are those where the water column is permanently mixed, with December ignored due to poor data coverage.

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Significant wave height data for the 20th century and the reconstructions of bed shear stress show that there were pronounced changes over the 20th century across much of the region (Fig. 6). Bed shear stress increased significantly across the entire shelf between the periods 1910-1929 and 1990-2019. However, there was pronounced geographic variation in these changes. The largest changes occurred in the central and eastern North Sea, and the northwest of Ireland. These increases were driven primarily by the geographic pattern of significant wave height changes, which similarly increased across the shelf over this period. In the southeast North Sea, increases of over 20% in significant wave height occurred over this time. In contrast, the northwest North Sea saw increases of only approximately 5%. The relative role of waves in determining bed shear stress (Fig. 2) has a strong influence on spatial variation in the changes. Regions such as the English Channel and Irish Sea that are tide dominated witnessed almost no changes in bed shear stress because any increase in waves will result in only a minor increase in overall stress. This also plays a key role in the North Sea, where the strong east-west difference in the pattern of bed shear stress is strengthened by the fact that the eastern North Sea is much more wind dominated.

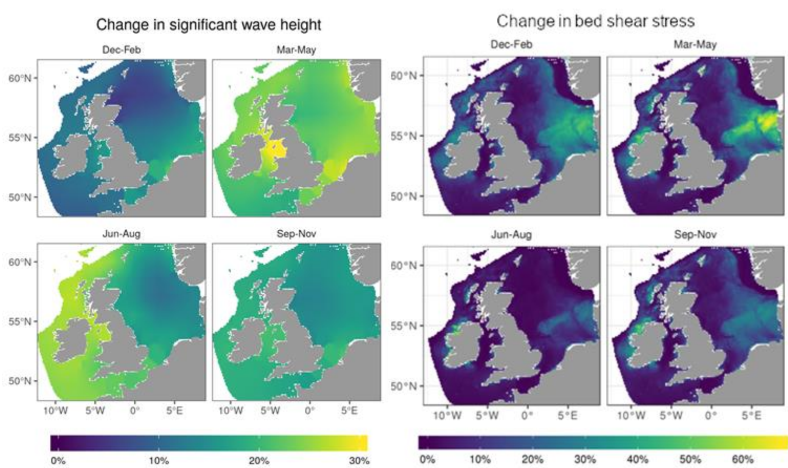

Figure 6. Left: changes in seasonal mean significant wave height over the 20th century. Right: changes in seasonal bed shear stress over the 20th century. Changes shown are between the climatological periods 1910-1929 and 1990 and 2009. Bed shear stress was calculated over the 20th century using the ERA20c wave reanalysis and present day tidal conditions, with significant wave height calculated using the ERA20c reanalysis wave heights.

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Estimated changes in SPM due to changes in bed shear stress over the 20th century show increases of >50% in January-March in the eastern North Sea (Fig. 4). In contrast, the western North Sea shows smaller increases of approximately 10%. There are negligible changes in tide-dominated areas such as the English Channel.

4. Discussion

We have shown that changes in the North Sea wave climate probably caused large reductions in water clarity during the 20th century. Since 1997, changes in SPM concentrations derived from remote sensing data are clearly correlated with changes in wave-induced bed shear stress, at least during winter months and in well-mixed regions of the shelf away from river plumes. Over the longer term, large parts of the southern and central North Sea experienced large increases in bed shear stress which would have had a large impact on water clarity.

Our results show that bed shear stress increased by over 20% in the eastern North Sea during the 20th century and rather less (around 10%) in the western and northern areas. Based on the regional regressions (Fig 4, Table 2), these changes would be expected to result in corresponding changes in SPM of approximately 10% (western) and 20% (eastern). This is corroborated to some extent by the historical Secchi disk depth data, which show that decreases in Secchi disk depth (implying increases in SPM) may have been concentrated in the southern and eastern North Sea (Fig. 4). Unfortunately, Secchi disk depth data are sparse in the western and northern North Sea, and it is impossible to rule out that observed changes are due to random environmental effects. Improvements in the historical Secchi disk depth record are possible, but perhaps unlikely. Online text mining approaches have already been used to locate data in published literature (Aarup, 2002), and these are all incorporated into the NOAA data set used here. There is also no evidence of the existence of other accessible Secchi disk depth data for the northern North Sea, which is sparsely covered in the databases used here, despite anecdotal reports of the use of the device in early 20th century oceanographic surveys.

A key motivation for this study was the recent use of trends in light attenuation (Devlin et al., 2008) to impute changes in gross primary production (Capuzzo et al. 2017) and phytoplankton phenology in the North Sea (Opdal et al., 2019). Capuzzo et al. concluded that North Sea primary production declined during the period 1988-2013, and that this trend influenced zooplankton abundances and fish recruitment, implying climate-induced ‘bottom-up’ changes in in the North Sea food web. Similarly, Opdal et al. (2019) concluded that phytoplankton bloom was delayed during the 20th century. A key driver of these conclusions was an apparent increase in light attenuation over their study periods.

Our combined analysis of bed shear stress and satellite remote sensing data on SPM shows that the 20th century decline in water clarity has reversed to some extent since 1997 (Fig. S1 and S2). Between 1997 and 2017, SPM and bed shear stress showed a declining linear trend in almost all parts of the North Sea (implying decreasing light attenuation). This is in direct contrast with the conclusions of Capuzzo et al. (2015, 2017), who determined that light attenuation had an increasing trend up to 2013. Indeed, this was a major factor in their imputed decline in gross primary production. However, Capuzzo et al. (2017) based regional estimates of light attenuation on sparsely distributed field measurements of light and SPM vertical profiles from

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Deleted: The key question explored by this study is what cause historic reductions in water clarity across the central and southern North Sea, in particular the decline since the early years of the 20 century implied by Secchi disc depth data (Capuzzo et al. 2015). is important because the consequent changes in light attenuation (Devlin et al., 2008) have been used to impute changes in gross primary production (using methods of Cole and Cloern, 1987) as basis for a cross-correlation analysis with higher trophic levels (Capuzzo et al. 2017). This concluded that North Sea primary production declined during the period 1988-2013, and that this tr influenced zooplankton abundances and fish recruitment, implyin climate-induced ‘bottom-up’ changes in in the North Sea food w A key driver of these conclusions was an apparent increase in lig attenuation over the study period.¶
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ships and moorings rather than remote sensing. Inspection of the spatial distributions of their field data suggests a possible bias leading to greater sampling of river plumes in later years. We therefore caution that resolving the spatial variations in SPM is necessary for robust estimates of the regional light environment and estimates of primary production trends.

Regressions of satellite remote sensing SPM versus bed shear stress across the southern North Sea when waters are mixed indicate that approximately half of the annual variance in SPM can be explained by bed shear stress. However, this is likely an underestimate of the influence of bed shear stress on SPM. 8-day estimates of SPM are uncertain due to the sporadic nature of the remote sensing data because of cloud cover. In addition, there is an imperfect relationship between satellite-derived SPM and in situ SPM, potentially because of a failure to distinguish between SPM and phytoplankton in some months (Jafar-Sidik et al. 2017). This implies that there will be a significantly large error term in our linear regressions due to differences between satellite and in situ SPM, and that the R^2 values reported here under-estimate the influence of bed shear stress on SPM.

Variations in biological activity in seabed sediments may also affect the sensitivity of SPM to bed shear stress. Heath et al. (2017) showed that seasonal patterns of in situ turbidity at a study site in the north-western North Sea could not be fully explained by variations in bed shear stress alone. It was argued that seasonal consolidation of sediments due to biological activity significantly affects re-suspension and hence turbidity. This phenomenon is well known in shallow estuaries but less so in deeper offshore regions. Here we provide further evidence for this effect. Monthly regressions of SPM versus bed shear stress showed that SPM has a seasonal component, even when bed shear stress is controlled for, and the analysis is restricted to times when the water column is mixed. Importantly, there is evidence that benthic communities have declined in parts of the North Sea (Capuzzo et al. 2015), which potentially influenced biological activity and sediment resuspension.

Geographic variations in the sensitivity of bed shear stress to wave properties will also affect the relationship with SPM. We would expect total bed shear stress to be insensitive to wave energy in areas where tidal currents are strong. Hence, tide-dominated regions, such as the English Channel, show little proportional change in bed shear stress over the 20th century.

We have shown that wave climate is an important control of water clarity and hence light attenuation. A potential continued increase in wave energy, and thus reduction in water clarity would act as a further climate change pressure on the North West European Shelf ecosystem. However, current projections using global assessments indicate that significant wave height will decline over the 21st century (Hemer et al., 2013, Wang et al., 2014, Wang et al., 2015), with greater reductions under higher emissions scenarios (Aarnes et al., 2017). However, the picture appears to be more complex when looking at regional models, which project clear increases in significant wave height in the eastern, but not western North Sea (Grabemann et al., 2015). Projections of the future impact of anthropogenic climate change on the world's shelf sea ecosystems should therefore consider the future evolution of wave regimes.

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Code availability

The code used for the calculation of bed shear stress is available as an R package on GitHub (https://github.com/r4ecology/bedshear).

Data availability

During peer review, monthly time series of bed shear stress from 1900-2010 and from 1997 to 2017 are available in netcdf format from https://strathcloud.sharefile.eu/d-s20cbaea41204964a and https://strathcloud.sharefile.eu/d-sdc05715d3c547f18 respectively. Post peer review, data will be made available with a permanent DOI.

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Author contributions

RJW drafted the manuscript and RJW and MRH contributed equally to its refinement. MRH was responsible for funding acquisition. Data analysis was carried out by RJW. Bed shear stress R package was created by RJW and MRH. Figures were prepared by RJW.

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References

Aarnes, O. J., Reistad, M., Breivik, Ø., et al.: Projected changes in significant wave height toward the end of the 21st century: Northeast Atlantic, Journal of Geophysical Research: Oceans, 122, 3394–3403, doi:10.1002/2016JC012521, 2017.

Aarup, T..:Transparency of the North Sea and Baltic Sea - A Secchi depth data mining study. Oceanologia, 44(3), 323–337. https://doi.org/http://ocean.ices.dk/Project/SECCHI/Secchi.pdf, 2002.

Aldridge, J. N., Parker, E. R., Bricheno, L. M., Green, S. L., van der Molen, J.: Assessment of the physical disturbance of the northern European Continental shelf seabed by waves and currents, Continental Shelf Research, 108, 121–140, doi:10.1016/j.csr.2015.03.004, 2015.

Capuzzo, E., Lynam, C. P., Barry, J., et al.: A decline in primary production in the North Sea over 25 years, associated with reductions in zooplankton abundance and fish stock recruitment, Global Change Biology, 24, 352–364, doi:10.1111/gcb.13916, 2017.

Capuzzo, E., Stephens, D., Silva, T., Barry, J., Forster, R. M.: Decrease in water clarity of the southern and central North Sea during the 20th century, Global Change Biology, 21, 2206-2214, doi:10.1111/gcb.12854, 2015.

Cole, B. E., Cloern, J. E.: An empirical model for estimating phytoplankton productivity in estuaries. Marine Ecology Progress Series, 36, 299–305. https://doi.org/10.3354/meps036299, 1987.

Coma, R., Ribes, M., Serrano, E., Jiménez, E., Salat, J., & Pascual, J.: Global warming-enhanced stratification and mass mortality events in the mediterranean. Proceedings of the National Academy of Sciences of the United States of America, 106(15), 6176–6181, , 2009.

De Dominicis, M., O'Hara Murray, R., Wolf, J.: Multi-scale ocean response to a large tidal stream turbine array, Renewable Energy, 114, 1160-1179, doi:10.1016/j.renene.2017.07.058, 2017.

De Dominicis, M., Wolf, J., & O'Hara Murray, R.: Comparative Effects of Climate Change and Tidal Stream Energy Extraction in a Shelf Sea. Journal of Geophysical Research: Oceans, 123(7), 5041–5067, 2018.

Dee, D. P., Uppala, S. M., Simmons, A. J., et al.: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society, 137, 553–597, doi:10.1002/qj.828, 2011.

Devlin, M. J., Barry, J., Mills, D. K., et al.: Relationships between suspended particulate material, light attenuation and Secchi depth in UK marine waters. Estuarine, Coastal and Shelf Science, 79(3), 429–439. https://doi.org/10.1016/j.ecss.2008.04.024, 2008.

Diesing, M., Stephens, D., Aldridge, J.: A proposed method for assessing the extent of the seabed significantly affected by demersal fishing in the Greater North Sea, ICES Journal of Marine Science, 70, 1085–109, doi:10.1093/icesjms/fst048, 2013.

Dupont, N., Aksnes, D. L.: Effects of bottom depth and water clarity on the vertical distribution of Calanus spp. Journal of Plankton Research, 34(3), 263–266, doi:10.1093/plankt/fbr096, 2012.

Dupont N, Aksnes D: Centennial changes in water clarity of the Baltic Sea and the North Sea, Estuarine, Coastal and Shelf Science, 131, 282–289, doi:10.1016/j.ecss.2013.08.010, 2013.

Eddelbuettel, D,, Francois, R., Allaire, J., Chambers, J., Bates, D., Ushey, K.: Rcpp: Seamless R and C++ integration, Journal of Statistical Software, 40, 1–18, 2011.

Gohin, F.: Annual cycles of chlorophyll-a, non-algal suspended particulate matter, and turbidity observed from space and in-situ in coastal waters, Ocean Science, 7, 705–732, doi:10.5194/os-7-705-2011, 2011.

Grabemann, I., Groll, N., Mollër, J., Weisse, R.: Climate change impact on North Sea wave conditions: a consistent analysis of ten projections, Ocean Dynamics, 65, 255–267, doi:10.1007/s10236-014-0800-z, 2015.

Gulev, S. K., Grigorieva, V.: Variability of the winter wind waves and swell in the North Atlantic and North Pacific as revealed by the voluntary observing ship data, Journal of Climate, 19, 5667–5685, doi:10.1175/JCLI3936.1, 2006.

Håkanson, L.: The relationship between salinity, suspended particulate matter and water clarity in aquatic systems, Ecological Research, 21, 75–90, doi:10.1007/s11284-005-0098-x, 2006.

Heath, M., Sabatino, A., Serpetti, N., McCaig, C., O'Hara Murray, R.: Modelling the sensitivity of suspended sediment profiles to tidal current and wave conditions, Ocean & Coastal Management, 147, 49-66, doi:10.1016/j.ocecoaman.2016.10.018, 2017.

Heath, M. R., Speirs, D. C., Steele, J.H.: Understanding patterns and processes in models of trophic cascades, Ecology Letters, 17, 101-114, 2014.

Hemer, M. A., Fan, Y., Mori, N., Semedo, A., Wang, XL.: Projected changes in wave climate from a multi-model ensemble, Nature Climate Change, 3, 471–476, doi:10.1038/nclimate1791, 2013.

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Jafar-Sidik, M., Gohin, F., Bowers, D., Howarth, J., & Hull, T.: The relationship between Suspended Particulate Matter and Turbidity at a mooring station in a coastal environment: consequences for satellite-derived products. *Oceanologia*, *59*, 365–378. https://doi.org/10.1016/j.oceano.2017.04.003, 2017.

Neill, S. P., Hashemi, M. R., Lewis, M. J.: Optimal phasing of the European tidal stream resource using the greedy algorithm with penalty function, Energy, 73, 997–1006, doi:10.1016/j.energy.2014.07.002, 2014.

O'Dea, E. J., Arnold, A. K., Edwards, K. P., Furner, R., Hyder, P., Martin, M. J., Siddorn, J. R., Storkey, D., While, J., Holt, J. T., Liu, H.: An operational ocean forecast system incorporating NEMO and SST data assimilation for the tidally driven European North-West shelf. Journal of Operational Oceanography, 5(1), 3–17. https://doi.org/10.1080/1755876X.2012.11020128, 2014.

Opdal, A. F., Lindemann, C., & Aksnes, D. L.: Centennial decline in North Sea water clarity causes strong delay in phytoplankton bloom timing. Global Change Biology, accepted, 2019.

Poli, P., Hersbach, H., Dee, D. P., et al.: ERA-20C: An Atmospheric Reanalysis of the Twentieth Century, Journal of Climate, 29, 4083–4097, doi:10.1175/JCLI-D-15-0556.1, 2016.

Quante, M., Colijn, F.: North Sea Region Climate Assessment. Springer. https://doi.org/10.1007/978-3-319-39745-0, 2016.

Schulzweida, U.: CDO User's Guide, pp. 1–206, 2017.

Semedo, A., Vettor, R., Breivik, Ø,, Sterl, A., Reistad, M., Soares, C. G., Lima, D.: The wind sea and swell waves climate in the Nordic seas, Ocean Dynamics, 65, 223–240, doi:10.1007/s10236-014-0788-4, 2015.

Soulsby, R.: Simplified calculation of wave orbital velocities, Tech. rep., HR Wallingford Ltd., Wallingford, 2006.

Soulsby. R. L., Clarke, S.: Bed shear-stresses under combined waves and currents on smooth and rough beds, HR Wallingford, Report TR137, 2005.

van der Molen, J., Ruardij, P., Greenwood, N.: A 3D SPM model for biogeochemical modelling, with application to the northwest European continental shelf, Journal of Sea Research, 127, 63–81, doi: 10.1016/j.seares.2016.12.003, 2016.

Vikebø, F., Furevik, T., Furnes, G., Kvamstø, N. G., Reistad, M.: Wave height variations in the North Sea and on the Norwegian Continental Shelf, 1881-1999, Continental Shelf Research, 23, 251–263, doi: 10.1016/S0278-4343(02)00210-8, 2003.

Wang, X. L., Feng, Y., Swail, V.R.: Changes in global ocean wave heights as projected using multimodel CMIP5 simulations, Geophysical Research Letters, 41, 1026–1034, doi:10.1002/2013GL058650, 2014.

Wang, X. L., Feng, Y., Swail, V.R.: Climate change signal and uncertainty in CMIP5-based projections of global ocean surface wave heights, Journal of Geophysical Research: Oceans, 120, 3859–3871, doi:10.1002/2015JC010699, 2015.

Weisse, R., von Storch, H., Niemeyer, H.D., Knaack, H.: Changing North Sea storm surge climate: An increasing hazard? Ocean and Coastal Management, 68, 58–68, doi:10.1016/j.ocecoaman.2011.09.005, 2012.

Wickham, H., Francois, R.: dplyr: A grammar of data manipulation, R package version 0.43, 2016.

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Wilson, R. J., Speirs, D. C., Sabatino, A., Heath, M. R.: A synthetic map of the north-west European Shelf sedimentary environment for applications in marine science, Earth System Science Data, 10, 109–130, doi:10.5194/essd-10-109-2018, 2018.

Wunsch, C.: The long-period tides. Reviews of Geophysics, 5(4), 447, 1967.

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